Lappeenranta
University of Technology

Juha Haakana

IMPACT OF RELIABILITY OF SUPPLY ON LONG-TERM DEVELOPMENT APPROACHES TO ELECTRICITY DISTRIBUTION NETWORKS

Thesis for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in the Auditorium 1382 at Lappeenranta University of Technology, Lappeenranta, Finland on the 5th of December, 2013, at noon.

Acta Universitatis
Lappeenrantaensis 547

Supervisor	Professor Jarmo Partanen Department of Electrical Engineering LUT Institute of Energy Technology LUT School of Technology Lappeenranta University of Technology Finland
Reviewers	Professor Emeritus Erkki Lakervi Department of Electrical Engineering School of Electrical Engineering Aalto University Finland
	Professor Pekka Verho Department of Electrical Engineering Tampere University of Technology Finland
Opponent	Professor Pekka Verho Department of Electrical Engineering Tampere University of Technology Finland

ISBN 978-952-265-507-3
ISBN 978-952-265-508-0 (PDF)
ISSN-L 1456-4491
ISSN 1456-4491
Lappeenrannan teknillinen yliopisto
Yliopistopaino 2013

Abstract

Juha Haakana
Impact of reliability of supply on long-term development approaches to electricity distribution networks
Lappeenranta 2013
85 p.
Acta Universitatis Lappeenrantaensis 547
Diss. Lappeenranta University of Technology
ISBN 978-952-265-507-3, ISBN 978-952-265-508-0 (PDF)
ISSN-L 1456-4491, ISSN 1456-4491

The Finnish electricity distribution sector, rural areas in particular, is facing major challenges because of the economic regulation, tightening supply security requirements and the ageing network asset. Therefore, the target in the distribution network planning and asset management is to develop and renovate the networks to meet these challenges in compliance with the regulations in an economically feasible way. Concerning supply security, the new Finnish Electricity Market Act limits the maximum duration of electricity supply interruptions to six hours in urban areas and 36 hours in rural areas. This has a significant impact on distribution network planning, especially in rural areas where the distribution networks typically require extensive modifications and renovations to meet the supply security requirements.

This doctoral thesis introduces a methodology to analyse electricity distribution system development. The methodology is based on and combines elements of reliability analysis, asset management and economic regulation. The analysis results can be applied, for instance, to evaluate the development of distribution reliability and to consider actions to meet the tightening regulatory requirements. Thus, the methodology produces information for strategic decision-making so that DSOs can respond to challenges arising in the electricity distribution sector. The key contributions of the thesis are a network renovation concept for rural areas, an analysis to assess supply security, and an evaluation of the effects of economic regulation on the strategic network planning. In addition, the thesis demonstrates how the reliability aspect affects the placement of automation devices and how the reserve power can be arranged in a rural area network.

Keywords: Renovation, reliability, electricity distribution, strategic planning, underground cabling, network automation, medium-voltage networks, supply security, economic regulation

UDC: 621.316:620.9:658.14/.17

Acknowledgements

The results of this doctoral thesis are mainly based on the research projects carried out during 2009–2013 at the Laboratory of the Electricity Markets and Power Systems, Institute of Energy Technology (LUT Energy) at Lappeenranta University of Technology.

I owe my deepest gratitude to the supervisor of this work, Professor Jarmo Partanen for his guidance, encouragement, valuable contribution during this work and long-time support on my research path.

I want to thank Dr. Jukka Lassila, Mr. Tero Kaipia and Dr. Samuli Honkapuro for their advice and experience that have promoted the completion of the thesis. I also want to thank all the co-workers in the Laboratory of Electricity markets and Power Systems who have created a great atmosphere to carry out the research work. In addition, I wish to thank the distribution utilities who have contributed to this work.

I thank the preliminary examiners Professor Emeritus Erkki Lakervi from Aalto University and Professor Pekka Verho from Tampere University of Technology for their invaluable feedback and comments, as well as their genuine interest in the topic and their willingness to engage with the pre-examination process.

Special thanks are reserved for Dr. Hanna Niemelä for her valuable assistance in the preparation of this manuscript.

Further, I want to thank Asset Vision Ltd, which has provided an excellent base for applying the developed methodology to practice in actual projects.

The financial support of Walter Ahlström Foundation, South Karelia Regional Fund of the Finnish Cultural Foundation, Fortum Foundation, Ulla Tuominen Foundation and the Finnish Foundation for Technology Promotion (TES) is gratefully acknowledged.

My warmest thanks go to my parents Maarit and Risto, who have always supported me and provided immeasurable support throughout my life.

Finally, my deepest thanks go to my wife Taina for her love during the process and my wonderful daughter Eevi for an inspirational family atmosphere.

Juha Haakana
November 2013
Lappeenranta, Finland

Contents

List of publications

1. Haakana, J., Lassila, J., Kaipia, T. and Partanen, J. (2012). ”Utilisation of reliability and asset management tool in strategic planning.” In *Proceedings of the CIRED 2012 Workshop, Integration of Renewables into the Distribution Grid*. Lisbon, Portugal.
2. Haakana, J., Lassila, J., Kaipia, T. and Partanen, J. (2010). “Comparison of Reliability Indices from the Perspective of Network Automation Devices.” *IEEE Transactions on Power Delivery*, Vol. 25, No. 3, pp. 1547–1555.
3. Haakana, J., Kaipia, T., Lassila, J. and Partanen, J. (2011). “Simulation Method for Evaluation of the Challenges in the Reliability Performance of Medium-Voltage Networks.” In *Proceedings of the 17th Power Systems Computation Conference PSCC 2011*. Stockholm, Sweden.
4. Haakana, J., Lassila, J., Honkapuro, S. and Partanen, J. (2012). “Renovation Strategies and Economic Regulation in Electricity Distribution.” *IET Generation, Transmission & Distribution*, Vol 6. No. 10, pp. 1019–1028.
5. Haakana, J., Lassila, J., Kaipia, T. and Partanen, J. (2009). “Underground Cabling Strategies in Rural Area Electricity Distribution Network.” In *Proceedings of the CIRED 2009, 20th International Conference and Exhibition on Electricity Distribution*. Prague, Czech.
6. Haakana, J., Lassila, J., Kaipia, T., Partanen, J., Niemelä, H. and Lohjala, J. (2012). “Cabling Concept in Large-Scale Renovation of Rural Area Networks.” *International Journal of Energy Sector Management*, Vol. 6, No. 3, pp. 282–300.
7. Haakana, J., Kaipia, T., Lassila, J. and Partanen, J. (2013). “Reserve power arrangements in rural area underground cable networks.” *IEEE Transactions on Power Delivery,* forthcoming.

Nomenclature

Roman letters

a	announced interruptions
c	unit outage cost
C	cost
$\hat{C}$	cost frontier
d	duration of interruptions
f	fault frequency
i	index of, index of line type
I	current
j	index of line condition
k	index of year, line index
l	load, line length, index of line
m	index of substation
n	number of interruptions
N	number of parameters
p	line index
q	line index
P	all placement configuration of automation devices
S	cost savings
t	index of year, time
u	unannounced interruptions
U	voltage
V	electricity network
W	energy
x	placement of automation device
X	company specific efficiency requirement
y	product variable in efficiency benchmarking
z	cabling rate in efficiency benchmarking

Acronyms

ASAI	average service availability index
ASIDI	average system interruption duration index
ASIFI	average system interruption frequency index
ATOTEX	allowed efficiency costs in the regulatory model
CAIDI	customer average interruption duration index
CAIFI	customer average interruption frequency index
CAP	capital costs
COC	customer outage costs
COPEX	controllable operational costs in the regulatory model
CPI	consumer price index

DAR	delayed autoreclosings
DEA	Data Envelopment Analysis
DSO	distribution system operator
EP	exceeding probability
ES	efficiency score
Eff.	efficiency
EMA	Energy Market Authority of Finland
ET	Finnish Energy Industries
IEEE	Institute of Electrical and Electronics Engineers
HSAR	high-speed autoreclosings
KTM	former Ministry of Trade and Industry in Finland
L	load
LV	low-voltage
MAIFI	momentary average interruption frequency index
Max	maximise
MDP	major-disturbance-proof
MDPR	major-disturbance-proof rate
Min	minimise
MV	medium-voltage
NPV	net present value
OP	owner's profit
OPEX	operational costs
Ref	reference
RMU	ring main unit
RRC	reasonable return on capital in the regulatory model
RV	replacement value
SAIDI	system average interruption duration index
SAIFI	system average interruption frequency index
SC	short circuit
SFA	Stochastic Frontier Analysis
SLD	straight-line depreciations
StoNED	Stochastic Non-smooth Envelopment of Data
SUB	Substation
TC	total costs
TEM	Ministry of Employment and the Economy in Finland
TOTEX	efficiency costs in the regulatory model
VD	voltage drop
WACC	weighted average cost of capital
WP	weatherproof
WPR	weatherproof rate

1 Introduction

The function of electricity distribution is to deliver electricity to the customers with an adequate quality of supply. The quality of supply can be divided into two categories: power quality and reliability of supply, which plays a key role in this doctoral thesis. At present, rural area electricity distribution is facing significant changes in the operating environment as the reliability of supply should be considerably improved while a significant part of the network asset is reaching the end of its lifetime especially in Finland, which is in the focus of the doctoral thesis.

The significance of the reliability of electricity supply has been emphasised over the recent years. Long interruptions are highly undesirable, and thus, the distribution system operators are often obliged to compensate long interruptions to the customers. In Finland, the recent storms causing long-lasting interruptions (even weeks) have made the regulator and other authorities to reconsider the state of supply quality. As a consequence, certain duration limits on the allowed supply interruptions have been determined to reduce the harm caused by interruptions. Modern society is highly dependent on electrical energy, and thus, supply interruptions cause serious problems to many activities and routines; industrial processes may fail, commercial services and lighting do not work, maintenance and operation of agricultural production are endangered, and households experience trouble in heating houses, cooling of refrigerators and freezers, and in many other daily routines.

1.1 Changes in the operating environment

The operating environment of the electricity distribution sector has changed considerably over the past ten years. In the present environment there are several elements impacting the focus of operation such as economic regulation, improvement in electric power distribution reliability, an increase in distribution automation, adoption of underground cabling and other new technologies, and finally, ageing of the distribution asset. These elements of change are illustrated in Figure 1.1, which highlights some key issues and events in the distribution business since 2001.

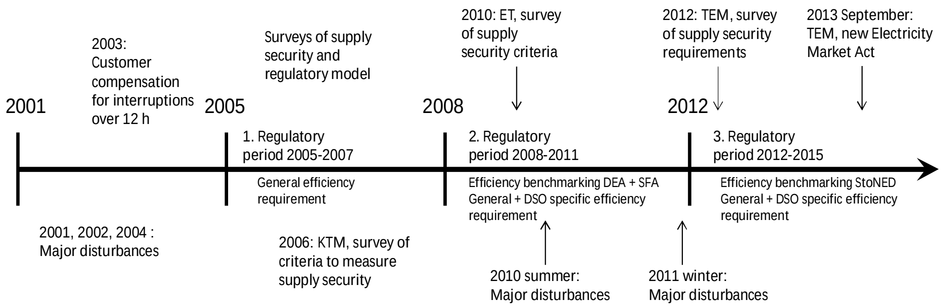

Figure 1.1. Important issues influencing the operating environment of the electricity distribution sector between 2005 and 2013. KTM (the Finnish Ministry of Trade and Industry, from 2008 onwards merged into the Finnish Ministry of Employment and the Economy, TEM), ET (Finnish Energy Industries).

In the early 2000s, the most important issues in the electricity distribution were the inclusion of economic regulation in the electricity distribution business, customer compensation payments and the improvement of distribution reliability. Economic regulation was fairly new in this line of business, and customer outage costs were considered to be an important factor to measure the quality of supply. Efficiency benchmarking was also coming into regulation. The aim of the distribution network development was to improve reliability at a general level, and thus, the role of network automation was significant. The trend of the time can be seen in the publications of this doctoral thesis, as two of the publications (Publications II and IV) deal with the issues (distribution automation and economic regulation) peculiar to the time. Further, at that time, the first initiatives towards rural area underground cabling were made as a result of large-scale disturbances caused by storms in Finland and in Sweden. However, the general opinion was not to carry out such an extensive supply security renovation program as it is now considered necessary with the present knowledge. The first studies considering underground cabling were carried out at the beginning of the 21st century. The first publication of this doctoral thesis concerning underground cabling renovation strategies was published in 2009 (Publication V).

With reference to certain long-lasting electricity supply disturbances in Finland (storms Pyry and Janika in 2001, Unto in 2002, Rafael in 2004) and in the neighbour country Sweden (Gudrun in 2005), the Finnish Ministry of Trade and Industry commissioned a study (Partanen et al., 2006) to determine a reasonable number for supply interruptions and draw up a recommendation for the supply security. As a result of the study, the Electricity Market Act was not yet tightened, but loose criteria were launched providing the first signals to limit the duration of supply interruptions in Finland. The report by Partanen et al. (2006) was a start for extensive studies to measure and evaluate the reasonable supply security. In 2010, the Finnish Energy Industries published supply security criteria and target levels of electricity distribution in a report by Partanen et al. (2010) as a continuation of the previous study. The studies provoked a lot of discussion about the distribution network development and underground cabling, and promoted the adoption of underground cabling in rural areas. An important element of the analysis was to assess the risk to experience a long supply interruption. For the analysis, a methodology was developed that determines the instruments (risk levels) to assess the fulfilment of the criteria in a network to be analysed. The methodology is discussed in Publication III.

The discussion about boosting the renovation activities, including a significant increase in the underground cabling rate, started in the 2010 after heavy summer storms that destroyed thousands of kilometres of distribution networks and left customers without electricity for several weeks at worst. The published supply security criteria seemed to be useful for the electricity distribution sector. However, only one year later, the next major storms reached Finland in the last days of 2011, and the supply interruptions lasted for two weeks. Finally, this led to the preparation of the new Electricity Market Act that sets certain time limits on allowed interruption durations. The most recent publications (Publications VI and VII) of this doctoral thesis provide a close view to the concept of underground cabling and reserve power arrangements in underground cable networks, which play a key role to meet the requirements of better supply security. The writing of these publications has been started before the final survey on supply security requirements (Partanen et al., 2012b).

1.2 Drivers in distribution network renovation

The main drivers for the renovation of the distribution networks are reliability issues and network ageing; nevertheless, also the load capacity, circumstantial factors and several other issues such as losses, voltage drops and short-circuit currents play their role in the evaluation of renovation. With this in mind, in the evaluations carried out in this thesis, the main drivers for the network renovation are listed as follows:

- Reliability
- Ageing of the distribution network
- Condition of lines
- Load capacity

In general, reliability is one of the main drivers in the electricity distribution development because of the importance of the distribution system on reliable power supply (Brown, 2009; Billinton and Allan, 1984). However, long disturbances caused by major weather events have emphasised the aspect of reliability. Within the past few years in Finland, the customers have experienced relatively long disturbances, even several weeks, as a result of major storms in the areas of several Finnish distribution companies mainly in the rural but also in urban areas. Experiences of the long interruptions have spurred the Finnish authorities to involve themselves in the electricity distribution, and thus, the legislation is evolving in a stricter direction.

Ageing of the network components is one of the topics to be addressed in asset management, which is, according to Brown and Humphrey (2005), “a corporate strategy that seeks to balance performance, cost and risk.” At present, ageing is a topical issue in the distribution systems, because a considerable proportion of electricity infrastructure has been constructed between the 1950s and 1970s in most of the western countries (Wijnia et al., 2006; Jongepier, 2007; Ghiani et al., 2008; Li and Guo, 2006). Thus, the existing distribution network is reaching its techno-economic lifetime or it has already been reached, when a typical lifetime of the distribution line is 40–50 years. In many cases, there is a significant distribution network volume waiting for renovation, especially in rural areas, which is a major challenge for electricity distribution. However, it is worth pointing out that ageing as such does not indicate a need for renovation, but rather the condition of the distribution line is the decisive factor in the considerations. An aged network component is more likely to fail than a new component (Willis et al., 2001). In the overhead line structure, poles are typically the components that decay and fail first. Nevertheless, the speed of the decay process varies significantly depending on several factors, which emphasises the importance of line condition monitoring.

Load capacity is one of the electrotechnical issues that may trigger the need for distribution system renovation. Typically, this concerns urban area networks where new infrastructure is built thereby causing load growth in normal network operation. However, also rural networks in the proximity of growth centres may be subject to a need for reinforcement to meet the requirements of better reliability. In rural areas, a more typical issue concerning the load capacity is the adequacy of reserve power in exceptional situations such as supply interruptions.

In addition to the above-mentioned main drivers, there are several additional issues that add to incentives for renovation. For instance, the following factors have to be taken into account:

- Implementation of smart grids
- Economic regulation

Smart grids may require new features from the distribution system, which steers DSOs to renew their distribution networks even if the existing network is still in a good shape (Gungor et al., 2011). For instance, the use of battery energy storages in a large scale as part of network control may lead to a need for network renovation. Further, island operation in the case where distributed generation and energy storages are installed to the network may require new features from the grid. Although the implementation of smart grids requires development of the distribution system, it also provides advantages such as a better reliability of supply (Fang et al., 2012). Further, the network design size can be kept moderate because the peak loads can be cut by using energy storages. However, a closer consideration of smart grid technologies and their effects on the distribution system renovation is outside the scope of this doctoral thesis.

Economic regulation determines the constraints on the distribution business. The regulation defines the rate of return in the business, and thus, it is an important factor in the network renovation. The regulatory model is tightly connected with the reliability of supply and ageing of the network, which also emphasises its role as a driver for the network renovation.

1.2.1 Reliability in distribution network renovation

In this doctoral thesis, the term ‘reliability’ covers definitions for both supply security and distribution network reliability in normal operating conditions. ‘Supply security’ indicates the reliability of the network during extreme events while ‘normal network reliability’ refers to average network reliability. According to the reliability terminology, a fault causes a network outage or interruption in service, and several simultaneous faults may cause a wider disturbance possibly interrupting electricity supply in large areas.

Reliability of electricity distribution plays a key role in the considerations for network renovation. The importance of reliability is explained by the crucial role of electricity in today’s society, where almost all functions are somehow dependent on electric power (Caperton and James, 2012). The importance of reliability can be observed from the outage unit costs discussed in more detail later in Chapter 2. An electricity distribution network can typically be divided into three different types; rural, urban and city area networks, which all have their specific impacts on the distribution reliability. City area distribution networks are usually very reliable, because they are typically built underground. Urban areas are often a combination of underground and overhead systems that supply the suburban areas and other urban communities. Thus, the lengths of the distribution systems are quite short, which reduces the risk of distribution interruptions. Finally, rural area networks comprise the rest of the distribution systems, and are mainly constructed as overhead lines, which are vulnerable to interruptions caused by adverse natural phenomena such as wind, snow and animals.

Figure 1.2 presents a distribution of typical causes of interruptions in Finland in 2010. That year, the major proportion of interruptions, 51 %, were due to wind and storms. Other significant causes are snow and ice, lightning, announced interruptions and interruptions the origin of which is unknown. The main causes indicate that a significant part of interruptions could be reduced by adopting new network techniques instead of using traditional overhead lines, which are the dominant structure in the medium-voltage distribution system and account for over 90 % of the total customer-experienced interruption time.

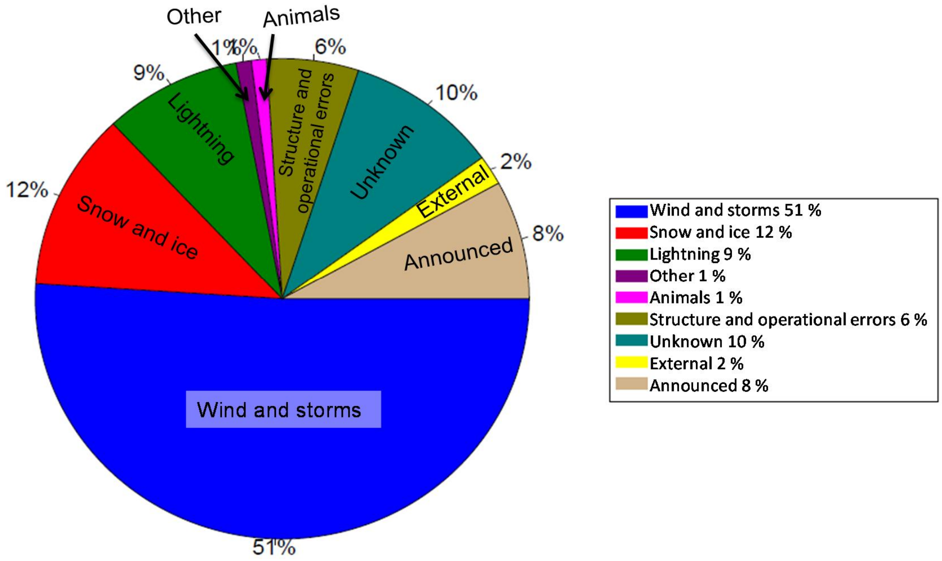

Figure 1.2. Average annual customer-experienced interruption durations (SAIDI) divided into causes of interruptions in per cent in Finland 2010 (Finnish Energy Industries, 2012).

Figure 1.3 illustrates the trend of interruptions in the long run. It can be observed that the duration of interruptions decreased from the 1970s to the end of the 1990s, but the interruption lengths have increased after the year 2000 including the years 2010 and 2011, when the average annual interruption duration was considerably higher than before. The long durations of interruptions were mainly a consequence of several major storms causing long-lasting interruptions for a considerable number of customers.

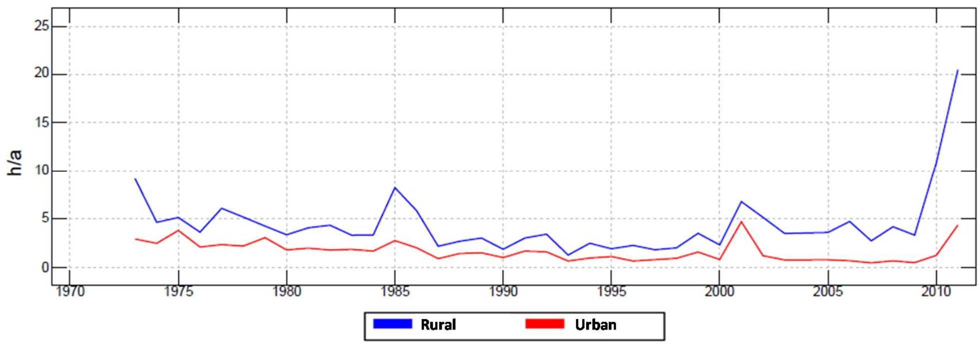

Figure 1.3. Annual average length of unannounced interruptions in the Finnish distribution system from 1973 to 2011 (Finnish Energy Industries, 2012).

Figure 1.4 illustrates the Finnish statistics of customer-experienced interruption durations in 2010 (Finnish Energy Industries, 2012), which was a special year from the viewpoint of major storms (the storms Asta and Veera in July and August 2010). The statistics is divided into three distribution conditions: rural, urban and city areas. The figure indicates that rural networks are the target in the network development where the effort in reliability improvement should be focused. The annual duration of interruptions was eight hours in rural networks while it was just over one hour in urban areas, and in the city conditions it was only 10 minutes.

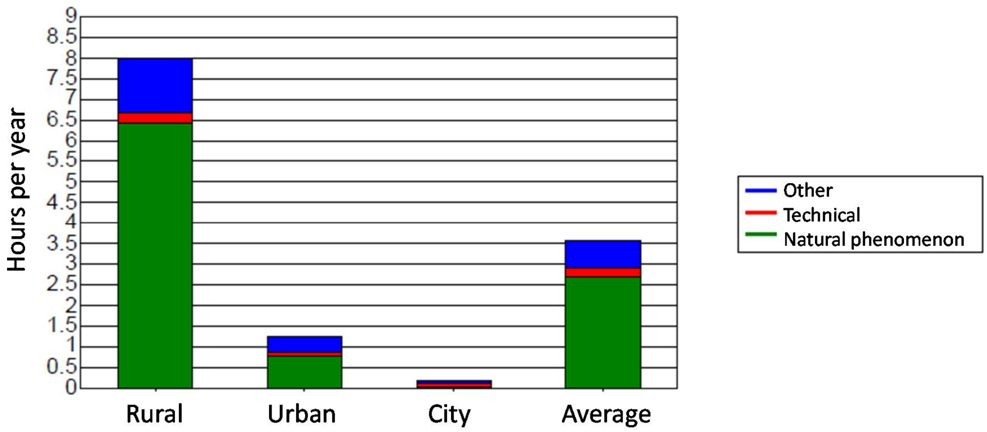

Figure 1.4. Average annual customer-experienced interruption durations (SAIDI) hours/year in Finland 2010 (Finnish Energy Industries, 2012).

1.2.1.1 Major disturbances

Major disturbances in the electricity distribution are, in general, caused by severe weather conditions such as major storms like hurricanes, tornados, strong winds or flooding (Entriken and Lordan, 2012). Earthquakes, fire, terror attacks and supply shortages may also lead to a major disturbance or blackout (Campbell, 2012). Nevertheless, the most critical disturbance type in each case depends considerably on the geographical location of the area. In the US there seems to be a trend that the number of extreme weather-related interruptions is increasing (Mills, 2012). Figure 1.5 shows that the number of incidents in electricity networks has increased within the past 20-year time period.

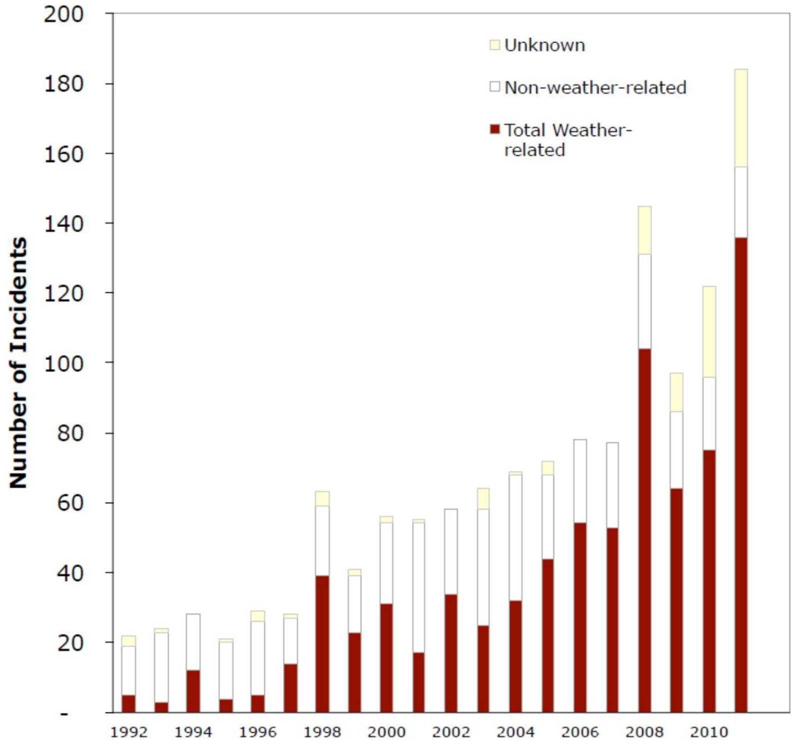

Figure 1.5. Number of significant electric grid disturbances in the US from 1992 to 2011 (Mills, 2012).

The best preparation technique varies depending on the major event type. For instance, underground cables are an efficient way to protect the network against strong wind and snow loads, but in the occurrence of floods, underground cables can be problematic (Brown, 2012). In Finland, major disturbances are usually caused by storms and strong winds, and in wintertime, by heavy snow loads. Therefore, the focus of contingency plans is typically on these weather-related phenomena.

The risk of major disturbances motivates the application of weatherproof (WP) and major-disturbance-proof (MDP) network structures such as underground cables. The difference between these two types is illustrated by the following examples: underground cables can be considered to be of both the WP and MDP type, because weather events do not usually cause any disturbances, whereas overhead lines located on fields can only be included in the category of MDP network structures. This is explained by the fact that trees cannot fall on lines on fields, and therefore, they do not require extensive fault repair after storms, which provides them with the status of MDP structure. However, overhead lines are not completely weatherproof, because lightning and tree branches transported by wind may cause fault incidents.

The past major disturbances in the Nordic countries have shown that the risk is real, and this aspect has to be taken into account. In Finland, the high proportion of overhead lines increases the risk of long disturbances, which are, of course, harmful to the customers. In Finland, with a typical line structure, where the overhead line is located in the middle of forest, the risk of trees falling on the line is significant. In these conditions, major disturbances are typically caused by trees falling on the line because of strong winds or heavy snow loads. Over the last ten-year period in Finland, the risk of major disturbances has become a reality several times causing long interruptions. The latest major incidents occurred in summer 2010 and winter 2011 causing interruptions that lasted even several weeks (see Figure 1.3 and Figure 1.4).

1.2.1.2 Supply security criteria and allowed interruptions

The significant role of electricity in today's society can be observed for instance from the valuation of interruption costs and the need to define limits for the number and duration of interruptions. The interruption unit costs are discussed in more detail in Chapter 2. In Finland, the first surveys of reliability criteria were made in 2006 and 2010 (Partanen et al., 2006; Partanen et al., 2010). The surveys were used by the Finnish Energy Industries as a basis to draw up a recommendation for the supply security criteria. After the criteria were published, the Finnish authorities and legislators stated that there was a need for definite limits on the allowed number and duration of interruptions. As a result, a new law came into effect in June 2013 (Finnish Electricity Market Act 588/2013).

Recommendation for the supply security criteria

In 2010, the Finnish Energy Industries established supply security criteria to guide the distribution companies to evaluate their reliability performance (Partanen et al., 2010; Lassila et al., 2010). The criteria set limits on the total annual interruption time and the number of short interruptions. The numbers are given in Table 1.1 for the three different types of distribution network; city, urban and rural areas.

Table 1.1. Target of reliability in different conditions (Finnish Energy Industries, 2010).

Criteria	City	Urban area	Rural area
Total interruption time	≤ 1 hour in a year	≤ 3 hours in a year	≤ 6 hours in a year
Number of short interruptions (< 3 min)	No short interruptions	≤ 10 interruptions in a year	≤ 60 interruptions in a year

The target values of the criteria are challenging to reach, especially in rural networks, because rural networks do not usually withstand even one storm without the total annual interruption time being exceeded. However, this is taken into account by assessing the fulfilment of the criteria for a period of three years, during which the target values may be exceeded once. Although the recommendation defines a tight target for network development, there is no coercive power (no sanctions) to enforce the reliability of the distribution network to the required level.

Official measures and regulations related to allowed interruptions

Over the recent years, also the governments have become interested in the supply security. For instance, in Sweden the government has determined that the durations of interruptions experienced by a customer should not exceed 24 hours from year 2011 onwards. The driving force of the Swedish law concerning supply security was the severe storms at the beginning of the 21st century, especially the storm Gudrun in 2005 that caused a supply interruption approximately for 450 000 customers (Setréus et al., 2007). The law came into effect in 2006 (Wallnerström and Bertling, 2009).

In 2012, the Finnish authorities were in the same situation as their Swedish colleagues in 2005, although the supply security requirements had been under consideration for almost a decade (Partanen et al., 2006; Partanen et al., 2010). The Finnish Ministry of Employment and the Economy (TEM) prepared a law concerning allowed interruptions based on the report by Partanen et al. (2012b) that considered the long interruptions caused by storms in summer 2010 and winter 2011. The law came into effect in September 2013 (Finnish Electricity Market Act 588/2013). The total duration of interruptions caused by storms was hundreds of hours, and therefore, it was considered necessary to tighten the regulations governing electricity distribution. The limits were set to six hours per occurrence in urban areas and to 36 hours per occurrence in rural areas. There is a 15-year transition period until 2028, in which the DSOs should improve their distribution systems so that they meet the required supply security. In the following, the important dates and targets in the transition period are given (Finnish Electricity Market Act 588/2013):

- 31 December 2019: 50 % of customers are not allowed to experience longer interruptions than 6 or 36 hours excluding holiday houses
- 31 December 2023: 75 % of customers are not allowed to experience longer interruptions than 6 or 36 hours excluding holiday houses
- 31 December 2028: 100 % of customers are not allowed to experience longer interruptions than 6 or 36 hours

The DSOs may be granted extra time to reach the required supply security target for 75 % and 100 % of the customers if the required network development actions involve a significant amount of underground cabling at both the MV and LV levels, and the proportion of the network that has to be renovated before the end of its techno-economic lifetime is large. The deadline of 75 % can be shifted from December 2023 to December 2028, and the deadline of 100 % can be shifted from December 2028 to December 2036. For the deferment, the DSOs have to submit an application by 31 December 2017. The application for a deferment is evaluated and approved by the Energy Market Authority of Finland (EMA).

All the DSOs have to prepare a development plan for the distribution network to reach the required supply security level. The plan has to take into account the operating environment based on historical experiments and describe the network technologies to be applied. The supervision is carried out by the EMA, which approves the supply security plan (Finnish Electricity Market Act 588/2013). The first part of the development plan has to be submitted to the EMA before the end of June 2014.

1.2.1.3 Customer compensation payments

In many countries, customers are entitled to compensation because of a long continuous interruption in the electricity supply. Thus, from this perspective, a customer compensation scheme gives an incentive for the DSO to develop its distribution network in order to avoid compensation costs of this kind. In the electricity distribution sector, compensation is paid to the customers for instance in Finland and Sweden. In Finland, there has been a customer compensation scheme since 2003 (Finnish Electricity Market Act 386/1995), and in Sweden, a compensation scheme was written into law in 2006 (Setréus et al., 2007; Swedish Electricity Act 1997:857) at the same time when the interruptions were given the maximum allowed duration.

In Finland, the new electricity market act includes some changes also to the customer compensation payments. Before the amendments to the law, there was a four-stage compensation scheme, where the payments started from a 12-hour interruption, for which the compensation was 10 % of the customer's annual distribution fee, but at maximum 700 € per interruption. The new act does not bring any changes to the lowest compensation categories. However, after the old maximum compensation, which is a 100 % compensation paid to the customer when the interruption duration exceeds 120 hours (700 € as the upper compensation limit), there are now two new compensation categories, which are 150 % and 200 % of the customer's annual distribution fee when the interruption lasts longer than 192 hours or 288 hours, respectively. Furthermore, in the amended electricity market act, the maximum compensation is raised from 700 € to 2000 € within the transition period, which limits the maximum compensation to 1000 € per customer if the interruption starts before 1 January 2016 and to 1500 € per customer if the interruption starts before 1 January 2018. Table 1.2 shows the existing and new compensation categories based on the new act (Finnish Electricity Market Act 588/2013).

Table 1.2. Categories of customer compensation payments according to the interruption duration (Finnish Electricity Market Act 588/2013).

Amount of compensation	Interruption duration	Note
10 %	interruption is between 12–24 hours	
25 %	interruption is between 24–72 hours	
50 %	interruption is between 72–120 hours	
100 %	interruption is between 120–192 hours	
150 %	interruption is between 192 –288 hours	Included in the law in 2013
200 %	interruption is more than 288 hours	Included in the law in 2013

Customer compensation payments in Finland between 2005 and 2012 are illustrated in Figure 1.6, which contains the annual statistics of all distribution companies. At the national level, the amount of compensation payments has remained under 5 million euros excluding the years 2010, 2011 and 2012, when major disturbances caused long interruptions.

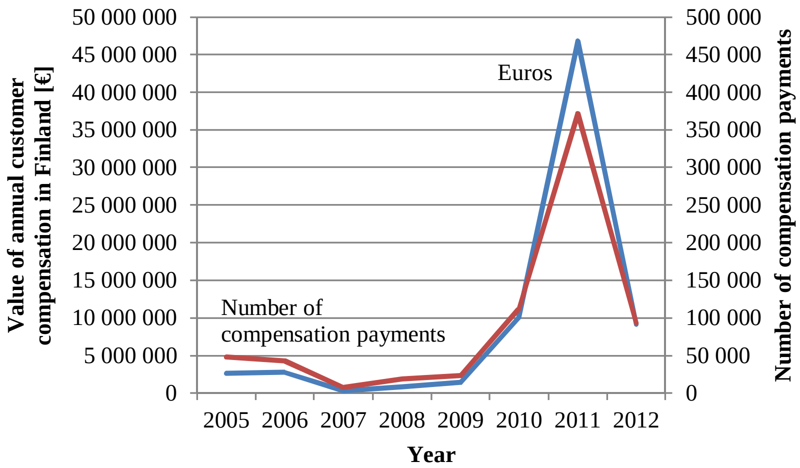

Figure 1.6. Customer compensation payments in Finland between 2005 and 2012.

1.2.2 Ageing of the electricity distribution system

The components of the electricity distribution system usually have long lifetimes. For instance, a typical lifetime of a switching component is 25 years, and the lifetime of overhead lines can be up to 50 years. At this moment, considering the current state of the components in the distribution system, a significant proportion of the network asset is relatively old. This is partly due to the cyclic nature of distribution network construction. For instance, the Finnish distribution networks have mainly been constructed from the 1950s onwards, when the electrification of rural areas started in a large scale, and therefore, the overhead lines have not yet been widely renovated.

Typically in rural areas in Finland, the peak in the network construction was in the 1960s and 70s, and thus, the age of these networks is between 40 and 50 years. This means that a significant part of the distribution networks has already exceeded or is reaching its techno-economic lifetime. The volume of the ageing network poses a challenge to manage the replacement of the poles or the conversion of the overhead lines into underground. Although managing of the ageing network infrastructure is challenging, it provides an opportunity to carry out a reliability-focused renovation program at an accelerated rate so that components are not removed from the network before the end of their lifetime. This can be a significant benefit that saves costs. Figure 1.7 illustrates the situation of wood poles in the Finnish distribution networks. It shows that over 65 % of the poles have been installed before the 1980s, which indicates a significant need for network renovation before problems related to ageing arise.

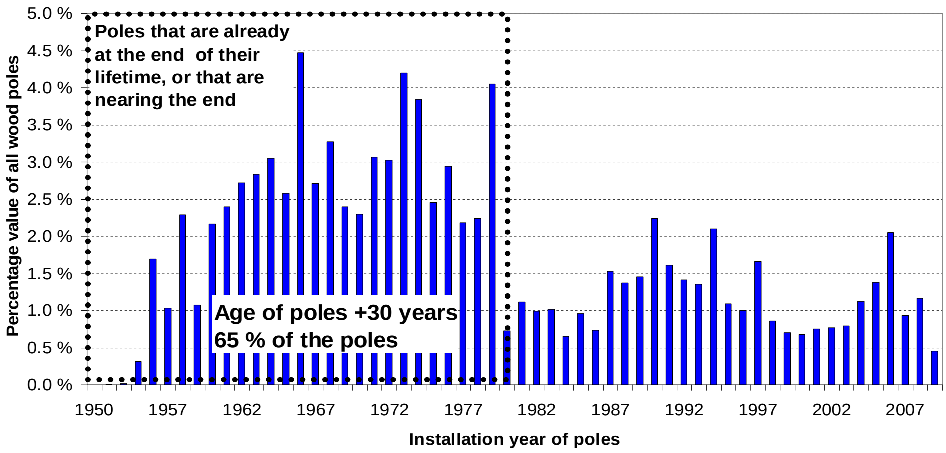

Figure 1.7. Age distribution of the wood poles in a medium-voltage network in the Finnish distribution network company (Publication I).

The ageing of the distribution system causes wear of the components, and often the most critical component in the overhead line distribution system, wood pole, is affected by some decomposing agent that decays and weakens the pole (Bertling 2002, Korpijärvi 2012). These effects are minimised by impregnating the poles for instance by creosote or salt. Nevertheless, the impacts of decay can yet be observed over time. In addition, the use of preservative chemicals may be problematic in overhead line networks because of the tightening environmental regulations and prohibition of certain chemicals. Further, substitute chemicals may not be as efficient.

1.2.3 **Load capacity of the distribution network**

Electricity consumption has considerably increased since the 1970s when the basis of the present electricity distribution infrastructure was constructed (Finnish Energy

Industries, 2013). Electricity consumption in Finland between 1970 and 2012 is depicted in Figure 1.8. The figure shows an increasing trend in electricity consumption. However, a slight drop can be observed in the total consumption over the last few years. In the household electricity consumption, the drop is almost non-existent. The main reason for the drop is the global financial crisis, which has a negative impact on electricity consumption. Nevertheless, in the near future when the crisis is anticipated to be over, it is reasonable to assume that the consumption will increase, especially in households, thereby providing a key driver to improve the quality of electricity supply.

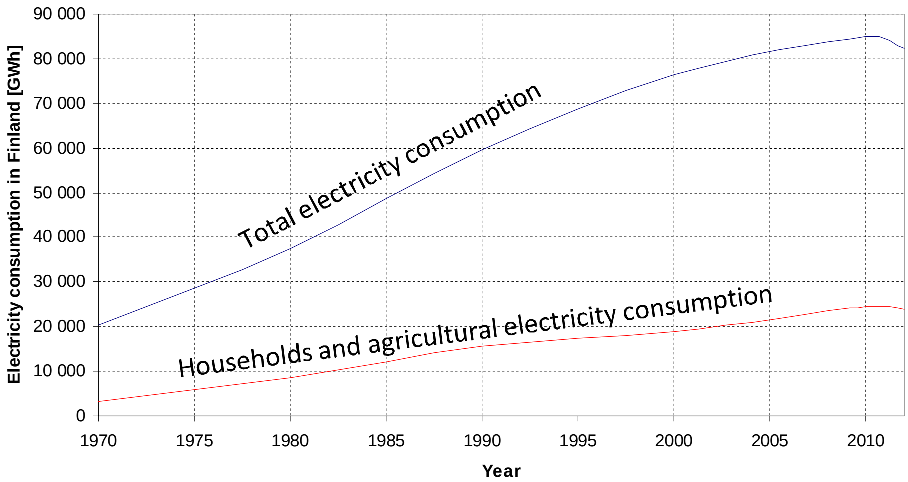

Figure 1.8. Electricity consumption in Finland between the years 1970 and 2012 (Finnish Energy Industries, 2013).

The growing electricity consumption will lead to a fact that at some point in time, the capacity of the network will run out. Figure 1.9 illustrates the influence of different factors and actions on the power and energy transfer on the network. Actions increasing and decreasing the power demand are listed in the figure. Load control is one of the options to reduce the peak power. The control of peak power can provide extra time to continue electricity distribution with the existing components and thereby save significant amount of investments. However, the benefits of load control depend on the purposes for which the load control is used. Thus, if the aim of the control is to purchase cheap energy from the market, the result can be totally opposite from the distribution system's perspective, and there is a risk that the peak power in the distribution network may grow.

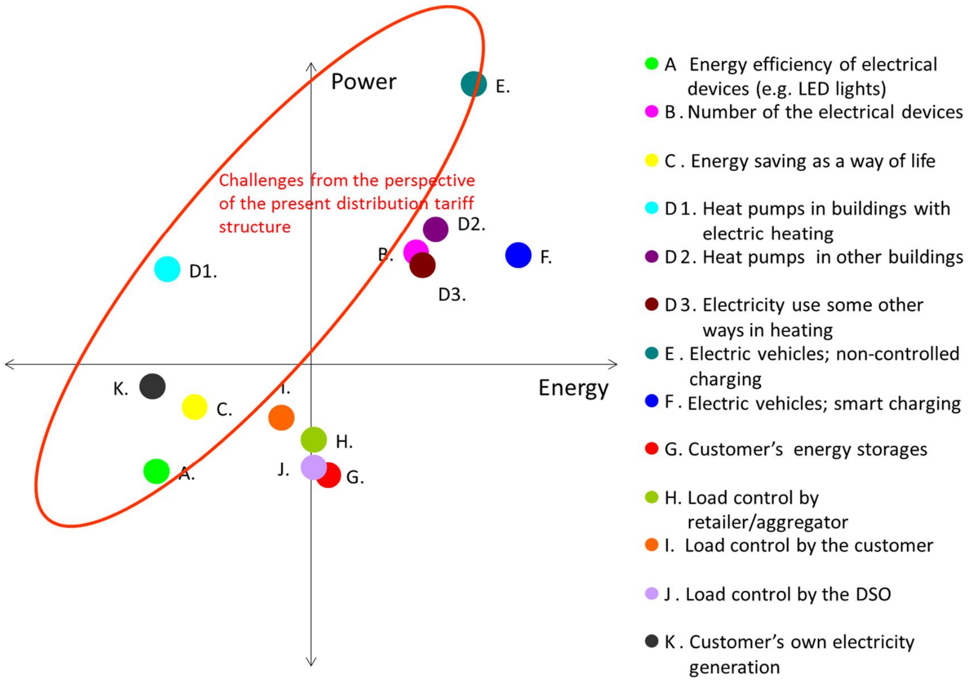

Figure 1.9. Changes in the electrical power and energy transmitted on the electricity distribution network (Partanen et al., 2012a).

The features of smart grids can offer several benefits from the perspective of load capacity. Besides the many useful features of smart grids, such as an improvement in the supply quality, they provide new opportunities for energy producers and customers by enabling easy connection of distributed generation, implementation of energy storages and island operation of the network. Energy storages, in particular, can be used to cut the peak power of the network by shifting the load to the hours when the consumption is lower. In the future, electric vehicles (EVs) may function as battery energy storages. When the EVs are parked for a longer time (e.g. hours), they are probably plugged in, and are thus ready to be used for load control or power supply during a power outage in the network upstream from the EVs. However, although the EV batteries can be used to cut the peak loads, vehicle charging increases the total consumption and power demand regardless of the charging method.

1.2.4 Summary of the renovation drivers

Reliability requirements steer the network renovation in a direction where reliability is the quantifying factor in the network planning. The importance of reliability, and especially, reduction of long interruptions has been emphasised over the last years. This is a consequence of the recommendation of the Finnish electricity industries and especially of the new electricity market act in Finland. Previously, no longer than five years ago in the late 2000s, the focus of network development was not on the reduction of long interruptions, but the average reliability was the key target. Thus, the research of that time focused on network automation, which improves the average reliability in a fast and cost-efficient way.

Yet another reason behind the requirements for renovation is the ageing of the distribution infrastructure, as a significant proportion of the network volume is relatively old in most of the distribution companies, and therefore calls for considerable renovation. However, the question of ageing can also be seen as an opportunity, because now the network can be renovated to meet the new supply security requirements without removing network assets that still have both techno-economic lifetime and net present value left. These two factors, reliability and network ageing, mainly determine the renovation process, but there are also other drivers that may affect the process. These drivers include for instance the condition of the lines, technical constraints and requirements of smart grids. Nevertheless, these are not typically the decisive factors, but in some cases they have an effect on the scheduling of the renovation.

1.3 Objective of the work

The objective of this doctoral thesis is to develop methodology for the renovation planning of electricity distribution networks to meet the requirements of present society as cost-efficiently as possible. The objective can be divided into the following tasks:

- Development of a network renovation concept
- Reliability analyses to assess supply security
- Analysis of the effects of economic regulation on network renovation

In particular, the methodology focuses on underground cabling to improve the supply security of the distribution network so that new requirements set for the electricity distribution are met not forgetting the ageing network asset that requires special attention. The methodology finds an answer to the questions as to where the renovation is started, what the applied renovation strategy is, and when the network is renovated. The network renovation concept is a result of a development process. In this thesis, the cabling concept plays the key role, because it is an essential factor in the improvement of supply security. The high significance of supply security is manifested in the development of supply security analysis, where a simulation methodology is introduced to enhance the network analysis. In addition to the reliability of supply, other important topics emerged in the planning process are asset management, consideration of different network structures, political views and business opportunities. The entity can be handled by a strategy analysis that combines a network analysis and asset management containing inputs from several sources such as a regulatory model determining the country-specific aspects for the analysis. The planning methodology consists of subtasks that are linked to the network planning. These tasks are:

- Optimisation of automation device placement
- Selection of a cost-efficient reserve power solution

Optimisation of automation devices provides information of the optimal placement of network automation. The optimisation is based on a network analysis that includes evaluation of the reliability improvement or the reduction in customer outage costs after the device has been installed. Selection of the reserve power strategy is another example of network planning subtasks. The consideration of reserve power involves determination of alternative reserve power solutions and cost functions of the strategies. The optimal strategy for the case-specific distribution network can be defined by the cost functions.

1.4 Outline of the work

Chapter 2 covers economic regulation and its effects on network renovation. The present Finnish electricity distribution regulatory scheme is considered, and the principles of the economic regulation are presented to demonstrate the relation of the regulatory scheme with the renovation planning.

Chapter 3 establishes the reliability and cost calculation methodology providing the basis for the cost analysis and reliability modelling. The chapter describes the use of reliability indices in network planning and their role in decision-making. Reliability analyses are also an important part of cost analyses after the reliability values are converted into customer outage costs (COC), which makes it possible to take COC into account in the total cost calculation.

Chapter 4 discusses different perspectives of network optimisation. The base of ownership and the owners' expectations may influence the aims of the DSO in network planning and operation. In general, there are two different ways to optimise the network; either by minimising the total costs or by maximising the profit. A closer consideration may reveal that an optimal network strategy is different from these two optimisation perspectives. In the chapter, the optimisation methodology is described, and the optimisation functions are presented.

Chapter 5 introduces a concept for network renovation with a special reference to underground cabling. The concept discusses the background work and strategic decisions behind the renovation. The concept provides answers to the questions as to where, how and when the renovation is carried out to find the optimal way to renovate the ageing network so that the tightening reliability requirements are taken into account in the strategic planning.

Chapter 6 addresses the importance of reserve power planning as a part of strategic planning to meet the requirements of network development. Appropriate preparation to arrange reserve power considerably reduces customer-experienced supply interruptions. Finally, the chapter provides an approach to optimise the reserve power strategy.

1.5 Scientific contribution

The main contributions of this doctoral thesis are an analysis of the effects of economic regulation on network renovation, a supply security analysis and a network renovation concept including in-depth considerations on the cabling methodology for an electricity distribution network. The scientific contributions are as follows:

1. Methodology to take into account the effects of economic regulation on network renovation
2. Method to apply a supply security analysis to network planning
3. Cabling concept for network renovation
4. Method to analyse reserve power arrangements in underground cable networks
5. Analysis method to assess the placement of network automation

Distribution system operators can use the listed contributions to compile a network strategy that meets the requirements of reliability thereby providing a good result for their customers and also taking the aims and expectations of the network owners into account.

1.6 Summary of publications

This doctoral thesis consists of seven publications, four of which are refereed journal articles and three are refereed conference publications. Figure 1.10 presents the timeline of the publications during the doctoral work. The first publication was published in 2009, and the last publication included in the thesis was accepted for publication in 2013. The author of this thesis is the primary author of the publications.

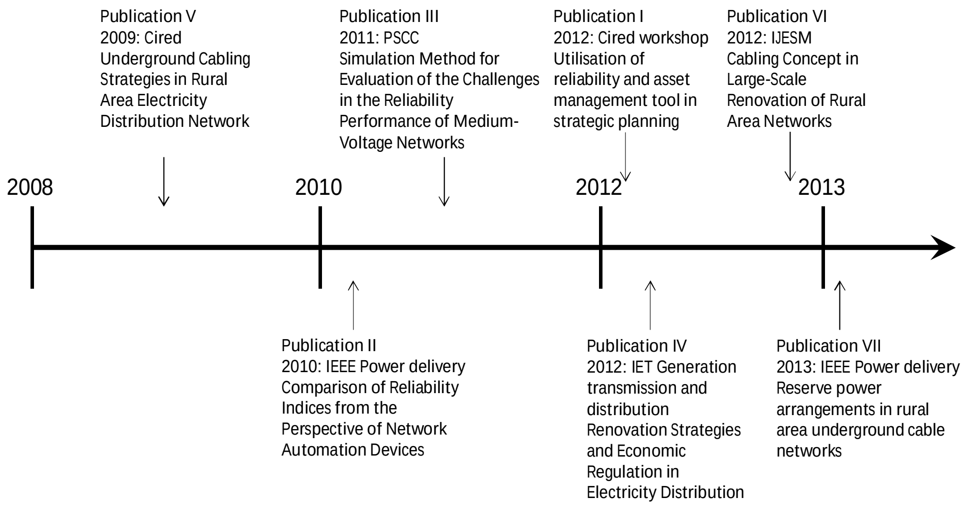

Figure 1.10. Timeline of the publications in the doctoral thesis.

Publication I *Utilisation of reliability and asset management tool in strategic planning.*

Publication I considers the elements that an evaluation tool should contain to handle the combination of reliability and asset management planning whilst taking into account the features of economic regulation. The publication demonstrates the key elements of the analysis tool and discusses the benefits of the tool in strategic planning. In this publication, the author of this doctoral thesis has developed the basis for the analysis of the reliability and asset management.

Publication II *Comparison of Reliability Indices from the Perspective of Network Automation Devices.*

Publication II focuses on the profitability of network automation taking into account the reliability perspective. The paper investigates different reliability indices for decision-making when considering installation of network automation to the network. In this publication, the author has constructed a method to analyse the effects of network automation investments on reliability, and simultaneously, on outage costs.

Publication III *Simulation Method for Evaluation of the Challenges in the Reliability Performance of Medium-Voltage Networks.*

Publication III concentrates on developing of a simulation method to stochastically analyse the reliability of the electricity distribution when considering different network renovation options for the future distribution scenario. The method helps to trace the sections on the network where the reliability issues cause most challenges. In this publication, the author has built a model for simulation and thereby the methodology for the stochastic evaluation and analysis of electricity distribution.

Publication IV *Renovation Strategies and Economic Regulation in Electricity Distribution.*

Publication IV discusses the relation between the Finnish economic regulation model and the profitability of different network strategies. The paper presents different perspectives to optimise the electricity distribution network taking into account the economic regulation. The different approaches to optimise the network are traditional minimisation of total costs, maximisation of the owner's profit and minimisation of customer's costs. In this publication, the author has studied the regulatory model and analysed the effects of different optimisation targets on the most profitable network renovation strategies.

Publication V *Underground Cabling Strategies in Rural Area Electricity Distribution Network.*

Publication V presents different strategies for underground cabling in rural electricity distribution. In the publication, the profitability of alternative underground cabling strategies is analysed in an actual rural area network. The author has played the key role in the development of the methodology and analysis of the presented strategies.

Publication VI *Cabling Concept in Large-Scale Renovation of Rural Area Networks.*

Publication VI proposes a concept for underground cabling in rural area network renovation. The concept considers the questions such as where, when and how the renovation should be carried out taking into account the external factors deriving from the operating environment. The question 'where' weights the prioritisation factor of the renovation that can be, for instance, the age or reliability values of the network. The question 'when' discusses the timing of the renovation. Finally, the question 'how' includes, for example, the variety of technical solutions to install cables and the selection of line routes. The author has developed the methodology and tested it with an actual network model.

Publication VII *Reserve power arrangements in rural area underground cable networks*

Publication VII discusses reserve power arrangements in a rural area electricity distribution system, with a special reference to rural area underground cable systems, where there are currently terminating branch lines without back-up power available. The paper presents three different approaches to secure the supply within only a few hours. The studied approaches are the use of reserve power cables, reserve power generators and looping of the terminating branch lines. The author has played the key role in the study, and the optimisation functions as well as the resulting analysis are carried out by the author.

2 Economic regulation

Electricity distribution is often a regulated business that is operated by franchised monopolies. Owing to the specific nature of the business, economic regulation is required to control the business (Jamasb and Pollitt, 2001; Ajodhia and Hakvoort, 2005). This is the situation for instance in most of the European countries, USA, Japan and Australia. The economic regulation consists of numerous components that together constitute the regulatory model. The regulatory models are constructed so that they provide incentives for the DSOs for good performance or reliability (Jamasb and Pollitt, 2007; Honkapuro 2008), which are part of the reward mechanism. If the performance is not adequate and the distribution reliability is decreasing, the model punishes the DSO. The reward or sanction can be based on measured reliability indices such as the system average interruption duration index (SAIDI) and the system average interruption frequency index (SAIFI), which is the indicator used for instance in Sweden (Alvehag and Söder, 2010), or customer outage costs, which are a derivative of system reliability that is used for instance in Norway (Kjolle et al., 2009) and Finland (Lassila et al., 2005; EMA, 2011). Another sanction mechanism in addition to the common reliability indices SAIFI and SAIDI can be customer compensation payments to the customers who experience long supply interruptions. However, the compensation payments are not a part of sanction mechanism of regulatory model, but they are an independent mechanism.

2.1 Finnish regulatory scheme 2012–2015

In Finland, the regulatory scheme has been under active development. The first regulatory period was 2005–2007, and the present regulatory period is the third one. The basic framework of the model has evolved so that the inputs in the allowed revenue have mostly remained the same between the models, but the specific calculation parts within the model have changed. For instance, the model still includes both a general and company-specific efficiency requirement, which is determined by efficiency benchmarking. However, the modelling of efficiency benchmarking has been developed within the regulatory periods. The current model applies a StoNED (Stochastic Non-smooth Envelopment of Data) model (EMA, 2011), which is a hybrid of the DEA (Data Envelopment Analysis) and SFA (Stochastic Frontier Analysis) models. The DEA and SFA models were both used in the previous regulatory models in the regulatory periods of 2005–2007 and 2008–2011. Efficiency benchmarking produces a reference value for actual efficiency costs, which both constitute the TOTEX bonus in the model. Other important elements affecting the allowed revenue are the quality bonus, the allowed depreciations and the reasonable return on capital. The basic scheme of the Finnish regulatory model is presented in Figure 2.1.

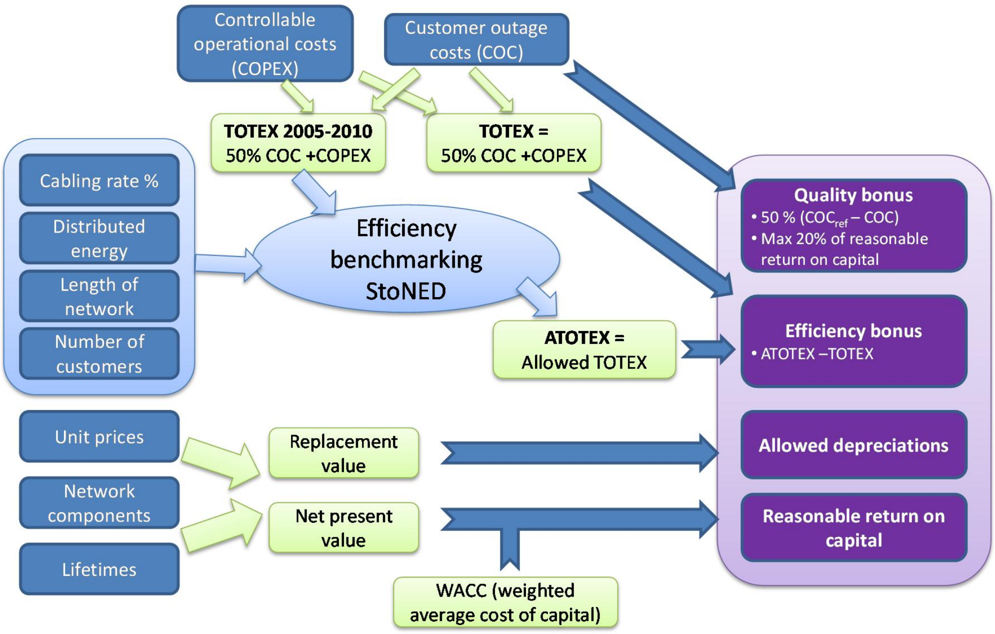

Figure 2.1. Outline of the Finnish regulatory model between 2012 and 2015 (EMA 2011).

2.1.1 Quality bonus

A quality bonus or a sanction is determined in the Finnish regulatory model by using customer outage costs (COC), which are calculated from unit costs and interruption statistics. The unit costs are based on a customer outage cost survey published in 2005 (Silvast et al. 2005). Interruption statistics that are applied in the outage cost calculation comprise sustained interruptions, consisting of both unannounced and announced interruptions, and momentary interruptions, including high-speed automatic reclosings (HSAR) and delayed automatic reclosings (DAR). For sustained interruptions, unit costs are defined for a number of interruptions and also for the duration of interruptions. The outage unit costs applied in Finland are presented in Table 2.1.

Table 2.1. Outage unit costs applied in the Finnish regulatory model in the monetary value of 2005 (EMA 2011).

Unannounced outages		Announced outages		HSAR	DAR
[€/kW]	[€/kWh]	[€/kW]	[€/kWh]	[€/kW]	[€/kW]
1.1	11	0.5	6.8	0.55	1.1

The bonus or sanction is calculated from the actual annual customer outage costs that are compared with the reference level of outage costs (COC_{ref}) based on a historical average of customer outage costs. The quality bonus is calculated so that the actual

COC are subtracted from the reference level. Because of the symmetry of the bonus system, the bonus can be either positive or negative (sanction).

$$\text{Quality bonus} = \left(COC_{\text{ref}} - COC\right) \cdot 50\,\% \,. \tag{2.1}$$

The COC in year *t* are calculated in the value of year *k* using actual interruption values based on actual interruption statistics

$$COC_{t,k} = \frac{W}{8760}\begin{pmatrix} c_{\text{u}} \cdot n_{\text{u}} + c_{\text{a}} \cdot n_{\text{a}} + c_{\text{ud}} \cdot d_{\text{u}} + \\ c_{\text{ad}} \cdot d_{\text{a}} + c_{\text{hsar}} \cdot n_{\text{hsar}} + c_{\text{dar}} \cdot n_{\text{dar}} \end{pmatrix} \cdot \frac{CPI_{k-1}}{CPI_{2004}}, \tag{2.2}$$

where

$COC_{t,k}$	customer outage costs in year *t* in the value of year *k*
W	annual distributed energy of the DSO (kWh/a)
c_{u}	unit cost for unannounced interruption (€/kW)
c_{a}	unit cost for announced interruption (€/kW)
c_{ud}	unit cost for unannounced interruption duration (€/kWh)
c_{ad}	unit cost for announced interruption duration (€/kWh)
c_{hsar}	unit cost for high-speed autoreclosing (€/kW)
c_{dar}	unit cost for delayed autoreclosing (€/kW)
n_{u}	customer's average annual number of interruptions weighted by annual energies, caused by unannounced interruptions in the 1–70 kV network in year *t*, number
n_{a}	customer's average annual number of interruptions weighted by annual energies, caused by announced interruptions in the 1–70 kV network in year *t*, number
d_{u}	customer's average annual duration of interruptions weighted by annual energies, caused by unannounced interruptions in the 1–70 kV network in year *t*, hour
d_{a}	customer's average annual duration of interruptions weighted by annual energies, caused by announced interruptions in the 1–70 kV network in the year *t*, hour
n_{hsar}	customer's average annual number of interruptions weighted by annual energies, caused by high-speed automatic reclosings in the 1–70 kV network in year *t*, number
n_{dar}	customer's average annual number of interruptions weighted by annual energies, caused by delayed automatic reclosings in the 1–70 kV network in year *t*, number
$CPI_{k\text{-}1}$	consumer price index in year *k*-1
CPI_{2004}	consumer price index in year 2004

In the regulatory model, the COC affect the quality bonus so that todays' outage costs are compared with the historical average of outage costs, which are the reference level for the present actual outage costs. The reference level of the COC is calculated as

$$COC_{\mathrm{ref},k} = \frac{\sum_{t=2005}^{2010}\left(COC_{t,k}\cdot\left(\frac{W_k}{W_t}\right)\right)}{6}, \tag{2.3}$$

where

$COC_{\mathrm{ref},k}$	reference customer outage costs for year *k*
$COC_{t,k}$	actual customer outage costs in year *t* in value of year *k*
W_k	annual supplied energy in year *k* (kWh/a)
W_t	annual supplied energy in year *t* (kWh/a)

The influence of the quality bonus is limited in two ways: first, only 50 % of the difference between the actual and reference COC is included in the quality bonus, and secondly, the maximum of the bonus or sanction is limited to 20 % of the reasonable return on capital. This means that if the allowed return on capital is close to zero for some distribution company, the quality bonus or sanction is also limited to zero.

2.1.2 Efficiency bonus

Efficiency benchmarking is one of the main objectives of the regulation. It yields valuable information of the performance of the distribution companies. An efficiency bonus or a sanction can be calculated similarly as the quality bonus. For the calculation of an efficiency bonus, the actual efficiency costs (TOTEX) and the reference level, that is, the allowed efficiency costs (ATOTEX) are required.

The efficiency bonus in year *t* is calculated as

$$\text{Efficiency bonus}_t = ATOTEX_t - TOTEX_t \ . \tag{2.4}$$

TOTEX is a combination of the controllable operational costs (COPEX) and 50 % of the COC. An equation for the actual efficiency costs is written as

$$TOTEX_t = COPEX_t + 0.5\cdot COC_t, \tag{2.5}$$

where

$TOTEX_t$	actual efficiency costs in year *t*
$COPEX_t$	actual controllable operational costs in year *t*
COC_t	actual customer outage costs in year *t*

The reference level ATOTEX is determined by the StoNED efficiency benchmarking method, the inputs of which are the estimated efficiency cost, the cabling rate, a company-specific efficiency score (ES) determined by the StoNED method and a general efficiency requirement, which is 2.06 % in Finland. Operational costs taken into account in the efficiency benchmarking are maintenance, fault repair and energy loss costs. ATOTEX is

$$ATOTEX_t = \frac{CPI_{t-1}}{CPI_{2009}} \cdot (1 - X)^{t-2019} \cdot \hat{C}(y_t, z_t), \qquad (2.6)$$

where

$ATOTEX_t$	reference level of the allowed efficiency costs in year *t*
$CPI_{t\text{-}1}$	average consumer price index in year *t*-1
CPI_{2009}	average consumer price index in year 2009
X	company-specific efficiency requirement
$\hat{C}$	cost frontier of the DSOs
y_t	product variable vector of the company in year *t*
z_t	cabling rate of the company in year *t*

The cost frontier $\hat{C}$ takes into account the network volume, the number of customers and the supplied energy, which are variables in the product variable vector y_t. The company-specific efficiency requirement *X* is calculated as

$$X = 1 - \sqrt[8]{ES} \cdot (1 - 2.06\ \%), \qquad (2.7)$$

where

ES	company-specific efficiency score
2.06 %	general efficiency requirement
8	length of the regulatory period in years

The efficiency score is a result of the average $TOTEX_{2005\text{–}2010}$ (operational and customer outage costs), the cabling rate, the network length, the distributed energy and the number of customers. $TOTEX_{2005\text{–}2010}$ is calculated by

$$TOTEX_{2005\text{–}2010} = \frac{\sum_{t=2005}^{2010} (COPEX_t + 0.5 \cdot COC_t)}{6}, \qquad (2.8)$$

2.1.3 Depreciations

In the Finnish regulatory model, investments in the network asset are encouraged by reasonable depreciations. In the model, reasonable depreciations are straight-line depreciations calculated from the replacement value (RV) and the lifetimes of the network components. The replacement value is calculated each year using the current unit prices defined by the Energy Market Authority (EMA, 2013). The unit prices are based on statistics gathered from the distribution companies. The techno-economic lifetimes of the components can be defined by the DSOs reflecting the time that the component is in the network before the replacement, but the lifetimes have to be between the predefined limit values given by the Energy Market Authority. The list of lifetime limits is presented for a typical distribution network component in Table 2.2.

Table 2.2. Techno-economic lifetimes for typical distribution system components (EMA 2011).

Component group		Lifetime [a]
Distribution substation	Pole-mounted	25–40
	Pad-mounted	30–40
Distribution transformer		30–40
Overhead line	Medium-voltage	30–50
	Low-voltage	25–45
Underground cable	Medium-voltage	30–45
	Low-voltage	30–45
Disconnector		25–30
Primary substation		30–45

Depreciation of a single component is calculated as

$$Depreciation = \frac{RV}{Lifetime}, \tag{2.9}$$

A special characteristic of the Finnish regulatory model is that it also provides depreciations for the over-aged network components, in other words, for the network the techno-economic lifetime of which has already been exceeded. This supports the maintenance of an aged network, because the regulatory model does not insist to remove these components.

2.1.4 Reasonable return on capital

Reasonable return on capital (RRC) is a part of the regulatory model that yields profit for the distribution company by applying the weighted average cost of capital method (WACC). The calculation of the WACC is demonstrated in (Honkapuro 2008, EMA 2011). The main factor in the return on capital, in addition to the WACC, is the net present value of the network (NPV). The NPV is calculated by using the component unit prices and the techno-economic lifetimes as well as the replacement value of the component. However, in this case, the value of the component reduces each year. The NPV is calculated by

$$NPV = \left(1 - \frac{Age}{Lifetime}\right) \cdot RV\,, \qquad \text{if age} \le \text{lifetime}$$
$$NPV = 0\,, \qquad \text{if age} > \text{lifetime} \tag{2.10}$$

where

NPV	net present value of the considered component
Age	age of the component
RV	replacement value of the component
Lifetime	techno-economic lifetime of the component

The reasonable return is calculated by NPV and WACC

$$RRC = NPV \cdot WACC\,, \tag{2.11}$$

where

RRC	reasonable return on capital
NPV	net present value
WACC	weighted average cost of capital

Typically, WACC is between 4 % and 6 % in the electricity distribution business. There are several influencing factors, but the greatest impact on the variation in WACC is with the 10-year state bond, which has varied from 1.6 % to 3.9 % over the last few years.

2.1.5 Impacts of economic regulation

The elements of the economic regulation determine the allowed revenue and thus the allowed return. The regulatory model contains several instruments that provide incentives to develop the distribution network. For instance, in the case where an unreliable, relatively old overhead line network is converted into an underground cable network that meets the requirements of supply security, the allowed profit is made up of the following elements of economic regulation including the quality and efficiency incentives, depreciations and a return component based on the network age:

- Quality bonus as a result of the improved distribution reliability and security
- Efficiency bonus because the operational costs are reduced as a result of the reduced number of faults and maintenance-free network technology
- Higher straight-line depreciation because network asset increases as a result of the use of more valuable network structures
- Higher net present value of the network asset yields a higher reasonable return on capital because the network age is reduced.

3 Determination of reliability and its impact on network planning

An electricity distribution network analysis involves a lot of calculation, both from economic and technical aspects. In this thesis, the focus of the analysis is based on distribution reliability and asset management analyses. To be able to assess comprehensive network development, both these aspects have to be modelled so that changes in the network asset are taken into account in the distribution reliability and vice versa. Managing the distribution system development requires extensive strategic analyses and calculation methodology with reference to asset management and reliability, as discussed in Publication I. The benefits of an advanced reliability analysis as part of electricity distribution network planning have been discussed for instance by Pylvänäinen et al. (2004 and 2009).

The analysis of network development requires assessment of the system asset and network reliability. Thus, a reliability model has to be applied to carry out a planning task. The developed reliability calculation model produces the information to assess the network reliability. As a result, it provides distribution-substation-specific reliability values that can be converted into system reliability indices and customer outage costs. From this perspective, a reliability analysis is integral to the assessment of distribution network development, and it serves as a link between the regulatory model and strategic planning cost estimation.

A challenge of network planning is demonstrated in Figure 3.1 and Figure 3.2, which illustrate the effect of different network technologies on distribution reliability. Figure 3.1 shows the effect of certain network technologies on normal statistical reliability, which can be indicated by well-known system reliability indices such as the system average interruption frequency index (SAIFI) and the system average interruption duration index (SAIDI). The figures show that there are several technologies to improve distribution reliability. It can be observed that the same technologies do not have similar impacts in all cases. For instance, network automation reduces the impacts of outages by limiting the faulted network area when a single fault occurs, but in the case where a storm fells trees, automation does not have a significant effect. Thus, from the perspective of supply security, the average system reliability indices cannot be applied as the sole indicators in the network strategic planning.

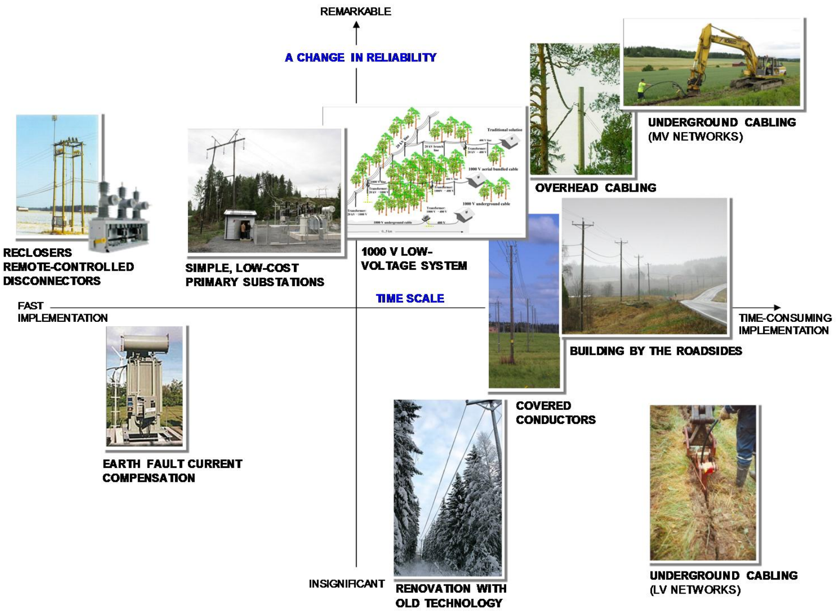

Figure 3.1. Effects of different network technologies on reliability (Lassila, 2009).

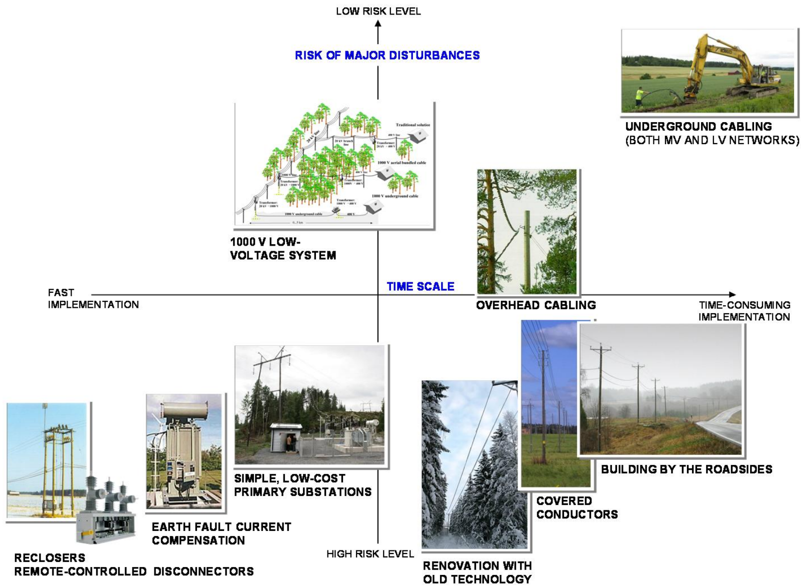

Figure 3.2 Effects of different network technologies on the major disturbance resiliency of the distribution networks in the case of major storms (Lassila, 2009).

Several indices are designed to describe the electric power distribution reliability. Typically, the indices such as SAIFI and SAIDI determine system-level performance, which does not yield information about the customer-level performance of the system. A benefit of the system-level indices is that they are commonly known and relatively easy to define. However, a disadvantage is that they are difficult to integrate straightforwardly into network planning. The index of customer outage costs (COC) is an example of a sophisticated reliability index that quantifies the network reliability in a monetary value, and even as a straight cost for the DSOs. This makes it easy to be included in the network planning process. Nevertheless, a disadvantage of the COC is that similarly as other system-level indices, it does not express customer-specific network performance. The problems related to traditional reliability indices and COC in the strategic decision-making have been approached in Publication II, which also touches on the optimisation of the network automation placement.

A step toward customer-oriented network planning is statistical planning criteria that set limits on customer-experienced interruptions. The recommendation of the Finnish Energy Industries (Partanen et al., 2010) is an example of this approach. In the network planning, the problem of this approach is the reliable estimation of distribution reliability that would take into account the topology of the network. A simulation methodology has been developed to analyse the statistical network performance. The issue is discussed in Publication III.

The final step to take the customers’ perspective into account in the network planning is to determine customer-specific interruption limits in the law. In Sweden, such limits are written in the law, and now Finland follows the Swedish policy by a new Electricity Market Act. The law imposes limits on supply interruptions, which have to be taken into account in network planning. Nevertheless, although the law sets a straightforward target for the DSOs, the planning criteria based on the law are not free of problems. From the network planning point of view, the difficulty is to define the worst-case situation to set the reference level for a disturbance.

3.1 Reliability indices

The reliability of electricity distribution can be measured by different indices. The focus of the indices such as SAIFI, SAIDI, MAIFI (momentary average interruption duration index), CAIFI (customer average interruption frequency index), CAIDI (customer average interruption duration index) and ASAI (average service availability index) has typically been on the system level. The indices are introduced in the IEEE (Institute of Electrical and Electronics Engineers) Guide for Electric Power Distribution Reliability Indices (2004). These indices are based on the number of customers served in the network area under consideration.

$$SAIFI = \frac{\sum \text{Total number of customers interrupted}}{\text{Total number of customers served}} \quad (3.1)$$

$$SAIDI = \frac{\sum \text{Customer interruption durations}}{\text{Total number of customers served}} \quad (3.2)$$

$$MAIFI = \frac{\sum \text{Total number of customer momentary interruptions}}{\text{Total number of customers served}} \quad (3.3)$$

$$CAIFI = \frac{\text{Total number of customer interruptions}}{\text{Total number of customers interrupted}} \quad (3.4)$$

$$CAIDI = \frac{\sum \text{Customer interruption durations}}{\text{Total number of customers interrupted}} = \frac{SAIDI}{SAIFI} \quad (3.5)$$

$$ASAI = \frac{\text{Customer hours service availability}}{\text{Customer hours service demand}} \quad (3.6)$$

Other indices such as ASIFI (average system interruption frequency index) and ASIDI (average system interruption duration index) are designed to determine distribution reliability based on load instead of the number of customers (IEEE, 2004). These indices are important when measuring the distribution reliability of areas with large-scale customers, such as industry and commerce. The indices are formulated as:

$$ASIFI = \frac{\text{Connected kVA interrupted}}{\text{Total connected kVA served}} \quad (3.7)$$

$$ASIDI = \frac{\text{Connected kVA duration interrupted}}{\text{Total connected kVA served}} \quad (3.8)$$

In addition to traditional reliability indices, customer outage costs (COC) can be considered an important index to measure distribution reliability, because this index converts reliability data into monetary value, and further, it is the only reliability index involved in the Finnish regulatory model.

3.2 Cost minimisation and reliability modelling

Minimisation of the total costs is a typical approach to distribution network planning. The minimisation function can be written as

$$\min Z = \int_{t=0}^{T} \left(\left(C_{\mathrm{CAP}}(t) + C_{\mathrm{OPEX}}(t) + C_{\mathrm{COC}}(t)\right)\right) dt, \tag{3.9}$$

where

T	planning period (lifetime)
t	time
$C_{\mathrm{CAP}}(t)$	annual capital costs for time t
$C_{\mathrm{OPEX}}(t)$	annual operational costs for time t
$C_{\mathrm{COC}}(t)$	annual customer outage costs for time t

when the following conditions of voltage drop (VD), short-circuit (SC) withstand capability and load capacity (L) are met:

- $U_{\mathrm{VD}} < U_{\mathrm{VD,max}}$
- $I_{\mathrm{SC}} < I_{\mathrm{SC,max}}$
- $I_{\mathrm{L}} < I_{\mathrm{L,max}}$

Capital costs are the annual annuity of investments, or alternatively, they can be the sum of investment depreciations carried out within the study period and the cost of funding (including the rate of interest). Operational costs comprise the costs of maintenance, fault repair, operational actions and energy losses. The customer outage costs cover harm and inconvenience caused to the customers by outages, which are converted into monetary costs with the outage unit costs. For underground cabling, the function of capital costs is written as

$$C_{\mathrm{CAP}}(t) = \begin{pmatrix} C_{\mathrm{cable}}(t) + C_{\mathrm{excavation}}(t) + C_{\mathrm{terminals\ and\ joints}}(t) \\ + C_{\mathrm{substations}}(t) + C_{\mathrm{compensation}}(t) + C_{\mathrm{reserve\ power}}(t) \end{pmatrix}, \tag{3.10}$$

where

C_{cable}	material and installation costs of underground cable
$C_{\mathrm{excavation}}$	excavation or ploughing costs
$C_{\mathrm{terminals\ and\ joints}}$	costs of cable terminals and joints
$C_{\mathrm{substations}}$	costs of pad-mounted substations
$C_{\mathrm{compensation}}$	costs of earth fault current compensation
$C_{\mathrm{reserve\ power}}$	costs of reserve power

The development of an electricity distribution network consists of a number of development actions in the long run. This path of actions generates the final costs that are to be minimised. Figure 3.3 illustrates a schematic of different paths between the years 0 and t. In the figure, vertical nodes describe the state of the distribution network at a specific moment, and the moment of the network development is presented horizontally so that the present moment is 0 and the end of the consideration is t. Thus, the development of the network constitutes a path of actions carried out in the network between the years 0 and t.

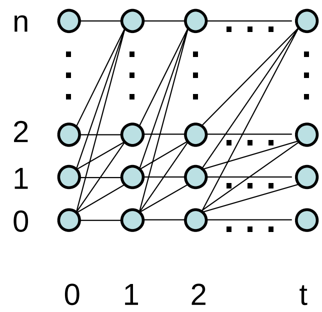

Figure 3.3. Schematic of distribution network investments.

3.2.1 Estimation of customer-experienced distribution reliability

Customer outage costs (COC) is a good indicator to assess customer-experienced distribution reliability. Calculation of the COC in the network analysis differs from the function (2.2) presented in the context of economic regulation. Now the COC is an estimate that is calculated separately for each substation, and also different interruption unit cost values of different customer groups can be taken into account. The function is written

$$C_{\mathrm{COC}} = \sum_{m=1}^{N_{\mathrm{sub}}} \frac{W_i}{8760} \begin{pmatrix} c_{\mathrm{u}} \cdot n_{\mathrm{u}} + c_{\mathrm{a}} \cdot n_{\mathrm{a}} + c_{\mathrm{ud}} \cdot d_{\mathrm{u}} + \\ c_{\mathrm{ad}} \cdot d_{\mathrm{a}} + c_{\mathrm{hsar}} \cdot n_{\mathrm{hsar}} + c_{\mathrm{dar}} \cdot n_{\mathrm{dar}} \end{pmatrix}, \tag{3.11}$$

where

- m index of distribution substation
- W_{i} annual energy of the substation i (kWh/a)
- c_{u} unit cost of unannounced interruption (€/kW)
- c_{a} unit cost of announced interruption (€/kW)
- c_{ud} unit cost of unannounced interruption duration (€/kWh)
- c_{ad} unit cost of announced interruption duration (€/kWh)
- c_{hsar} unit cost of high-speed autoreclosing (€/kW)

c_{dar} unit cost of delayed autoreclosing (€/kW)
N_{sub} number of distribution substations on the feeder
n_{u} estimate of the number of unannounced interruptions
n_{a} estimate of the number of announced interruptions
d_{u} estimate of the duration of unannounced interruptions
d_{a} estimate of the duration of announced interruptions
n_{hsar} estimate of the number of high-speed autoreclosings
n_{dar} estimate of the number of delayed autoreclosings

The estimates of interruptions are calculated from the actual MV network data using the fault statistics of the network under evaluation. The interruptions are defined separately for all the substation sections so that the customers of a MV/LV substation experience the same number and duration of interruptions. Therefore, the interruptions can be approached by substation-specific figures. The annual number of all types of interruptions (unannounced, announced, high-speed autoreclosings and delayed autoreclosings) can be defined by

$$n_{\mathrm{interruption},m} = \sum_i \sum_j \sum_k f_{ij} \cdot l_{ijk} \,, \tag{3.12}$$

where $n_{\mathrm{interruption},m}$ is the number of interruptions experienced by the customers of the distribution substation m, f is the fault frequency, l is the length of the line, i is the type of the line (e.g. overhead line, covered conductor, underground cable), j is the location of the line (forest, open space, roadside) describing the fault sensitivity, and k is the index of the lines that have an effect on the substation m. Correspondingly, the duration of annual interruptions (unannounced and announced) is determined as follows, divided into three time sequences t_1, t_2 and t_3 that describe the restoration durations of the disconnector sections:

$$\begin{aligned} d_{\mathrm{interruption},m} &= t_1 + t_2 + t_3 \\ &= \sum_i \sum_j \sum_k f_{ij} \cdot l_{ijk} \cdot t_{\mathrm{remote}} + \sum_i \sum_j \sum_p f_{ij} \cdot l_{ijp} \cdot t_{\mathrm{manual}} + \sum_i \sum_j \sum_q f_{ij} \cdot l_{ijq} \cdot t_{\mathrm{repair}} \,, \end{aligned} \tag{3.13}$$

where $d_{\mathrm{interruption},m}$ is the duration of interruptions experienced by the customers of the substation m, t_1 is the duration of switching times of the remote-controlled disconnectors; for instance, the interruption time that all the customers of the feeder experience, t_2 is the duration of switching times of manually controlled disconnectors, that is, the time required to trace the faulted disconnector section, and t_3 is the repair time of the faulted line that influences all the customers inside the faulted disconnector section and the customers of other disconnector sections that can be supplied only through the faulted section. The index k denotes the lines that cause an interruption of duration t_{remote} (switching time of the remote-controlled disconnectors), the index p

denotes the lines that cause an interruption of duration t_{manual} (switching time of manually controlled disconnector), and *q* denotes the lines that cause an interruption of duration t_{repair} (repair time of the fault) for the substation *m*. The disconnection sequence that determines the duration of interruptions is shown in Figure 3.4.

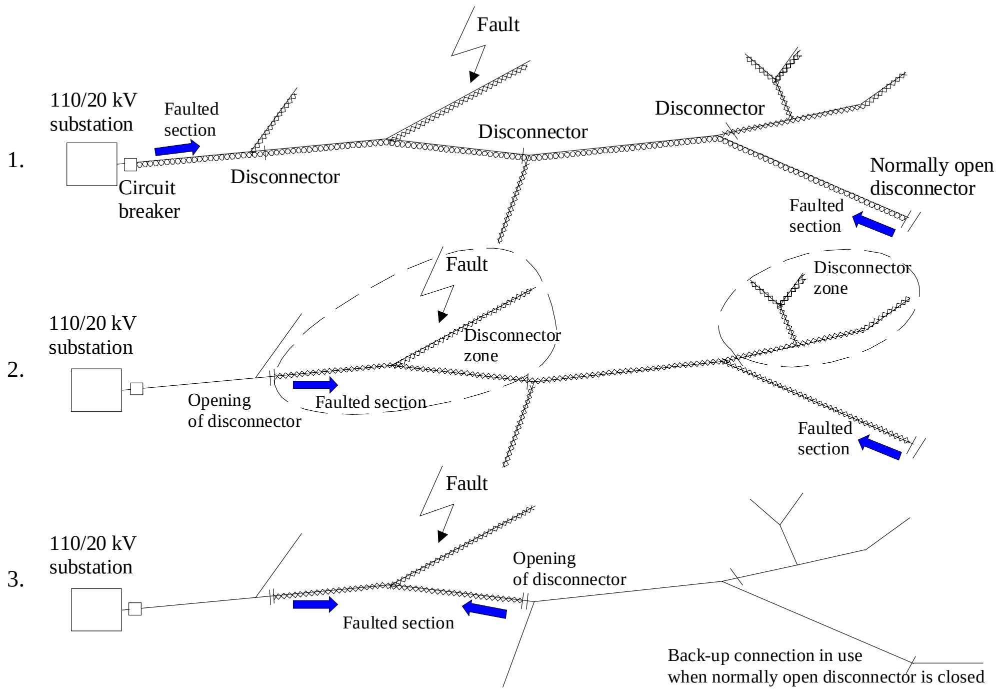

Figure 3.4. Fault isolation process. In the first step, the circuit breaker is operated. In the second step, the disconnector in front of the fault is opened. In the third step, the disconnector after the fault is opened and the back-up switch is closed (Kaipia et al. 2010).

3.3 Impact of reliability on network automation placement

Network automation is an effective way to improve the reliability of supply, and thus, it is widely utilised in the electricity distribution. An advantage of automation is fast implementation, and often also the affordability of the investment compared with the influence of the investment (Leite da Silva et al., 2004). The significant impact of automation on network reliability can also be observed in the economic values considered in the economic regulation. For instance, the customer outage costs decrease when the number of customer-experienced interruptions decreases. The topic of network automation is discussed in Publication II, which considers the correlation of several reliability indices and customer outage costs to define the optimal placement of network reclosers and remote-controlled switches.

The objective of the optimisation of network automation is to maximise benefits. Hence, considering maximum benefits to the customers, the target may be to maximise network reliability, while the DSO's aim may be to minimise costs. The benefits can be measured either by monetary values or reliability indices. If the monetary values are applied, the target can be to minimise the total costs, or in some cases, to maximise the profits. If the aim is to optimise reliability, a natural goal is to minimise the harm and costs of customer-experienced interruptions, to minimise SAIFI, SAIDI or other corresponding index. However, when using the interruption index as part of decision-making, it is difficult to determine the limit value at which it is profitable to invest in automation. This problem can be solved more easily when the optimised function is given in monetary value. In this case, it suffices to consider the investment and operational costs, and the monetary annual benefit of the automation device. The general optimisation function for network automation devices is written as

$$\max\left(Benefits(x)\right) \qquad x(\mathrm{P}) \in \mathrm{P} \in \mathrm{V}, \tag{3.14}$$

where

x	placement of the automation device
P	all placement configurations
V	electricity network

when all the boundary conditions are met.

3.3.1 Network reclosers

Network reclosers provide an easy way to improve distribution reliability because they provide same functions as circuit breakers but they can be installed in the MV network. They do not reduce the actual number of faults but they restrict the interrupted network sections so that a smaller number of customers experience the interruption.

Usually, network automation does not set many limits on the network operation. In the case of network reclosers, the selectivity of the protection has to be taken into account, and auxiliary power during outages has to be secured. For instance, the selectivity may restrict the number of series reclosers if the tripping times cannot be set tight enough (Billinton and Jonnavithula, 1996).

The benefits of a recloser are simple to calculate. In theory, only the annual capital costs C_{CAP} caused by recloser purchases $\|x\|$ have to be subtracted from the annual cost savings S that the improved reliability produces. The cost savings are basically achieved by decreasing the number and duration of customer-experienced interruptions in the network sections between the primary substation and the network recloser. The cost savings $S = C_0 - \mathrm{C(x)}$, where C_0 is the reference level of costs in year zero and $C(x)$ are the costs with the considered recloser placements x. The optimisation function for network reclosers is written as

$$\max\left(S(x) - C_{CAP} \cdot \|x\|\right) \qquad x(\mathrm{P}) \in \mathrm{P} \in \mathrm{V}, \tag{3.15}$$

when selectivity and other functional conditions are met.

Other option to optimise the performance of a network recloser is to maximise the reduction in the number of customer-experienced interruptions or the duration of interruptions. In that case, the optimisation function of the object reliability index such as SAIDI is written

$$\max\left(SAIDI_0 - SAIDI(x)\right) \quad x(\mathrm{P}) \in \mathrm{P} \in \mathrm{V}, \tag{3.16}$$

where $SAIDI_0$ is the system average interruption duration index without extra reclosers and $SAIDI(x)$ is the system average interruption duration index with the considered recloser placements x.

Figure 3.5 presents a simplified profitability curve of network recloser installation as a function of average power before a recloser and the length of the network downstream from the recloser. Other parameters behind the results are the installation price of the recloser, the interest rate, the lifetime and the outage unit costs presented above in Table 2.1.

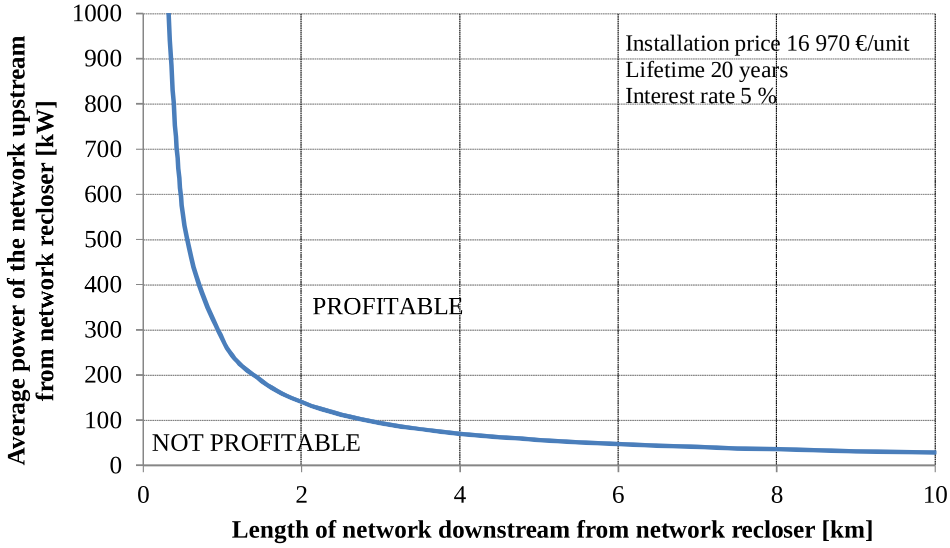

Figure 3.5. Profitability curve of a network recloser as a function of network length downstream from the recloser and average power upstream from the recloser. The fault rates for long interruptions are 10 faults/100 km,a, hsar 79 faults/100 km,a and dar 18 faults/100 km,a. The duration of interruptions is 3 hours/interruption. The fault rates are collected from the network presented in Figure 3.6.

Figure 3.6 illustrates the profitability of different recloser placements in an actual network. The figure provides a comparison of two different indices: customer outage costs (COC) and SAIDI. As it can be observed, the best placement option is different with these two indices, which emphasises the importance of defining the right object function for optimisation. For instance, if the objective is to maximise the benefits in COC savings, the best recloser placement strategy cannot be estimated by calculating the best placement option from the SAIDI perspective.

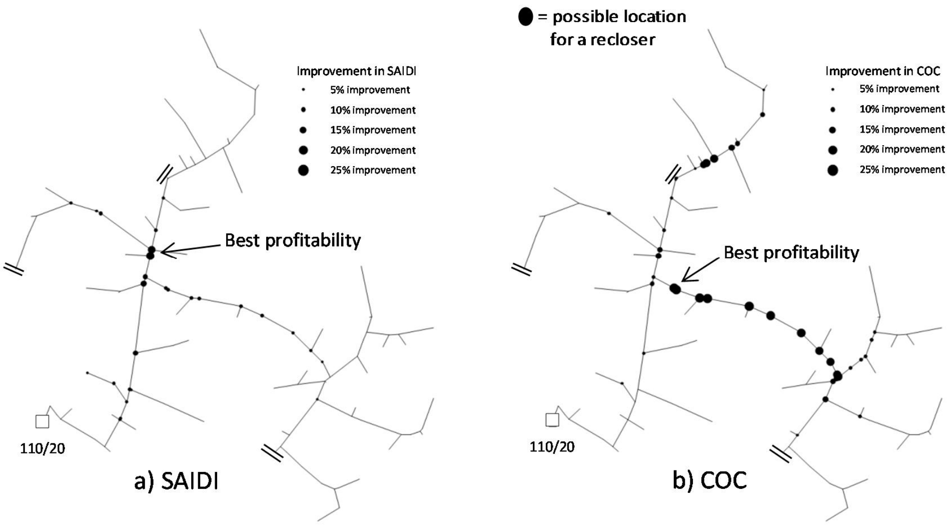

Figure 3.6. Profitability of recloser placement options on a MV distribution network feeder (Publication II).

3.3.2 Remote-controlled disconnecting switches

Remotely controlled switches provide an option for the DSOs to minimise the influence of an interruption by reducing the duration of the interruption experienced by the customer. The remote-controlled switch limits the network into smaller disconnecting switch sections similarly as a manually controlled switch. The difference to manual switches is the disconnection time, which is a few minutes with remotely controlled switches and typically an hour with manual switches. The optimisation functions for the installation of switches can be written in the same form as was introduced for network reclosers in (3.15) and (3.16). The marginal cost curves for remote-controlled switch installation in a network without a back-up connection are presented in Figure 3.7. The marginal costs are calculated assuming that the reduced interruption time is 60 minutes, which corresponds to the time between the remote-controlled and manually controlled switching events.

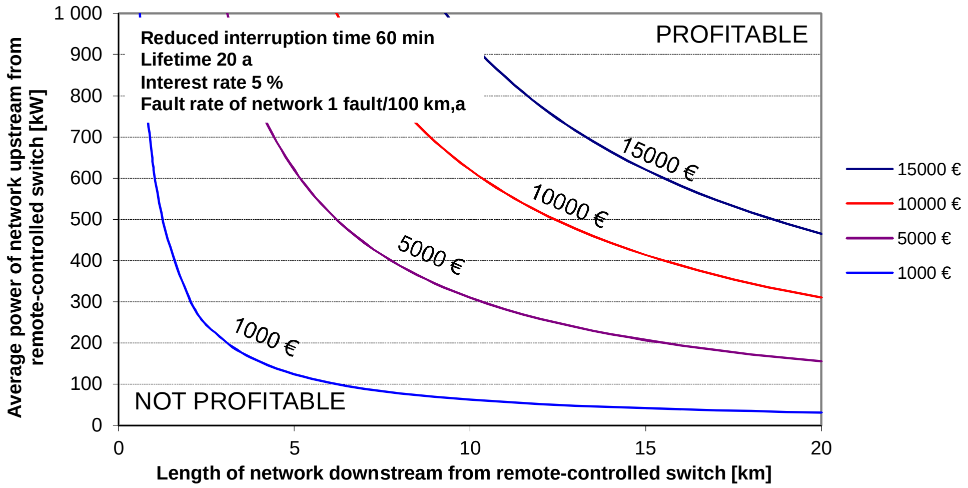

Figure 3.7. Profitability curves for a remote-controlled switch with different marginal costs of installation. The curves are valid for a network topology without a back-up connection.

3.3.3 Fault indicators

The function of fault indicators is to expose the faulted line section to the operator. The benefit of the indicators arises from the reduced interruption duration, because the faulted component can be disconnected without a test connection. Another benefit is that components are often preserved from high short-circuit currents that produce high mechanical stress to the components, because the number of test connections can be reduced. This can be a considerable benefit in the underground cable network where the location of the fault can be difficult to determine without fault indicators. Fault indicators can be used both in overhead and underground networks regardless of the type of the disconnecting switch (manual or remote-controlled). However, if the network is already sectionalised using remote-controlled switches, it is difficult to achieve economic feasibility because the switching times of remote-controlled switches are short already without fault indicators, and thus, the extra reduction in the operation time of the switch is not significant. If the reduction in the switch operation time is longer, for instance 30 minutes, which can be the situation in the network with manually controlled switches, the economic feasibility can be achieved in the network with lower loads. This can be observed from Figure 3.8, where the COC savings are compared with the capital costs caused by a fault indicator investment. The profitability of the fault indicators can be calculated using the same optimisation function as in the cases of network reclosers and remote-controlled switches (3.14)–(3.16).

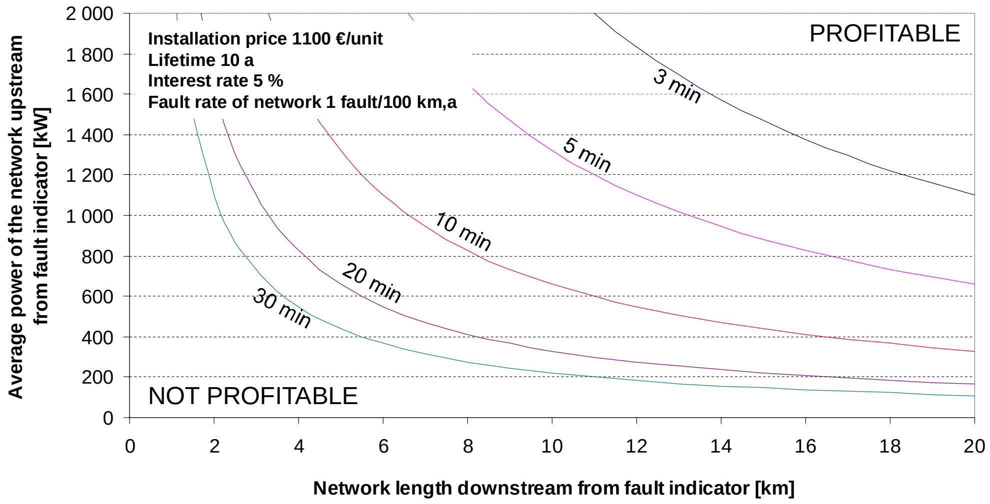

Figure 3.8. Profitability curves for a fault indicator with different reduction times in switch operation. The curves are valid for a network topology without a back-up connection.

3.4 Stochastic reliability model for the evaluation of reliability performance

The recommendation of the Finnish Energy Industries (Partanen et al., 2010) already introduced certain limits on interruptions; however, unlike in the present interruption limits defined in the law, one event of exceeding the limits was allowed within a three-year reference period. In order to analyse the approach, a novel reliability analysis was required, in which the risk to experience long interruptions within a certain time period is evaluated. A stochastic reliability model provides an opportunity to assess the performance of a distribution system. The topic is addressed in Publication III, where a Monte Carlo simulation method is used to measure the electricity distribution network performance as a part of the distribution network development process. The Monte Carlo method is one of the options to construct a stochastic reliability model (Brown, 2009; Bieda, 2012). The presented method yields information for the strategic decision-making by taking the network performance into account. The importance of risk management is emphasised especially in the cases where the regulator or other authority requires the DSOs to meet certain reliability standards, such as the Finnish supply security criteria. The analysis produces information of the interruption durations at a distribution substation level. This information is important to evaluate the probability of long interruptions experienced by the customers. The simulation methodology at the core of the analysis is demonstrated in Figure 3.9.

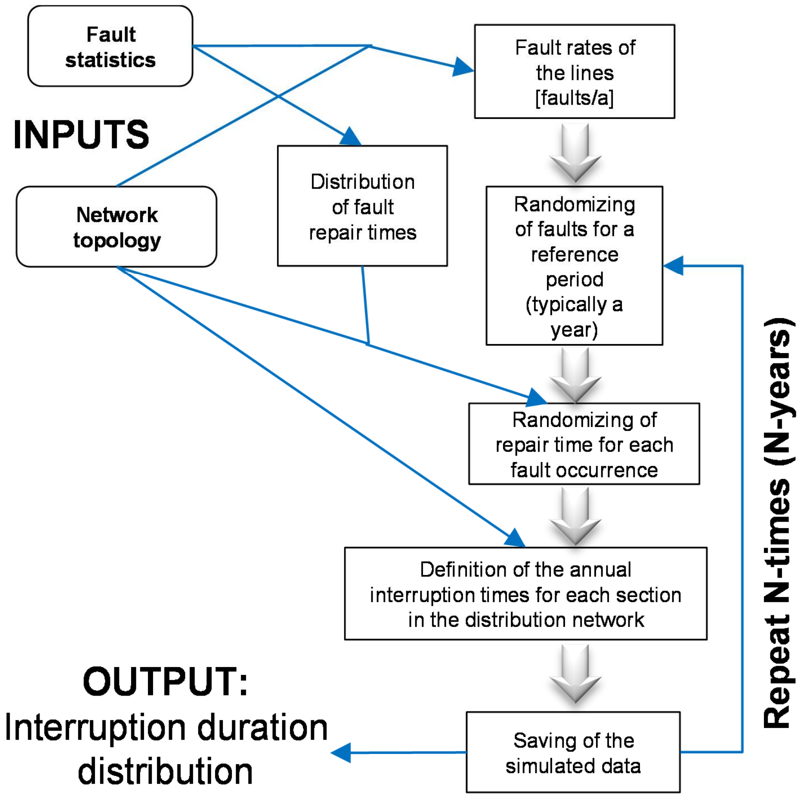

Figure 3.9. MV network fault simulation sequence by applying the Monte Carlo simulation method (Publication III).

The simulation applies fault and interruption statistics to define the fault rates and repair times for each fault taking into account the network topology and structure. The simulation is a sequential Monte Carlo simulation, which is repeated n times (N-years) to achieve a sufficient confidence for the simulated artificial interruption statistics (Balijepalli et al., 2004; Billinton and Wang, 1999). The number of repeated sequences can be for instance 1000 loops.

Interruption statistics are the basis of the network reliability assessment. To be able to analyse network reliability, data including long-term fault statistics are required, and the data should provide detailed information of the faults in order to be able to classify the faults (Brown et al., 2005). This makes it possible to compile fault distributions for different network types, but also distributions for fault repair and disconnection durations. Figure 3.10 presents an example distribution of fault repair times gathered in a Finnish distribution system within an eight-year period.

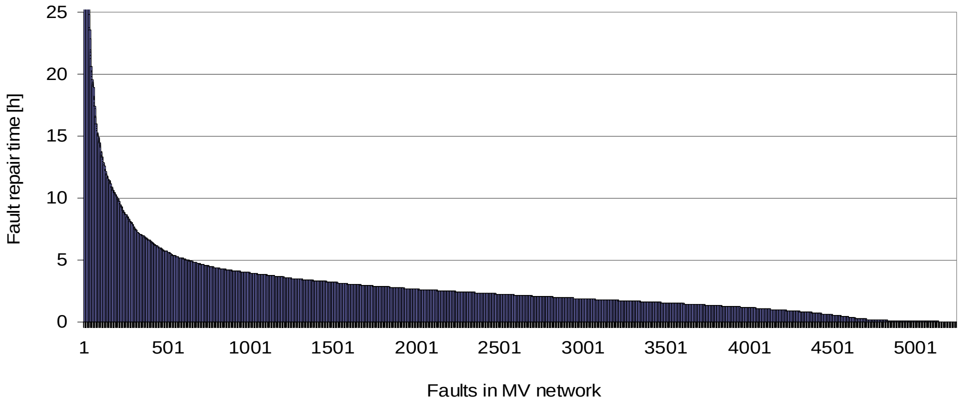

Figure 3.10. Distribution of fault repair time in a medium-voltage network for an eight-year period (2000–2008). Total length of the MV network is approximately 10 000 km.

As a result of the simulation, artificial fault statistics are obtained, which can be used to evaluate the reliability performance. An example result is the cumulative annual interruption duration distribution with a certain probability, as illustrated in Figure 3.11. It shows three curves for a distribution network with 400 distribution substations. Each curve shows a cumulative annual interruption duration with an exceeding probability (5 %, 25 % or 50 %) that describes the probability to exceed the specified value. The stochastic reliability model can be used, for instance, to compare different network strategies to estimate the best strategy by carrying out a simulation for each variation.

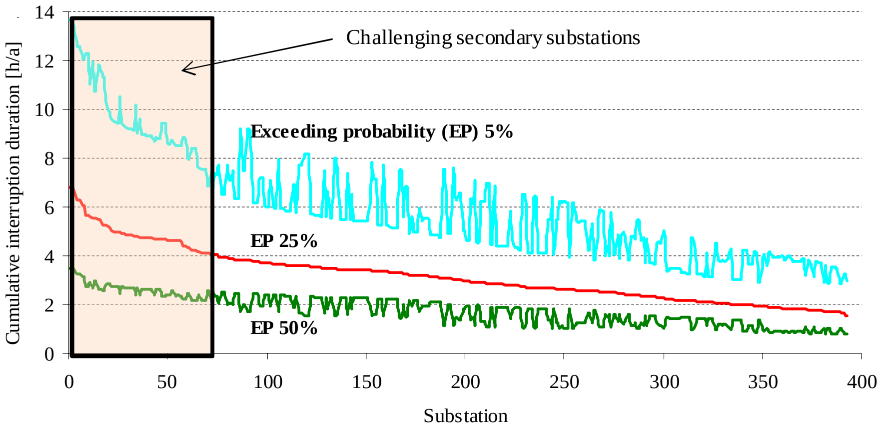

Figure 3.11. Cumulative annual interruption times in the distribution substations with different exceeding probabilities (Publication III).

The proposed simulation method provides a useful tool to analyse statistical electricity distribution network performance. The method could be developed further to assess the rates of major-disturbance-proof (MDP) or weather-proof (WP) network required for restoration of supply within 36 hours from a severe weather event (such as a major storm) with a certain probability. However, for this purpose, the simulation model should also be calibrated with actual storm data. Thus, the simulation model cannot be applied as such in its present form to the analysis to determine the required MDPR of the network.

4 Impact of the optimisation target on network planning

The objectives of the distribution system operators have an influence on the strategic planning of distribution networks. The planning is carried out observing the optimisation target, which depends on the expectations of the network owner. In general, the objective is to minimise the costs of electricity distribution, which reflects the aspect of national economy. However, because the electricity distribution networks can be owned by limited companies (Ltd), the aim of the company owners may be to get profit on their investments, and thus, the objective of the distribution company is to maximise the profit of the owners. Another approach can be to minimise the customer payments. All these objectives constitute different object functions that may lead to a different result thereby influencing the network structure, and consequently, customer-experienced distribution reliability. An overview to different objectives of the DSOs is given in Publication IV.

4.1 Minimisation of the total costs (TC)

Minimisation of the total costs is the traditional way to plan distribution networks. In the optimisation, all the costs of the DSO are taken into account in the formula. The costs comprise all the capital and operational costs but also customer outage costs. The general form of the minimisation function can be presented as follows:

$$\min Z_1 = \int_0^T \text{Total costs}(t)\,dt. \tag{4.1}$$

Taking into account the different cost terms, the minimisation function is written as

$$\min Z_1 = \int_{t=0}^{T} \left(C_{\text{CAP}}(t) + C_{\text{OPEX}}(t) + C_{\text{COC}}(t)\right)dt, \tag{4.2}$$

where

T	planning period (lifetime)
t	time
C_{CAP}	actual capital costs
C_{OPEX}	actual operational costs
C_{COC}	customer outage costs

Capital costs are the annual annuity of investments, or alternatively, they can be the sum of investment depreciations carried out within the study period and the cost of funding (including the rate of interest). Operational costs comprise the costs of maintenance, fault repair, operational actions and energy losses. The customer outage costs cover harm and inconvenience caused to the customers by outages. The function of customer outage costs has been presented in (3.11).

4.2 Maximisation of the owner's profit (OP)

The aims of the distribution network owner may represent an opposite approach to the network optimisation compared with the minimisation of total costs. From the business perspective, the aim is to maximise the profit of the owner, and thus, all the components affecting the profit have to be taken into account. Calculation of the owner's profit requires knowledge of the regulatory model to determine the allowed revenue that the DSO can get. Finally, the allowed revenue is subtracted by the actual costs of distribution system operation. Maximisation of the profit is formulated in the following equation:

$$\max Z_2 = \int_0^T \left(\text{Allowedrevenue}(t) - \text{Actualcosts}(t)\right)dt \,. \tag{4.3}$$

When the maximisation equation is written in the full form, the function becomes

$$\begin{aligned} \max Z_2 &= \int_{t=0}^{T} \left(\left(\mathrm{RRC}(t) + SLD(t) + Eff.Bonus(t) + Qua.Bonus(t)\right) - \left(C_{\mathrm{CAP}}(t)\right)\right)dt \,, \\ &= \int_{t=0}^{T} \begin{pmatrix} \left(\mathrm{RRC}(t) + SLD(t) + ATOTEX(t) + 0.5 \cdot COC_{\mathrm{Ref}}(t)\right) \\ -\left(0.5 \cdot COC + 0.5 \cdot COC\right) - \left(C_{\mathrm{CAP}}(t) + C_{\mathrm{OPEX}}(t)\right) \end{pmatrix} dt \end{aligned} \tag{4.4}$$

where

RRC	reasonable return on capital
SLD	straight-line depreciations
Eff.Bonus	bonus or sanction related to the efficiency costs
Qua.Bonus	bonus or sanction related to the reliability of supply
ATOTEX	allowed efficiency costs affecting the efficiency bonus
COC_{Ref}	reference of customer outage costs affecting the quality bonus
COC	annual customer outage costs affecting the efficiency and the quality bonus
C_{CAP}	actual capital costs
C_{OPEX}	actual operational costs affecting the efficiency bonus

Reasonable return on capital is the value calculated to be the profit that the regulatory model guarantees to the distribution company. The value is determined by the weighted average cost of capital (WACC) method. Straight-line depreciations express the reduction in the net present value of the network caused by ageing (in a year). The performance of the distribution companies is taken into account in an efficiency bonus, which is in accordance with the efficiency requirement of the company. A quality bonus or a sanction is determined from the reference value of the customer outage costs and annual customer outage costs.

4.3 Comparison of the optimisation approaches

The presented approaches to optimise the DSO's operation may produce different optimal strategies. It is expected that one network renovation strategy cannot be the best solution from all the perspectives. This is illustrated by a simplified 1 km network with a 1000 kW average load. The results are presented in Figure 4.1, where the total costs and profits are calculated for four network renovation strategies:

- Pole change: Replacement of the wood poles at the end of their techno-economic lifetime (40 years).
- Roadside: Transfer of the overhead line to the roadside at the end of its techno-economic lifetime (40 years); the transfer is carried out only for those sections that are located in forest, while the rest are renovated by pole replacement.
- Underground cable: Cabling starting from the oldest sections within a 40-year time period.
- Pole change 60: Replacement of the wood poles is carried out at the end of the extended lifetime (60 years), while the study period is still 40 years. The extended lifetime is provided by extended maintenance that raises operative costs.

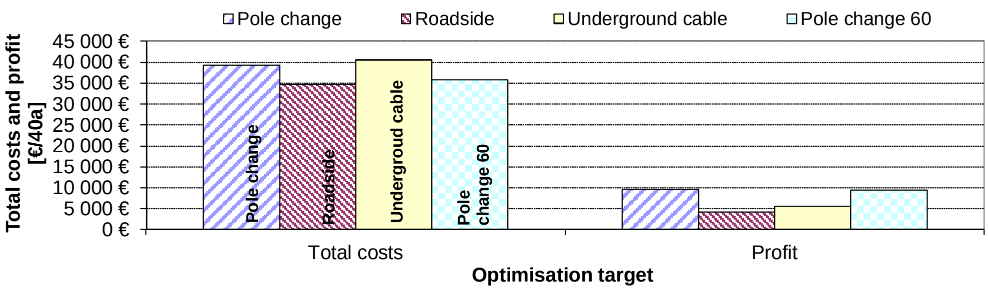

Figure 4.1. Comparison of the total costs and profits of the network renovation strategies (Publication IV).

The comparison shows that the considered optimisation functions produce different optimal strategies with the applied parameters. For instance, the use of the "Roadside" strategy produces the lowest total costs, but also the lowest profit. In other words, from the total costs' perspective it is the best solution, but from the profit perspective the worst. The most feasible strategy from the profit perspective is the "Pole change" strategy that causes the second highest total costs. The strategy "Pole change 60" is the second best from both perspectives. The profitability of the "Underground cable" strategy seems to be poor, because it produces the highest total costs, and the profit is second lowest in the comparison. However, the analysis is fairly sensitive to the parameters applied. If the load is doubled to 2000 kW, underground cabling becomes the best strategy from the total costs' point of view. Thus, to determine the best strategy for the network, the analysis has to be carried out with case-specific parameters.

We may conclude that both the approaches, that is, the cost minimisation and the profit maximisation, probably result in different optimal network strategies, and thus the best strategy for each DSO is selected depending on the objectives of the DSO. However, the differences between the strategies are often not significant enough to determine the only one best strategy. This can be observed from the sensitivity analyses, where the significance of the network load, the number of interruptions and valuation of interruption unit costs may essentially influence the profitability order of the strategies. In the following, the minimisation principle is used as the target of network planning and optimisation.

5 Approach to renovation investments

Renovation of electricity distribution networks from the perspective of supply security is a current topic in the Finnish distribution system. There are several reasons for this, but the most important drivers are the requirement to improve the supply security and tackle the issues related to the ageing distribution systems. Traditionally, distribution systems have been constructed with overhead lines, especially in rural areas; however, after the introduction of strict reliability requirements, underground cabling has become one of the most important technologies in network renovation. The rationale behind the utilisation of underground cables in rural area distribution is discussed in Publication V and Publication VI.

A network renovation process typically involves several strategic decisions. The process considers issues such as:

- What is the overall target for the weatherproof/major-disturbance-proof network?
- Where does the renovation begin?
- What is the priority order of the network areas (e.g. urban area feeders first)?
- What are the technologies to be applied?
- What are the network structures to be used in the renovation (e.g. underground cables and overhead lines with covered conductors located by the roadside)?
- What is the time schedule?
- Is the target to renovate the main part of the network within a faster time schedule (e.g. in 20 years)?
- What is the role of the existing network structure in the future?
- Is the existing network at the end of rural feeders planned to be maintained so that it can be operated well in the future?
- What is the renovation strategy or priority order?
- How does the renovation proceed? What are the lines that are renovated first in the selected feeder or supply area?

The importance of strategic decisions is emphasised when the scope of the process is extended. The length of an electricity distribution system can be tens of thousands of kilometres in a medium-size electricity distribution company in Finland. This means that the replacement value of the network is hundreds of millions of euros. Thus, for instance the question of the technologies to be applied has to be considered carefully. Typically, the distribution network can be built with several parallel technologies such as:

- Traditional bare overhead line
- Covered conductor overhead line
- Aerial cable
- Underground cable
- Low-voltage distribution line (1000 V) to replace a medium-voltage line
- Aerial cable
- Underground cable

As it can be observed, there are various optional technologies, which may be taken into consideration in the strategy work. When the boundary conditions are set by the operating environment and requirements are taken into account, guidelines of the renovation process can be given.

Timing of the renovation has a significant influence on the ageing of the network, and vice versa. The long lifetimes of the distribution network pose a challenge to the process; nevertheless, the ageing infrastructure also provides a unique chance to take advantage of the situation. From the business point of view, the techno-economical lifetime of the network components should be used to the full, but the other constraints such as reliability may not support this. Thus, compromises have to be made when considering the timing issue.

5.1 Supply security analysis

Supply security criteria based on Electricity Market Act (588/2013) set the key limits on the network renovation, and they have to be taken into account in renovation planning. A significant proportion of the distribution networks has to be assessed, and the renovation schedule has to meet the supply security requirements. An analysis covering the network performance is needed to determine the development actions to achieve adequate supply security using either weatherproof (WP) or major-disturbance-proof (MDP) network structures. A WP network consists of underground cables while an MDP network consists of both underground cables and overhead lines located on fields.

Supply security criteria emphasise the role of the LV network. Usually in the strategic network planning, the importance of the LV network is lower than that of the MV network. This is explained by the scope of the area influenced by a fault event or disturbance. A fault in the LV network usually causes a supply interruption only for a few customers, while in the case of an MV fault the number of customers can be counted in hundreds, and thus, the costs resulting from faults are much higher in the MV case. However, supply security criteria do not distinguish whether the interruption is a consequence of a MV or LV fault. Therefore, both of the networks have to be included in the analysis.

Major disturbance modelling is illustrated in Figure 5.1. There are four main inputs that finally determine the scope of the supply security renovation. These are information of the customers, network and faults, and also the information of the fault repair organisation during the major disturbance. The final required weatherproof rate (WPR) or major-disturbance-proof rate (MDPR) can be computed using the initial data. The storm modelling is also considered by Lassila et al. (2013).

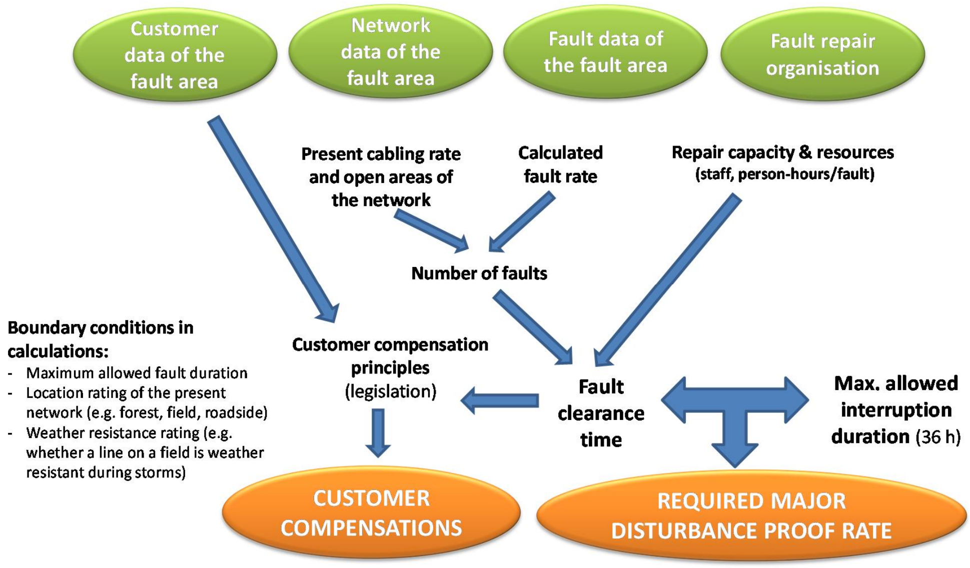

Figure 5.1. Elements of major disturbance modelling (adapted from Partanen et al., 2012b).

Another approach to assess the required major-disturbance-proof rate could be the application of the proposed simulation method (Publication III), but the method should be developed further to better fit the major disturbance analysis. In addition, the model should be calibrated with major disturbance data. Thus, the benefits of the simulation method compared with the method presented in Figure 5.1 are slight.

Figure 5.2 presents the average required WPR to restore the electricity supply within 36 hours in two different storm cases in Finland based on the interruption and network statistics of seven DSOs. The figure shows that on average, the worst-case situation is a summer storm. However, the average WPR cannot be used as an objective for the DSOs, because the operating environment and the network structures vary significantly between the DSOs. Nevertheless, the figure shows that the supply security has to be improved in all of the rural area networks.

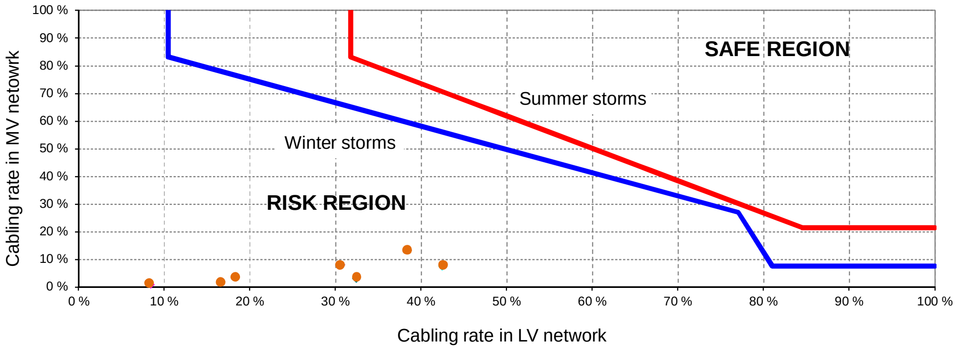

Figure 5.2. Average required weatherproof rate in a Finnish distribution network based on storms in summer 2010 and winter 2012 (Partanen et al., 2012b).

There are several ways to improve the supply security and reach a sufficient security level in a distribution network. However, common to all these is the target to increase the length of the MDP network regardless of the voltage level. A straightforward way is to build the MV network underground starting from the primary substation and renovate the LV networks when the MV renovation reaches the MV/LV substations. Another opportunity can be, for instance, to apply 1000 V technology to replace low-loaded overhead MV branch lines by LV cables, which significantly improves the WPR by removing the fault-prone overhead branch lines. However, also the simultaneous renovation of the LV networks by underground cables reduces the length of LV lines, which are vulnerable to faults. In this case, the situation is improved simultaneously in both the MV and LV networks.

5.2 Cabling concept

Underground cabling is one of the most interesting technologies to be used in network renovation in the present operating environment. As it has been discussed above, cabling offers an effective way to improve supply security to reach the supply security limits. However, cabling brings many challenges that have to be taken into account. These issues can be addressed by the questions as to when, where and how the cabling is implemented, in other words, which parts of the MV network are the most feasible ones for underground cabling, and how the cabling can be focused on the most aged (oldest) targets. An overview of the questions and tasks related to the determination of the cabling concept is presented in Figure 5.3. It illustrates the basic questions involved in the cabling process. The concept helps to find out the best strategy for cabling.

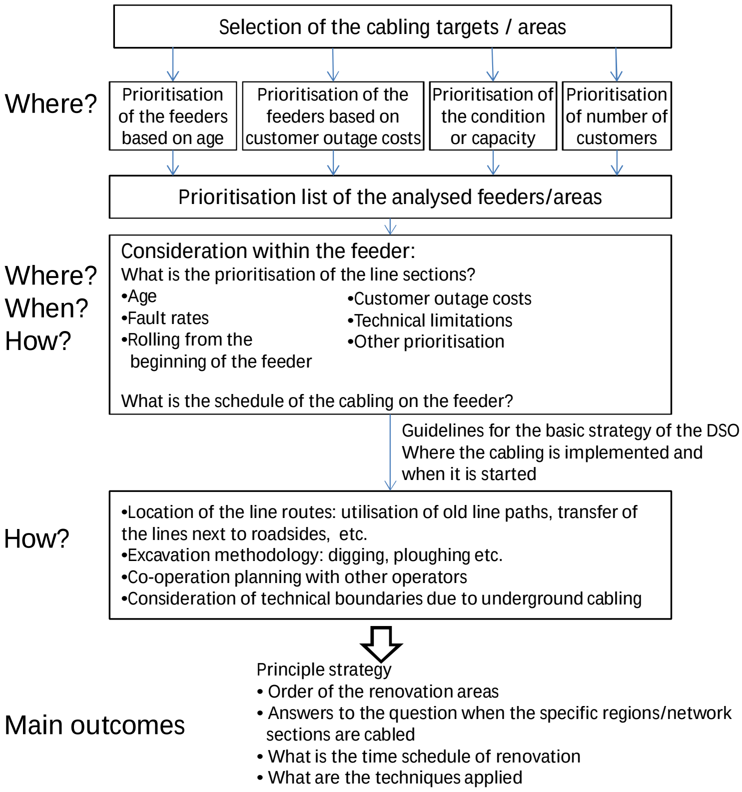

Figure 5.3. Flow chart of the cabling concept (Publication VI).

The cabling concept addresses the above questions where, when and how the underground cabling is carried out. The process can be divided into separate blocks as it is demonstrated in Figure 5.3. The first blocks answer to the question where the cabling is implemented. This includes the prioritisation of the substation areas and feeders. When the consideration is at the feeder level, the age structure of the network and other issues such as technical limitations affecting the renovation schedule have to be dealt with. By the analysis, an estimate schedule of the process can be determined (the question When?). At the same time, the consideration provides answers to the question of how the cabling proceeds at the feeder level. At this phase, the target network structure for the area under renovation has to be determined so that possible new line routes can be examined in the renovation planning to estimate the method to lay the cable in the ground, as it plays a key role in the costs. Another issue that is linked to the line route planning is the connection of the MV and LV networks. For instance, if the MV line route is transferred from forest to the roadside, it may cause a need to renovate also the LV networks. If the MV network renovation is carried out so that the line route is not changed, there is no immediate need to renovate the LV network, because the location of the distribution substation can remain the same. The only change may be the replacement of an old pole-mounted substation by a pad-mounted substation, which is reasonable to be used in the underground MV network.

Renovation of MV feeders starts from the selection of the cabling strategy based on the priority order of the line sections. The prioritisation involves at least the following options:

- Renovation from the beginning of the feeder by a rolling strategy
- Renovation of the oldest line parts
- Renovation of the most fault-prone parts
- Renovation of parts causing most customer interruption costs

The prioritisation of the feeder sections in the four-year renovation schedule is demonstrated in Figure 5.4. In the network of the figure, the renovation is carried out based on the age of the lines. The advantage of the age-based renovation is that the lifetime of the network can be maximised, and thus, premature investments can be minimised. On the other hand, there is a risk that the reliability or supply security does not improve if the investments are allocated only based on age information. The same risk may also be involved in the other prioritisation strategies that are not based on reliability, which again emphasises the importance of network planning.

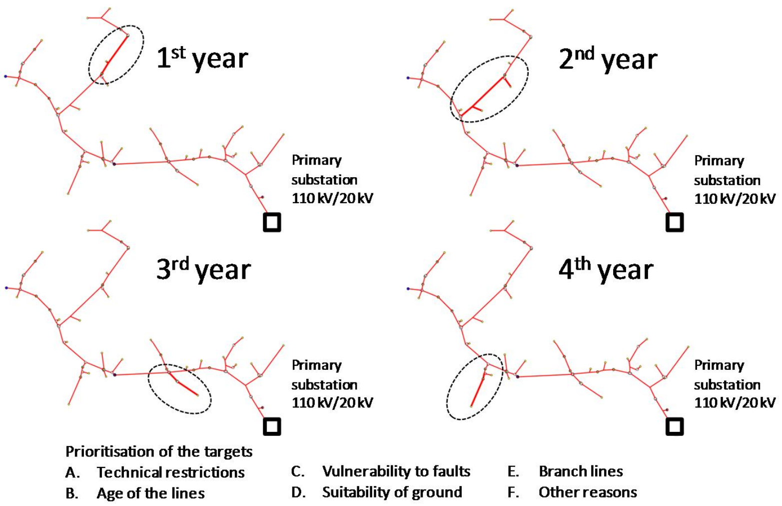

Figure 5.4. MV feeder renovation with the priority on the oldest line sections (Publication VI).

Supply security requirements determine a tight schedule for network development. In order to keep to the schedule, the network renovation has to be designed to proceed smoothly. A natural renovation order is to start from the feeders with the highest loads per line kilometre, usually urban feeders with low line lengths. It is reasonable to carry out the renovation of these at once; this should guarantee that the target of 2019 is achieved (50 % of customers are within the criteria). On rural feeders, the best influence on supply security and asset management is achieved when the oldest and most vulnerable network sections are renovated. However, this cannot be the only determining factor. These priority orders can be taken into account in the selection of the feeder renovation order, but the prioritisation within the feeder would be preferable to carry out by rolling from the primary substation. This way, the renovation can be carried out as efficiently as possible, which is important when considering the requirements of the supply security written in the law. Moreover, the selection of the rolling strategy is in line with the objectives of the law, where the six-hour time limit is set for urban areas, and 50 % of customers have to be within the criteria before the end of 2019. The target would be more difficult to reach if other strategies were applied. This is because the customer density is often at highest close to primary substations.

5.3 Investment scenario based on the network renovation concept

Preparation of an investment scenario requires definition of the present state of the network. Supply security plays a key role in the Finnish electricity distribution network planning because of the stringent limits on the allowed interruption durations. Thus, in addition to the present state, the target of network planning has to be clear. The objective can be a certain level of major-disturbance-proof (MDP) network that determines the volume of reliability investments required.

The proposed network renovation concept is applied to actual network renovation planning. The network under study is a rural area network comprising ten feeders, of which a few supplies a small population centre. The basic information related to this network is presented in Table 5.1. The table contains the information that the initial rate of the major-disturbance-proof network is 9 % in the MV network and 45 % in the LV network, when underground cables and overhead lines in the field environment are considered to be major-disturbance-proof. This is the starting point of the supply security analysis to define the total minimum network development to reach the required major-disturbance-proof rate (MDPR).

Table 5.1. Basic information of the analysed network in year 2012.

MV line lengths	Bare overhead lines	580	km
	Covered overhead lines	5	km
	Underground cables	5	km
MV line locations	Forest	70 %	
	Field	8 %	
	Roadside	22 %	
LV line lengths	Overhead lines	425	km
	Underground cables	115	km
LV line locations	Forest	70 %	
	Field	30 %	
Number of customers	Total	4 460	
Number of distribution substations	20/0.4 kV	448	
Number of disconnecting switches	Manual	323	
	Remote-controlled	29	
Peak power	Total	8.2	MW
Energy consumption	Annual	42	GWh/a
	Residential	54 %	
	Agriculture	6 %	
	Industry	9 %	
	Public	18 %	
	Service	13 %	

5.3.1 Required major-disturbance-proof rates (MDPR)

In the supply security analysis, after the present state of the network has been determined, the next task is to define the required MDPR level to find out the minimum scope of the renovation by comparing the present state with the required MDPR. The required MDPR level is determined by using the information of the fault repair organisation, network and fault data. The fault information to be used can be the worst major disturbance occurred in the analysed distribution network, or if no major disturbances have been recorded, the reference major disturbance can be estimated from the data of another DSO operating in similar circumstances. The minimum major disturbance information to calculate the required MDPR level is presented in Table 5.2. The information derives from an actual major disturbance occurred a few years ago in the analysed distribution network. The major disturbance information contains actual fault data during the major disturbance in both the MV and LV networks, fault rates estimated from the fault numbers for the network affected by the major disturbance (overhead lines vulnerable to falling trees), the average number of working personnel and fault repair time per fault. Yet another important parameter is the allowed interruption time, which is now 36 hours in rural areas. The number of parameters seems to be low, but an in-depth analysis is required to correctly determine different parameters and ensure that the results are appropriate for the purpose. Further, in a more specific analysis, the number of parameters can be higher involving additional information such as a peculiar fault repair time of the LV network or number of working hours per day per worker.

Table 5.2. Major disturbance information

	MV network	LV network
Fault number during the disturbance	72	78
Fault rates [faults/100 km]	13.4	26.3
Resources/ Fault repair organisation	18	Persons
Fault repair time	12	Person working hours / fault in both the MV and LV networks

The required MDPR level can be estimated from the major disturbance information so that the extreme values are determined first. This means for instance the minimum MDPR for the LV network when all the fault repair resources can be allocated to the LV network because the MV network is 100 % major-disturbance-proof. Intermediate points can be determined by drawing a line between the extreme values. The minimum MDPR points can be calculated by

$$MDPR = 1 - \frac{\text{Allowed interruption time}}{\text{Fault repair time}} \cdot \frac{\text{Number of resources}}{\text{Fault rate} \cdot \text{Length of network}} . \qquad (5.1)$$

By substituting the parameters, the $MDPR_{\text{LV}}$ and $MDPR_{\text{MV}}$ become

$$MDPR_{\text{LV}} = 1 - \frac{36\ \text{h}}{12\ \text{h/fault}} \cdot \frac{18\ \text{person}}{26.3\ \text{faults/100 km} \cdot 540\ \text{km}} = 62\ \%,$$

when $MDPR_{\text{MV}} = 100\ \%$

$$MDPR_{\text{MV}} = 1 - \frac{36\ \text{h}}{12\ \text{h/fault}} \cdot \frac{18\ \text{person}}{13.4\ \text{faults/100 km} \cdot 590\ \text{km}} = 32\ \%,$$

when $MDPR_{\text{LV}} = 100\ \%$

Figure 5.5 presents an example of the required MDPR where the extreme values are (LV 62 % / MV 100 %) and (LV 100 % / MV 32 %). The network feeders under study are indicated in the figure to illustrate the present state of the network compared with the required MDPR. At present, the MDPR of the MV network is 9 % and 45 % for the LV network. The figure shows that to reach the adequate supply security, the average

MDPR of the network on the LV side has to be improved by 50 %-points and on the MV side by 31 %-points.

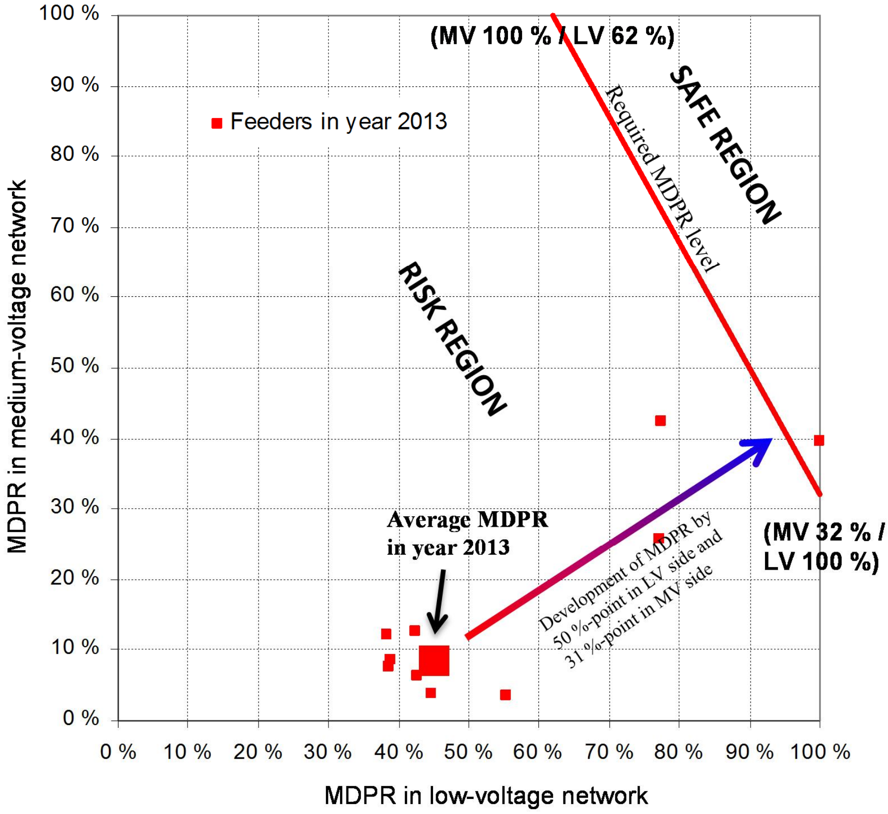

Figure 5.5. Present state of the distribution network and the required major-disturbance-proof rate (MDPR) of the network to meet the supply security requirements.

5.3.2 Network technologies

The calculated minimum improvement in the MDPR in the analysed network indicates that the network requires a significant effort to reach the sufficient supply security. This imposes stringent requirements on the network renovation. The renovation has to be carried out so that costs of the network are minimised in the long term as it has been presented in (4.2) or maximised (4.4). The minimisation calls for the use of cost-efficient network structures and observation of both the normal-state and major disturbance reliability (fault rates presented in Table 5.3) so that the customer outage costs are taken into account. Thus, replacing the existing overhead MV lines by MV underground cables is not the only solution. It has to be considered whether it is possible, for instance, to improve the existing lines so that they can be classified as major-disturbance-proof ones or to replace the MV lines by 1000 V technology taking advantage of the cost-efficient LV technology. The objective of the renovation is that the number of fault incidents decreases considerably, which, in general, reduces the benefits of network automation. However, network automation cannot be set aside at least on rural feeders, because the rural network is extensive, and the network also includes lines that are not MDP in the future as can be observed from Figure 5.5. For instance, if the MDPR of the LV network is 95 %, the MDPR of the MV network has to be at least 42 % to meet the criteria. Thus, 58 % of the MV lines can be non-MDP.

Table 5.3. Fault rates in the case network

Overhead line (OHL)	Permanent faults (faults/100 km,a)	High-speed autoreclosings (faults/100 km,a)	Delayed autoreclosings (faults/100 km,a)
forest	10	21.9	30
roadside	6	10.95	15
field	1.3	4.38	6
Covered conductor OHL			
forest	5	2.92	4
roadside	2	2.19	3
field	1	2.19	3
Underground cable	1	-	-

5.3.3 Investment schedule

It is advisable to start to improve the supply security from urban areas. The main reason is the high customer density per line length in these areas. Another fact supporting this approach is the requirement that 50 % of the customers should be within the supply security criteria before the end of 2019. The limit of the six-hour interruption duration means that, in practice, the urban area network has to be completely weatherproof or major-disturbance-proof, because one severe fault on the overhead line alone may cause exceeding of the allowed six-hour interruption duration. Nevertheless, the proportion of urban area networks is relatively low, which releases investment resources to rural area networks where the most challenging network areas from the supply security perspective are typically located. Figure 5.6 shows an example investment schedule that leads to an optimal network structure in the case network. The investment program is scheduled between the years 2013–2028 so that the network renovation can be carried out before the end of the supply security transition period, and the required MDPR will be achieved in 2028. The investments are scheduled to start in 2014 in the urban area network and proceed to rural areas in 2016 when the urban areas have completely been renovated.

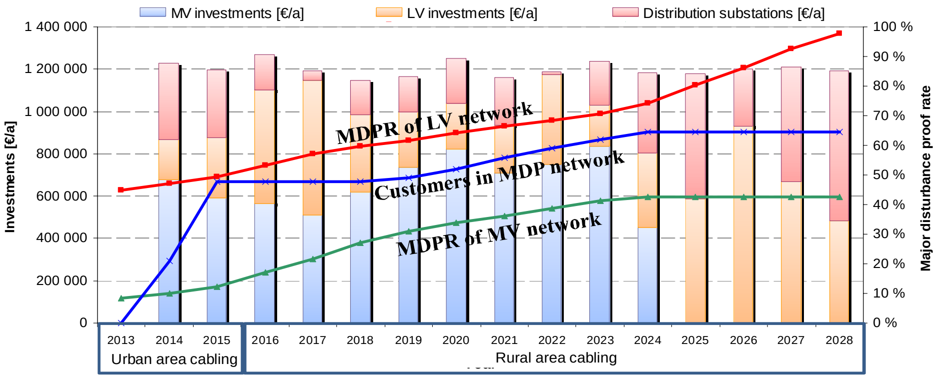

Figure 5.6. Example renovation investment schedule between the years 2013 and 2028.

It can be observed that the major-disturbance-proof rates increase in the LV network from the initial 45 % to 98 % and in the MV network from 9 % to 42 %. The number of customers in the major-disturbance-proof network increases from the initial 0 % to 65 %. The curve of customers in the MDP network describes the number of customers whose primary power supply line is completely major-disturbance-proof. The annual amount of investments is planned to be approximately 1.2 M€ throughout the investment schedule; only the annual target of investments in the distribution network varies. At the beginning, the investments are allocated quite equally to the MV network, the LV network and the distribution substations. When the urban areas have been renovated, the focus shifts to the MV network renovation. The MV network renovation is carried out to the point where it is economically profitable to install a network recloser to separate the MDP network from the network that is not major-disturbance-proof. After this point, the benefits of the MV network development are relatively low, which is due to a decrease in the COC savings, because the load density reduces towards the end of feeders. This supports the investments in the LV networks instead of the MV networks especially in the case where investing in the LV networks is more cost-efficient and inexpensive compared with the MV network investments. Thus, at the end of the investment schedule, the investments are focused only on the LV networks and distribution substations to achieve the required MDPR in the most cost-efficient way. Estimations of the average reliability numbers (SAIFI and SAIDI), customer outage costs, maintenance costs and fault repair costs are presented in Figure 5.7. The figure shows that the average reliability values decrease over 50 % from the initial values; SAIFI from 1.98 pcs/a to 0.74 pcs/a and SAIDI from 2.21 h/a to 1.04 h/a. The sum of customer outage costs, maintenance costs and fault repair costs also decreases from 425 000 €/a to 270 000 €/a, where the decrease in the outage costs constitutes the most significant proportion. The maintenance costs and fault repair costs contain both the MV and LV network costs. The maintenance and fault repair costs seem to remain at the same level as they were at the beginning of the year 2013. This is mainly a consequence of the remaining aged MV overhead lines, which require more maintenance and fault repair resources. For instance, at the end of the investment period, the network contains over 90 km MV network that is over 60 years old. These lines are located on the rural feeders downstream from the installed network recloser.

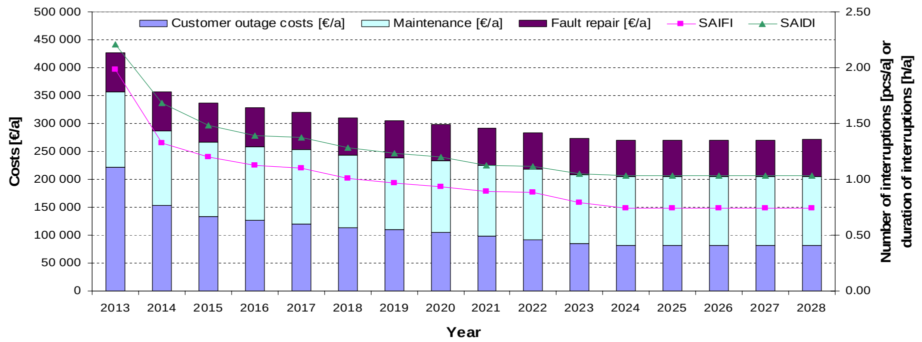

Figure 5.7. Development of customer outage costs, maintenance costs, fault repair costs and SAIFI and SAIDI during the renovation investment schedule between the years 2013 and 2028.

The positions of the feeders on the analysed network at the end of 2028 in the MDPR graph are presented in Figure 5.8. It shows that the reliability of the most feeders is better than required, and also the average MDPR of the feeders rises slightly above the required level. Thus, the network meets the 36 h supply security requirement in rural areas and the 6 h requirement in urban areas.

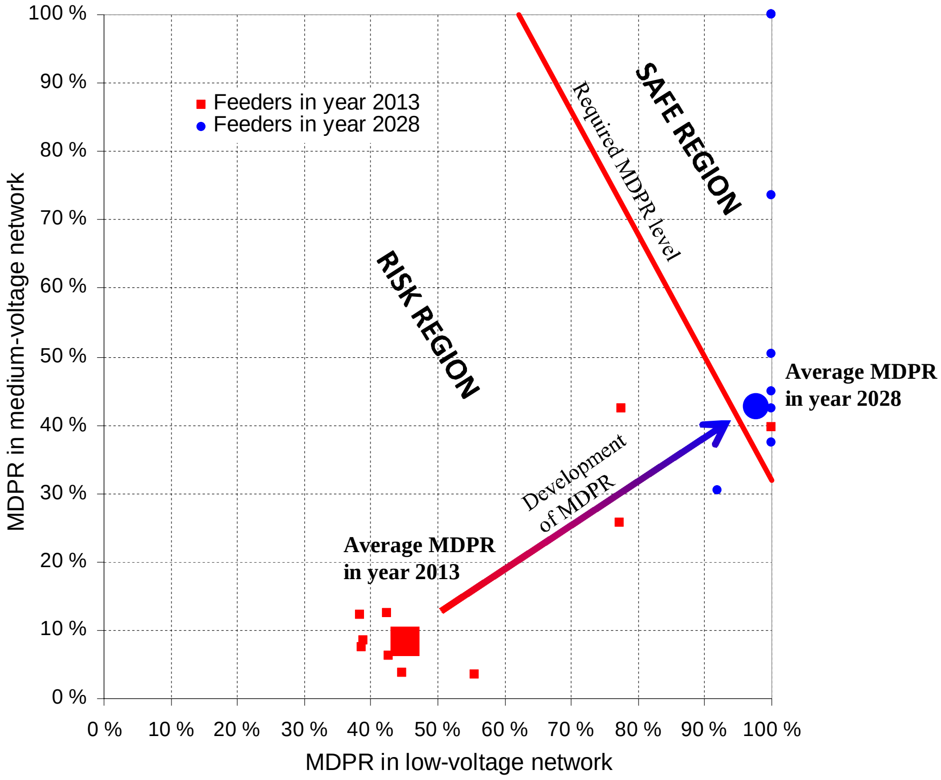

Figure 5.8. Development of the major disturbance resiliency in the network between the years 2013 and 2028.

6 Reserve power during supply interruptions

Reserve power is an important means to reduce the inconvenience experienced by customers in the occurrence of outages (He et al., 2010). In some cases, it is essential to prepare a reserve power plan for the network to meet the supply interruption limits set by the authorities. In the Finnish distribution systems, the maximum interruption duration of six hours in the urban areas requires that, in practise, the electricity supply has to be restored without time-consuming repair actions on the network. This means that the network has to be meshed thus providing permanent back-up supply routes, or the network has to include connection points for reserve power generators or reserve power cables to allow rapid restoration of the supply. However, the 36-hour interruption limit in rural areas does not necessarily guarantee supply restoration fast enough, because the allowed time may not suffice to repair some fault types. For instance, repair of a fault in an underground cable network and restoration of power supply may take several days. Thus, a reserve power plan should also be provided for rural areas.

An optimal reserve power strategy depends highly on the network structure including the customer density, the line length and the number of disconnection switches. Moreover, the objectives of the network development give indication of the profitability of the reserve power. A benefit of an overhead line network compared with an underground cable network is that faults are often relatively fast to repair, that is, within a few hours on average, whereas in an underground network, a fault may cause an interruption of days, which is prohibited in the new Electricity Market Act in Finland. This implies that the underground cable network may require additional reserve power solutions, at least for those network sections where back-up power cannot be supplied, such as on terminating branch lines.

The proposed reserve power options all require a different approach to network construction. The reserve power strategy to be applied should be determined before the renovation or network construction is commenced so that the required loops can be added to the network configuration or the network can be equipped with suitable components. The topic is discussed in Publication VII, which presents the cost functions for three reserve power strategies.

6.1 Placement of disconnecting switches

The policy concerning the placement of disconnecting switches such as line and transformer switches has a considerable influence on the interruption durations experienced by the customers (Haakana et al., 2012). In addition, the network type typically influences the placement policy. Faults in underground cable networks are of rare occurrence; however, cables are not fault free. The faults are time consuming to repair, which calls for reserve power arrangements to supply loads during the fault. Therefore, distribution substations in urban underground cable networks are often equipped with switches, and thus, each line section can be disconnected from the network. In rural networks instead, switches are often installed only to the significant nodal points on the network. However, in such cases the network is usually of overhead line type, not underground one. Nevertheless, if rural networks are also built underground, the switch placement strategy should be carefully reconsidered to avoid a situation where a fault leads to a long interruption for several distribution substations.

Switch placement can be considered on a simplified network scheme shown in Figure 6.1. In the figure, the network is divided into sections, where the switch positions are denoted by D1, D2, Dt and Db. To meet the time limit on the allowed interruption duration, the faulted network section has to be disconnected so that reserve power can be supplied. There are several alternatives to construct the network so that this requirement is met, such as installation of line switches to the beginning and end of each line section (D1 and D2), installation of transformer switches to each substation, installation of switch D1 or D2 to the ring main unit (RMU), and providing an option to cut the distribution line in the connection point of the RMU without a switch (for instance, if switch D1 is installed, D2 is a possible place to cut or release the cable from the terminal in the RMU).

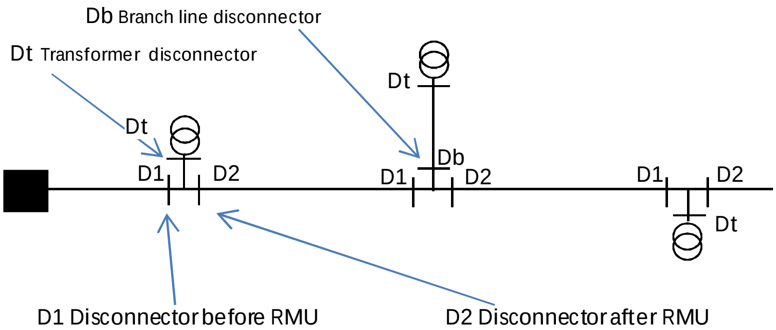

Figure 6.1. Network schematic with different disconnector placement options.

6.2 Optimal reserve power strategy

There are several alternative reserve power strategies that can be applied to secure electricity supply in the long term. The reserve power strategies under study are:

- Reserve power generators
- Reserve power cables
- Looping of the lines

The strategy involving reserve power generators is based on the use of transportable reserve generators that can be powered for instance by diesel. The use of such generators requires connection points so that the reserve power can be supplied to the network. In addition, it has to be possible to disconnect the network supplied by a reserve generator from the normal distribution system before the reserve power is connected. Reserve power cables can be used in a situation where the distribution network is equipped with connection points at which the reserve cables can be plugged in to bypass the faulted line section. Thus, the normal centralised distribution continues while the faulted line section is under repair. Nevertheless, the faulted network has to be disconnected from the healthy network to be able to restore the supply. The strategy applying looping of the lines is based on a meshed distribution system. In order to operate correctly, the system has to be well looped and there cannot be terminating branch lines.

Figure 6.2 presents an example of the use of reserve power generators in a network where a branch line fault has isolated three distribution substations from the healthy network. After the faulted line is isolated and reserve generators are in use, the faulted network section can be repaired ignoring the pressure of the maximum allowed interruption duration.

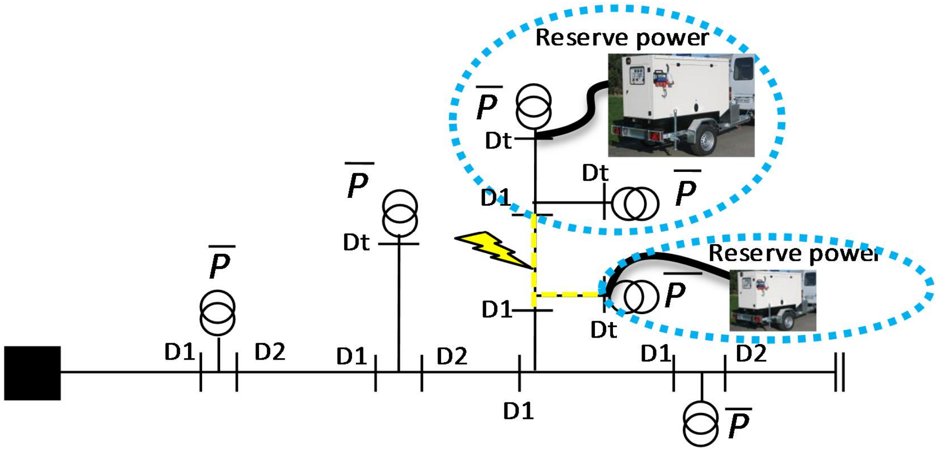

Figure 6.2. Reserve power generators are connected to supply customers in the network sections downstream from the faulted line section (Publication VII).

The profitability of the reserve power strategies varies as a function of network parameters. However, the study shows that the decisive parameter is the length of the line without a back-up connection (branch lines). The studies in (Publication VII) indicate that when the branch lines are shorter than 200 m, it is profitable to invest in looping of the branches. When the lines are between 200 and 500 m long, it is profitable to apply the reserve power cable strategy. Reserve power generators are the most profitable solution when the length of the branch lines exceeds 500 m. Figure 6.3 shows a cost comparison of the reserve power strategies in the example network.

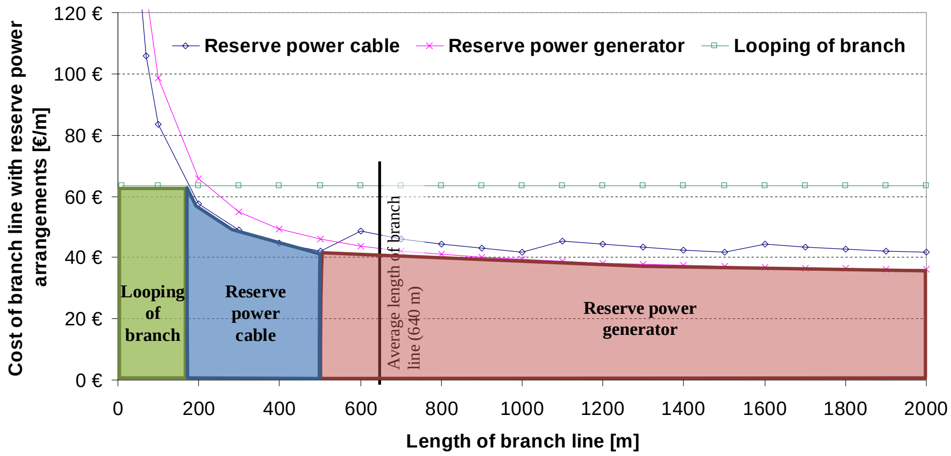

Figure 6.3. Cost comparison of the reserve power strategies as a function of branch line length (Publication VII).

6.3 Summary of reserve power planning

It is advisable to involve reserve power planning in distribution network planning. A supply outage in a radially supplied network without back-up connections causes a long-lasting interruption, which is a typical situation in Finnish distribution networks. Especially in underground cable networks, the issue cannot be neglected, because the fault repair takes time, and the supply security requirements limit the allowed interruption duration to 6 or 36 hours. The adopted reserve power strategy has an impact on the equipment installed on the distribution system. If the whole underground system is looped so that each distribution substation can be supplied through a back-up connection, other reserve power solutions are not required. In the case of reserve power cables, the system has to include connection points so that reserve cables can be connected to bypass the faulted lines. Further, it is necessary to be able to disconnect the faulted line sections from the healthy network. In the case of reserve power generators, the substation has to be equipped with a terminal to connect the generator. Again, there has to be an opportunity to disconnect the faulted lines from the network.

A benefit of reserve power solutions (reserve power cables and generators) is that the system does not require several reserve power sources. Faults in the cable network are of relatively rare occurrence, and thus, the reserve power supply in an underground cable network with hundreds of kilometres of lines can be guaranteed with only a couple of generators or cables. Considering the profitability of the strategies, looping of the lines provides the most benefits when the branches on the network are short on average. In a network with branch lines of medium length (~200–500 m) instead, reserve power cables are a beneficial strategy. With the longest branch lines, the use of reserve power generators yields the best result.

7 Conclusions

Adequate electric power distribution reliability is one of the key objectives of the distribution network operators. The importance of distribution reliability is emphasised in Finland as the authorities have set a limit on the allowed duration of interruptions in rural areas to 36 hours, and in urban and city areas to six hours. These limits are to be reached gradually during a transition period by the end of 2028. The new limits are a response to the long-lasting interruptions (even weeks) caused by several major storms over the past few years. The target to meet these limits poses a significant challenge to many DSOs. The main reasons are the tight schedule, and in some cases, the need to renovate the entire distribution network within a time that is considerably shorter than what is normally required for large-scale renovation of distribution networks. A further challenge in the process is the ageing network asset, which forces the DSOs to focus the reliability investments also on areas where the best benefits are not reached from the perspective of network reliability or major disturbance resiliency.

The key contribution of this doctoral thesis is a method for distribution network analysis that produces knowledge of the network development process for strategic decision-making. The thesis introduces methodology to develop distribution networks not forgetting asset management. The keystone of the network development process is a method to analyse the improvement of electric power distribution reliability. As a result of the analysis method, a network renovation concept is proposed that can be applied to prepare an investment program for the purposes of strategic planning. The main contributions of the thesis are:

- Network renovation concept considering the applied network techniques (in particular underground cabling) and implementation schedule taking into account the supply security target. The renovation concept covers several issues such as: what are the targets, when is the renovation started, and how is it implemented.
- Method to analyse benefits of network automation devices to find the best placement option for the device
- Methodology to analyse the effects of the economic regulation on distribution network renovation that gives information of the profitability of the network strategies
- Stochastic method to assess statistical supply security that provides information of the performance of the network in the most challenging network sections
- Methodology for reserve power planning with an opportunity to evaluate the feasibility of parallel reserve power strategies such as a reserve power generator, a reserve power cable and looping of terminating branch lines

The methodology has been tested with actual Finnish rural area distribution networks, and it provides information that facilitates the distribution companies to develop the distribution networks to meet the reliability requirements in an economically feasible manner. Although the case examples are from the Finnish electricity distribution sector only, the methodology developed in the thesis is generic and can be applied to distribution system development under various circumstances. Especially, the methodology developed for the network development process (e.g. network renovation concept, feasibility analysis of network automation, supply security analysis) can be applied to any operating environment. Although the regulatory model in the analyses is country specific (Finland), the methodology can also be applied under other regulatory regimes and operating conditions by adjusting the parameters and boundary conditions accordingly. Finally, the methodology has been applied to practice in several cases to demonstrate its validity.

Distributed generation and smart grids were not in the main focus of the thesis. However, their weight will obviously grow in network planning in the future, which also raises a need to reconsider and update the proposed methodologies or to search for new approaches. In addition, the significance of the statistical analysis of supply security will increase in the future, which may give signals to continue the development of the stochastic network reliability analysis.

References

Ajodhia, V. and Hakvoort, R. 2005. “Economic regulation of quality in electricity distribution network.” *Utilities Policy, Special Issue on Utility Service Quality*, September 2005, Vol. 13, No. 3, pp. 211–221.

Alvehag, K. and Söder, L. 2010. “Financial risk assessment for distribution system operators regulated by quality regulation.” In *Proceedings of the PMAPS 2010, 11th International Conference on Probabilistic Methods Applied to Power Systems, IEEE*, pp. 475–480.

Balijepalli, N., Venkata, S.S. and Christie R.D. 2004. “Modeling and analysis of distribution reliability indices.” *IEEE Transactions on Power Delivery*, Vol. 19, No. 4, pp. 1950–1955.

Bertling, L. 2002, *Reliability Centered Maintenance for Electric Power Distribution Systems*. Doctoral Thesis, Department of Electric Power Engineering, KTH, Stockholm.

Bieda, B. 2012. *Stochastic Analysis in Production Process and Ecology Under Uncertainty*. Berlin, Heidelberg: Springer.

Billinton, R. and Allan, R.N. 1984. *Reliability Evaluation of Power Systems*. London, U.K: Pitman Publishing Inc.

Billinton, R. and Jonnavithula, S. 1996. “Optimal switching device placement in radial distribution systems.” *IEEE Transactions on Power Delivery*, Vol. 11, No. 3, pp. 1646–1651.

Billinton, R. and Wang, P. 1999. “Teaching distribution system reliability evaluation using Monte Carlo simulation.” *IEEE Transactions on Power Systems*, Vol. 14, No. 2, pp. 397–403.

Brown, R.E., Engel, M.V. and Spare, J.H. 2005. “Making sense of worst-performing feeders.” *IEEE Transactions on Power Systems*, Vol. 20, No. 2, pp. 1173–1178.

Brown, R.E. and Humphrey, B.G. 2005. “Asset management for transmission and distribution.” *IEEE Power and Energy Magazine*, Vol. 3 No. 3, pp. 39–45.

Brown, R.E. 2009. *Electric Power Distribution Reliability*, 2nd Edition. Boca Raton, FL: CRC Press, Taylor & Francis Group.

Brown, R.E. 2012. “Changing infrastructure requirements for major weather events.” In *Proceedings of Power and Energy Society General Meeting 2012, IEEE*.

Campbell, R.J. 2012. *Weather-Related Power Outages and Electric System Resiliency. CRS Report for Congress*, Washington D.C., USA: UNT Digital Library. http://digital.library.unt.edu/ark:/67531/metadc122249/. accessed 23 May 2013.

Caperton, R.W. and James, A. 2012. "How to Keep the Lights On: More Reliable Electricity Will Require Smart Investments and Clean Energy Solutions." http://www. americanprogress.org, accessed 10 May 2013.

Energy Market Authority of Finland (EMA). 2011. *Sähkön jakeluverkkotoiminnan ja suunrjännitteisen jakeluverkkotoiminnan hinnoittelun kohtuullisuuden valvontamenetelmien suuntaviivat vuosille 2012–2015* [Guidelines for assessing reasonableness in pricing of electricity distribution network and high voltage distribution network operations for 2012–2015], (in Finnish), http://www.energiamarkkinavirasto.fi, accessed 14 December 2012.

Energy Market Authority of Finland (EMA). 2013. *Sähkönjakeluverkon komponenttien yksikköhinnat vuodelle 2013* [Unit price list of network components for 2013], (in Finnish), http://www.energiamarkkinavirasto.fi, accessed 1 May 2013.

Entriken, R. and Lordan, R. 2012. "Impacts of extreme events on transmission and distribution systems." In *Proceedings of the Power and Energy Society General Meeting, IEEE, 2012*, pp. 1–10.

Fang, X., Misra, S., Xue, G. and Yang, D. 2012. "Smart Grid — The New and Improved Power Grid: A Survey". *IEEE Communications Surveys & Tutorials*, Vol. 14, No. 4, pp. 944–980, Fourth Quarter 2012.

Finnish Energy Industries. 2010. *Sähkön toimitusvarmuus 2030, Suositus 2010* [Recommendation of supply security in 2030], (in Finnish), http://energia.fi/julkaisut/sahkon-toimitusvarmuus-2030-suositus-2010, accessed 10 May 2013.

Finnish Energy Industries. 2012. *Keskeytystilasto 2010* [Outage statistics 2010], (in Finnish), Finnish Energy Industries, Helsinki. Version 2011-05-27.

Finnish Energy Industries. 2013. *Electricity comsumption and network losses*. http://energia.fi/tilastot-ja-julkaisut/sahkotilastot/sahkonkulutus/sahkon-kaytto-ja-verkostohaviot, accessed 10 May 2013.

Finnish Electricity Market Act 386/1995.

Finnish Electricity Market Act 588/2013.

Ghiani, E., Pilo, F., Celli, G. and Mocci, S. 2008. "Renewal planning of aged distribution networks." In *Proceedings of the PMAPS 2008, 10th International Conference on Probabilistic Methods Applied to Power Systems*. Rincon, Puerto Rico.

Gungor, V.C., Sahin, D., Kocak, T., Ergut, S., Buccella, C., Cecati, C. and Hancke, G.P. 2011. "Smart Grid Technologies: Communication Technologies and Standards." *IEEE Transactions on Industrial Informatics*, Vol. 7, No. 4, pp. 529–539.

Haakana, J., Kaipia, T., Lassila, J. and Partanen, J. 2012. "On considering topology changes in network renovation." In *Proceedings of the NORDAC 2012, Tenth Nordic Conference on Electricity Distribution System Management and Development*, pp. 449–464.

He, Y., Nilsson, A. and Carlsson, F. 2010. "Mobile power equipment: Its impact on power supply reliability." In *Proceedings of the ISGT Europe 2010, Innovative Smart Grid Technologies Conference Europe, IEEE PES*.

Honkapuro, S. 2008. *Performance benchmarking and incentive regulation-considerations of directing signals for electricity distribution companies*. Doctoral Thesis, Lappeenranta University of Technology, Acta Universitatis Lappeenrantaensis 309, Lappeenranta.

IEEE. 2004. 1366-2003. *IEEE Guide for Electric Power Distribution Reliability Indices*. New York: The Institute of Electrical and Electronics Engineering.

Jamasb, T. and Pollitt, M. 2001. "Benchmarking and regulation: international electricity experience." *Utilities Policy*, September 2001, Vol. 9, No. 3, pp. 107–130.

Jamasb, T. and Pollitt, M. 2007. "Incentive regulation of electricity distribution networks: lessons of experience from Britain." *Energy Policy*, 2007, Vol. 35, No. 12, pp. 6163–6187.

Jongepier, A.G. 2007. "Ageing networks: consume, prolong or replace." *Electricity Briefing Paper*, Leonardo-Energy.

Kjolle, G., Samdal, K. and Brekke, K. 2009. "Incorporating short interruptions and time dependency of interruption costs in continuity of supply regulation." In *Proceedings of the CIRED 2009, 20th International Conference and Exhibition on Electricity Distribution*.

Korpijärvi, J. 2012. *Aging based maintenance and reinvestment scheduling of electric distribution network*. Doctoral Thesis, Lappeenranta University of Technology, Acta Universitatis Lappeenrantaensis 481, Lappeenranta.

Lassila, J., Honkapuro, S., Viljainen, S., Tahvanainen, K., Partanen, J., Kivikko, K., Antila, S., Mäkinen, A. and Järventausta, P. 2005. “Power quality factors in efficiency benchmarking.” In *Proceedings of the CIRED 2005, 18th International Conference and Exhibition on Electricity Distribution.*

Lassila, J. 2009. *Strategic Development of Electricity Distribution Networks – Concept and Methods*. Doctoral Thesis, Lappeenranta University of Technology, Acta Universitatis Lappeenrantaensis 371, Lappeenranta.

Lassila, J., Kaipia, T., Haakana, J. and Partanen, J. 2010. “Customer-Based Reliability Monitoring Criteria for Finnish Distribution Companies.” In *Proceedings of the PQ 2010, Electric Power Quality and Supply Reliability Conference.*

Lassila, J., Kaipia, T., Haakana, J. and Partanen, J. 2013. “Emerging reliability requirements for distribution systems in extreme weather conditions.” In *Proceedings of the CIRED 2013, 22th International Conference and Exhibition on Electricity Distribution.*

Leite da Silva, A.M., Cassula, A.M., Resende, L.C., Almeida, R.M., Yamasaki, M.T. and Paula, G.M.F. 2004. “Reliability evaluation of distribution systems considering automatic reclosers.” In *Proceedings of the International Conference on Probabilistic Methods Applied to Power Systems, PMAPS 2004*, pp.100–105.

Li, Z. and Guo, J. 2006. “Wisdom about age [aging electricity infrastructure].” *IEEE Power and Energy Magazine*, Vol. 4 No. 3, pp. 44–51.

Mills, E. 2012. “Electric Grid Disruptions and Extreme Weather.” http://evanmills.lbl.gov/presentations/Mills-Grid-Disruptions-NCDC-3May2012.pdf, accessed 7 May 2013.

Partanen, J., Lassila, J., Kaipia, T., Matikainen, M., Järventausta, P., Verho, P., Mäkinen, A., Kivikko, K., Pylvänäinen, J. and Nurmi, V-P. 2006. *Sähkönjakeluverkkoon soveltuvat toimitusvarmuuskriteerit ja niiden raja-arvot sekä sähkönjakelun toimitusvarmuudelle asetettavien toiminnallisten tavoitteiden kustannusvaikutukset* [Criteria and limit on reliability and the cost effects of the operational targets for reliability in electricity distribution], (in Finnish). Research report, Lappeenranta University of Technology and Tampere University of Technology.

Partanen, J., Honkapuro, S., Lassila, J., Kaipia, T., Verho, P., Järventausta, P., Strandén, J. and Mäkinen, A. 2010. *Sähkönjakelun toimitusvarmuuden kriteeristö ja tavoitetasot* [Reliability criteria and target levels of electricity distribution], (in Finnish). Research report, Lappeenranta University of Technology and Tampere University of Technology.

Partanen, J., Honkapuro, S. and Tuunanen, J. 2012a. *Tariff scheme options for distribution system operators*. Research report, Lappeenranta University of Technology.

Partanen, J., Lassila, J., Kaipia, T. and Haakana, J. 2012b. *Sähkönjakelun toimitusvarmuuden parantamiseen sekä sähkökatkojen vaikutusten lieventämiseen tähtäävien toimenpiteiden vaikutusten arviointi* [Assessment of measures aiming at improving the security of electricity supply in distribution networks and relieving the adverse effects of supply interruptions], (in Finnish). Research report, Lappeenranta University of Technology.

Pylvänäinen, J., Järvinen, J. and Verho, P. 2004. "Advanced reliability analysis for distribution network." In *Proceeding of DRPT 2004, IEEE International Conference on Electric Utility Deregulation, Restructuring and Power Technologies*. Vol. 2, pp. 457–462

Pylvänäinen, J., Lehtinen, H., Kohtala, J. and Verho. 2009. "Reliability-based network analysis in optimal asset management." In *Proceedings of the CIRED 2009, 20th International Conference and Exhibition on Electricity Distribution*.

Setréus, J., Wallnerström, C.J. and Bertling. L. 2007. "A comparative study of regulation policies for interruption of supply of electrical distribution systems in Sweden and UK." In *Proceedings of the CIRED 2007, 19th International Conference and Exhibition on Electricity Distribution*.

Silvast, A., Heine, P., Lehtonen, M., Kivikko, K., Mäkinen, A. and Järventausta, P. 2005. *Sähkönjakelun keskeytyksestä aiheutuva haitta* [Costs of electricity supply outages], (in Finnish, with an English summary). Research Report, Helsinki University of Technology.

Swedish Electricity Act 1997:857.

Wallnerström, C.J. and Bertling, L. 2009. "Risk management applied to electrical distribution systems." In *Proceedings of the CIRED 2009, 20th International Conference and Exhibition on Electricity Distribution*.

Wijnia, Y.C., Korn, M.S., de Jager, S.Y. and Herder, P. M. 2006. "Long term optimization of asset replacement in energy infrastructures." In *Proceedings of the SMC '06, IEEE International Conference on Systems, Man and Cybernetics*, Taipei Taiwan, Vol. 3, pp. 2615–2621.

Willis, H.L., Welch, G.V. and Schrieber, R.R. 2001. *Aging Power Delivery Infrastructures.* New York, USA: Marcel Dekker, Inc.

ACTA UNIVERSITATIS LAPPEENRANTAENSIS

506. NISKANEN, ANTTI. Landfill gas management as engineered landfills – Estimation and mitigation of environmental aspects. 2012. Diss.

507. QIU, FENG. Surface transformation hardening of carbon steel with high power fiber laser. 2012. Diss.

508. SMIRNOV, ALEXANDER. AMB system for high-speed motors using automatic commissioning. 2012. Diss.

509. ESKELINEN, HARRI, ed. Advanced approaches to analytical and systematic DFMA analysis. 2013.

510. RYYNÄNEN, HARRI. From network pictures to network insight in solution business – the role of internal communication. 2013. Diss.

511. JÄRVI, KATI. Ecosystem architecture design: endogenous and exogenous structural properties. 2013. Diss.

512. PIILI, HEIDI. Characterisation of laser beam and paper material interaction. 2013. Diss.

513. MONTO, SARI. Towards inter-organizational working capital management. 2013. Diss.

514. PIRINEN, MARKKU. The effects of welding heat input usability of high strength steels in welded structures. 2013. Diss.

515. SARKKINEN, MINNA. Strategic innovation management based on three dimensions diagnosing innovation development needs in a peripheral region. 2013. Diss.

516. MAGLYAS, ANDREY. Overcoming the complexity of software product management. 2013. Diss.

517. MOISIO, SAMI. A soft contact collision method for real-time simulation of triangularized geometries in multibody dynamics. 2013. Diss.

518. IMMONEN, PAULA. Energy efficiency of a diesel-electric mobile working machine. 2013. Diss.

519. ELORANTA, LEENA. Innovation in a non-formal adult education organisation – multi-case study in four education centres. 2013. Diss.

520. ZAKHARCHUK, IVAN. Manifestation of the pairing symmetry in the vortex core structure in iron-based superconductors. 2013. Diss.

521. KÄÄRIÄINEN, MARJA-LEENA. Atomic layer deposited titanium and zinc oxides; structure and doping effects on their photoactivity, photocatalytic activity and bioactivity. 2013. Diss.

522. KURONEN, JUHANI. Jatkuvan äänitehojakautuman algoritmi pitkien käytävien äänikenttien mallintamiseen. 2013. Diss.

523. HÄMÄLÄINEN, HENRY. Identification of some additional loss components in high-power low-voltage permanent magnet generators. 2013. Diss.

524. SÄRKKÄ, HEIKKI. Electro-oxidation treatment of pulp and paper mill circulating waters and wastewaters. 2013. Diss.

525. HEIKKINEN, JANI. Virtual technology and haptic interface solutions for design and control of mobile working machines. 2013. Diss.

526. SOININEN, JUHA. Entrepreneurial orientation in small and medium-sized enterprises during economic crisis. 2013. Diss.

527. JÄPPINEN, EERO. The effects of location, feedstock availability, and supply-chain logistics on the greenhouse gas emissions of forest-biomass energy utilization in Finland. 2013. Diss.

528. SÖDERHOLM, KRISTIINA. Licensing model development for small modular reactors (SMRs) – focusing on the Finnish regulatory framework. 2013. Diss.

529. LAISI, MILLA. Deregulation's impact on the railway freight transport sector's future in the Baltic Sea region. 2013. Diss.

530. VORONIN, SERGEY. Price spike forecasting in a competitive day-ahead energy market. 2013. Diss.

531. PONOMAREV, PAVEL. Tooth-coil permanent magnet synchronous machine design for special applications. 2013. Diss.

532. HIETANEN, TOMI. Magnesium hydroxide-based peroxide bleaching of high-brightness mechanical pulps. 2013. Diss.

533. TYKKÄLÄ, TOMMI M. Real-time image-based RGB-D camera motion tracking and environment mapping. 2013. Diss.

534. PEKKOLA, SANNA. Performance measurement and management in a collaborative network. 2013. Diss.

535. PANOREL, IRIS CHERRY. Pulsed corona discharge as an advanced oxidation process for the degradation of organic compounds in water. 2013. Diss.

536. TORKKELI, LASSE. The influence of network competence of internationalization of SMEs. 2013. Diss.

537. MOLANDER, SOLE. Productivity and services – safety telephone services for the elderly. 2013. Diss.

538. SITARZ, ROBERT. Identification of research trends in the field of separation processes. Application of epidemiological model, citation analysis, text mining, and technical analysis of the financial markets. 2013. Diss.

539. KATTEDEN, KAMIEV. Design and testing of an armature-reaction-compensated permanent magnet synchronous generator for island operation. 2013. Diss.

540. HÄMÄLÄINEN, HARRI. Integration of learning supportive applications to development of e-portfolio construction process. 2013. Diss.

541. RATCHANANUSORN, WARIN. Development of a process for the direct synthesis of hydrogen peroxide in a novel microstructured reactor. 2013. Diss.

542. PERFILEV, DANIIL. Methodology for wind turbine blade geometry optimization. 2013. Diss.

543. STROKINA, NATALIYA. Machine vision methods for process measurements in pulping. 2013. Diss.

544. MARTTONEN, SALLA. Modelling flexible asset management in industrial maintenance companies and networks. 2013. Diss.

545. HAKKARAINEN, JANNE. On state and parameter estimation in chaotic systems. 2013. Diss.

546. HYYPIÄ, MIRVA. Roles of leadership in complex environments
Enhancing knowledge flows in organisational constellations through practice-based innovation processes. 2013. Diss.