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Assessment of Electricity Distribution Reliability - Interruption Statistics, Reliability Worth, and Applications in Network Planning and Distribution Business Regulation

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Assessment of Electricity Distribution Reliability - Interruption Statistics, Reliability Worth, and Applications in Network Planning and Distribution Business Regulation

Thesis for the degree of Doctor of Science in Technology to be presented with due permission for public examination and criticism in Tietotalo Building, Auditorium TB109, at Tampere University of Technology, on the 26th of November 2010, at 12 noon.

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ABSTRACT

In modern information society requirements and expectations associated with the continuity of power supply have become increasingly important. Electricity is not a luxury article anymore like it was a few decades ago, but it has become a necessity and a part of our everyday life. Even short interruptions can be harmful when the amount of computers, programmable logics etc. in industry and as well in households have increased rapidly. Large blackouts around the world have also aroused the customers' interest in electricity distribution and the reliability of distribution networks. The reliability of supply is again of great interest.

This thesis introduces new methods for reporting interruption data. This includes the development of interruption statistics and the methods of gathering interruption data while taking into account the needs of different interest groups, i.e. the DSO, its customers and the regulator.

Reliability worth and interruption costs are becoming widely used in the regulation of distribution companies. The main objective of the regulation is to increase the cost-efficiency in the electricity network businesses for the benefit of the customers, while still maintaining acceptable levels of supply reliability. In the distribution system operators operating environment where there is an increased demand for cost-efficiency, the sufficient level of reliability can be ensured with continuity of supply regulation, and with the use of interruption costs in regulation.

This thesis presents methods used to compose reliability worth estimates and to eliminate strategic responses from customer survey data. The regulation model used in Finland is outlined from the reliability of supply point of view. The results of the reliability worth study show that there has been a significant increase in the reliability worth estimates during the past ten years, which is also reflected to customer expectations on supply reliability.

For distribution network companies, the reliability-based network analysis can offer an excellent tool for focusing network investments in the most critical areas in the network, and thus use the assets in the best way to increase the level of reliability. Interruption statistics, in turn, produce valuable source information for reliability analysis.

Reliability-based network analysis is presented in this thesis with the help of example calculations in the cases where different reliability parameters are examined. The results show the total costs (divided into operational, investment and interruption costs) during the technical lifetime of the network. As customer expectations on reliability worth and economical significance of interruption costs increase, more reliable, but also more expensive, network development alternatives become more attractive.

PREFACE

The results of this thesis are mainly obtained in the research projects carried out during the years 2002-2006 in the Institute of Power Engineering at Tampere University of Technology (TUT). These projects have been funded and organised in cooperation with the Finnish Funding Agency for Technology and Innovations (Tekes), Energy Market Authority, Ministry of Trade and Industry, and a number of Finnish distribution network companies and representatives of the industry. Several of the projects have been carried out in association with the Laboratory of the Electricity Markets and Power Systems, Institute of Energy Technology at Lappeenranta University of Technology or Laboratory of Power Systems and High Voltage Engineering at Helsinki University of Technology.

I would like to address my gratitude to the supervisor of this thesis, Professor Pertti Järventausta, for his guidance and encouragement during this work. You have patiently guided me through this long journey. A special acknowledgement goes to Antti Mäkinen, Lic. Tech., for the valuable advice and profound analysis of my work. I also want to thank Merja Teimonen, institute secretary, for the general arrangements.

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Above all, I want to thank my wife Kaisa-Kreetta. You have encouraged me and allowed me the possibility to finalize this thesis. It wouldn't have been possible without your support and understanding.

Finally, I owe this thesis to my children, Iida 6 years and Matias 3 years. You always bring such a joy to my life. Little things in life bring us the greatest happiness.

Pori, October 2010

Kimmo Kivikko

LIST OF PUBLICATIONS

[P1] Kivikko, K., Antila, S., Mäkinen, A., Järventausta, P. Web-Based Customer Interruption Monitoring Using DMS System Database. Proceedings of the AUPEC 2003 Conference, Christchurch, New Zealand, 28th September – 1st October 2003.

[P2] Kivikko, K., Mäkinen, A., Verho, P., Järventausta, P., Lassila, J., Viljainen, S., Honkapuro, S., Partanen, J. Outage Cost Modelling for Reliability Based Network Planning and Regulation of Distribution Companies. Proceedings of the 8th International Conference on Developments in Power System Protection DPSP 2004. Amsterdam, Netherlands, April 2004.

[P3] Kivikko, K., Järventausta, P., Mäkinen, A., Eklund, T., Lehtomäki, E., Alasalmi, O., Isoviita, T., Vainiola, K. Developing of Compilation of Interruption Statistics in Finland to Meet Various New Requirements. Proceedings of the 18th International Conference on Electricity Distribution CIRED. Turin, Italy, 6 – 9 June 2005.

[P4] Kivikko, K., Antila, S., Järventausta, P., Mäkinen, A., Lassila, J., Viljainen, S., Tahvanainen, K., Partanen, J., Mogstad, O., Tapper, M. Comparison of Interruption Statistics and Their Use in Network Business Regulation in Nordic Countries. Proceedings of the 18th International Conference on Electricity Distribution CIRED. Turin, Italy, 6 – 9 June 2005.

[P5] Kivikko, K., Mäkinen, A., Järventausta, P. Modelling and Compilation of Interruption Statistics – Requirements of the Renewing Electricity Market. Proceedings of the 3rd IEE International Conference on Reliability of Transmission and Distribution Networks RTDN 2005. London, UK, February 2005.

[P6] Kivikko, K., Järventausta, P., Mäkinen, A., Silvast, A., Heine, P., Lehtonen, M. Research and analysis method comparison in Finnish reliability worth study. Proceedings of the 19th International Conference on Electricity Distribution CIRED. Vienna, Austria, 21 – 24 May 2007.

[P7] Kivikko, K., Mäkinen, A., Järventausta, P., Silvast, A., Heine, P., Lehtonen, M. Comparison of reliability worth analysis methods: data analysis and elimination methods. IET Generation, Transmission & Distribution, Volume 2, Issue 3, May 2008, p. 321-329.

[P8] Kivikko, K., Pylvänäinen, J., Järventausta, P., Mäkinen, A., Verho, P., Kaipia, T., Lassila, J., Partanen, J. Applying Reliability Worth in Distribution Network Life-Cycle Cost Evaluation and Reliability-Based Analysis. International Review on Modelling and Simulations (IREMOS), vol. 1 No. 2, pp. 334 – 342, December 2008.

ABBREVIATIONS

ASAI	Average System Availability Index
ASIDI	Average System Interruption Duration Index
ASIFI	Average System Interruption Frequency Index
BCI	Building Cost Index
CAIDI	Customer Average Interruption Duration Index
CCM	Combined Cost Model
CENS	Cost of Energy Not Supplied
CIC	Customer Interruption Cost
CCDF	Composite Customer Damage Function
CD	Interrupted demand
CDF	Customer Damage Function
COC	Customer Outage Cost
DEA	Data Envelopment Anaysis
DMS	Distribution Management System
DOI	Disutility of Interruptions
DSO	Distribution System Operator
EENS	Expected Energy Not Supplied
ENS	Energy Not Supplied
ET	Finnish Energy Industries Association
IC	Interruption Costs
IEAR	Interruption Energy Assessment Rate
MAIFI	Momentary Average Interruption Frequency Index
OPEX	Operational Costs
PAM	Preparatory Action Method
RRM	Rate-related Method
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory Control And Data Acquisition
SCDF	Sector Customer Damage Function
Sener	Finnish Electricity Association
SFA	Stochastic Frontier Analysis
SLD	Straight-line Depreciations
VOLL	Value of Lost Load
WTA	Willingness To Accept
WTP	Willingness To Pay

CONTENTS

1 INTRODUCTION

The reliability of power supply gained in new-found importance during the past several years as outages shut down power in many regions around the world. Parts of Europe, e.g. London [Na03], Sweden [El03] and Italy [UCTE04] experienced blackouts in 2003 that affected hundreds of thousands of people. The east coast of US and Canada [USCa04] suffered from similar disturbances almost at the same time, and our own Helsinki blackout [EMA03] on August 23rd, 2003 revealed the vulnerability of Finnish transmission and distribution systems. Due to extreme weather conditions, Finland has suffered from large blackouts again in July 2010 leaving thousands of customers without electricity supply for weeks. These massive blackouts indicate that electric power is a vital element of modern society. It has become a commodity of necessity, or almost civil right, and thus electricity distribution reliability is currently a topic of great interest.

In the current deregulated and regulated electricity market environment, it is becoming increasingly more important to justify capital, operating and maintenance expenditures based on benefits derived by the Distribution System Operator (DSO) and the customer. Increasing socioeconomic pressure to create safe and reliable power systems is being exerted on DSOs by authorities, customers and society in general. The goals of these interest groups are similar: reliable electricity supply with low costs. This probably is in contradiction to the DSO’s shareholders objectives. The shareholders require maximum profit on their investments. The regulator faces both of these aspects and has to balance between the two points of view. While allowing the DSO’s shareholders attractive profits to ensure necessary investments, the regulator must also be on the customers’ side and demand sufficient reliability with lower costs.

Increasingly, DSOs are being squeezed between the conflicting demands of customers who require a higher level of supply reliability with lower tariffs, the DSO's shareholders who require higher profits on the capital they have invested and the regulator whose intention is to assure adequate reliability of service with reasonable costs. Putting all this in one regulation model makes it quite difficult. Hence, the directing signals of the regulation model to the DSO’s operating environment and for example to network investments are rather complex.

Regardless of the regulation, electricity supply reliability will also be a major issue in the future. Customers’ expectations of undisturbed electricity supply are increasing. This can also be seen from the reliability worth studies: the reliability worth estimates have doubled during the past ten years. At the same time, the climate change probably makes extreme weather conditions more common, which hinders achieving the goal of reliable electricity supply with low costs. This should be considered in future network design. Due to these aspects, a cabled medium-voltage network may become a profitable alternative even in the countryside.

Customer interruption costs play an important role in present day electricity distribution operation, planning and regulation. The use of interruption costs as a part of network business regulation and in network planning leads to network solutions that assure a reasonable level of reliability in normal operation conditions. Regulation should result in the distribution companies' business models and data systems to develop so that they assure the most cost-effective operation methods.

Interruption statistics form a basis e.g. for the calculation of actual interruption costs of the network for regulation purposes, and for the evaluation of failure rates of the network components for the purpose of reliability analysis. Hence, interruption statistics include essential input data for the regulation and reliability analysis, but also customers require more information about electricity distribution reliability. Several DSOs have introduced systems on the internet that show the unsupplied areas of their distribution network in real-time. As laptop computers have become more common, customers are also capable of utilising this data. Customers are also provided with the possibility of receiving SMS messages about interruptions to their mobile phones.

1.1 Framework and contributions of the thesis

Electricity supply at reasonable cost and quality levels has become a necessity for development, economical growth and welfare. The more developed societies are, the more vulnerable they are to electricity supply interruptions. The dependence on reliable electricity supply implies that costs are associated with these interruptions. In this thesis, one of the targets is to define the reliability worth parameters for e.g. regulation purposes. This thesis also presents the development of the interruption statistics taking into account the needs of different interest groups, i.e. the DSO, its customers and the regulator.

Electricity distribution is a natural monopoly business. To prevent the companies from taking advantage of their dominant market position, they are subject to regulation. Main goal of the regulation is to secure electricity supply at acceptable levels of quality and at reasonable tariffs. Regulation should provide the companies with incentives to be cost-efficient in a way that benefits the society. This thesis outlines the principles of incorporating reliability of supply in distribution business regulation in Finland.

Improvements in the continuity of supply require investments in the network. Large assets are committed to the distribution networks and therefore the most cost-efficient alternatives need to be recognised. The objective of this thesis is also to evaluate the use of reliability worth and interruption costs in the reliability-based network analysis and planning. The reliability worth is assessed from the customer, regulator and DSO point of view, neither technical constraints (e.g. voltage drop, thermal limitations) nor the electricity retailer point of view are especially addressed in the thesis.

DSO's costs are an increasing function of reliability, as higher capital and maintenance costs are required to increase the reliability of supply. The customer supply interruption costs decrease as the reliability increases, because higher reliability reduces the frequency and duration of interruptions. The total societal cost, which is ultimately borne by customers, is the sum of the two curves. The shape of these two curves ensures that the total cost curve has a minimum and reliability an optimum value. In Figure 1.1, curve *a* represents the costs incurred by customers as a result of supply interruptions, curve *b* represents the costs incurred by a network company in providing the availability of supply and curve *c* represents the total costs. [BiAl84], [BiAl96], [Bo00]

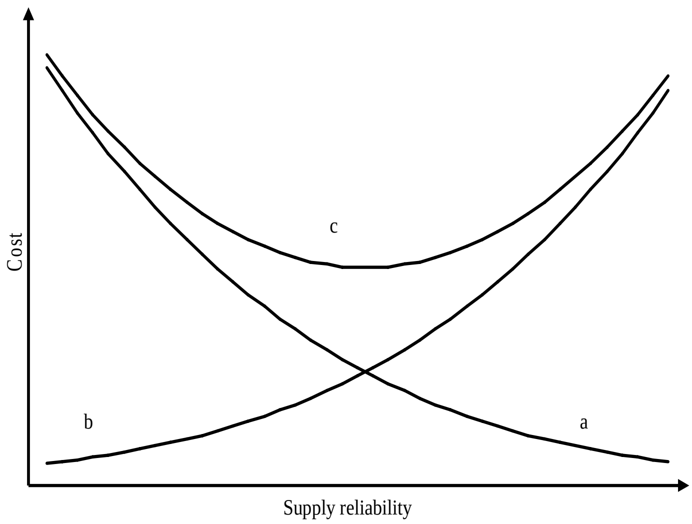


Figure 1.1: Balance between DSO and customer costs.

Succeeding in the minimising of total societal cots presented in Figure 1.1 requires ensuring the correct incentives for electricity distribution business. From the viewpoint of this thesis, the electricity distribution business can be directed into the desired direction by affecting the regulation model, network planning conditions and the customers’ awareness about supply reliability. The main target of this thesis is answering the question: can interruption statistics be compiled, and electricity distribution reliability worth modelled, so that the methods direct the electricity distribution business socio-economically most cost-efficiently? This thesis discusses the question from the customer, the regulator and the DSO point of view.

This thesis concentrates on distribution network reliability evaluation and expected customer interruption cost estimation. Reliability-based network analysis is presented, and the results are discussed. The use of interruption costs in network business regulation is analysed in the context of the Finnish regulation model. The customer viewpoint is approached by the development of tools for increasing the customers' awareness about electricity distribution interruptions. Figure 1.2 illustrates the context of this thesis.

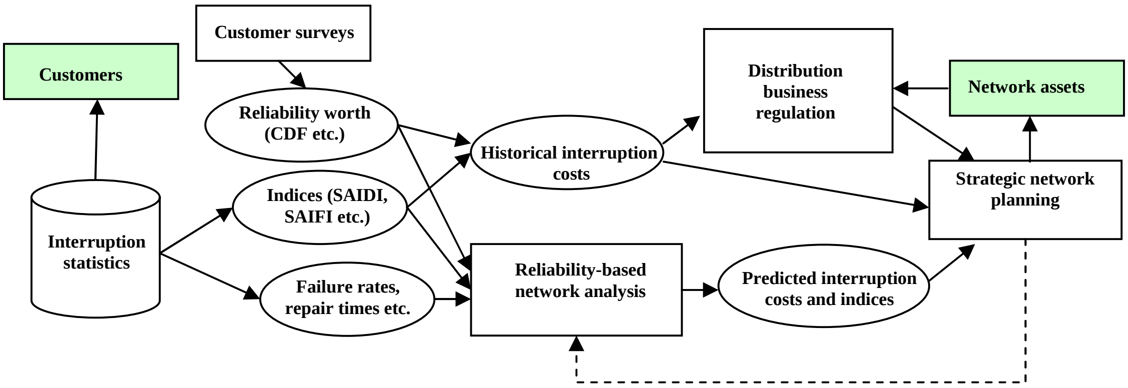


Figure 1.2: Framework of electricity distribution reliability assessment.

Achieving the main target requires development of new methods, tools and technology, and assessment of the effects of reliability considerations on network planning and distribution business regulation. The sub-targets supporting the achieving of the main target are:

1. Development of modelling and compilation of the interruption statistics taking into account the needs of different interest groups, i.e. the DSO, its customers and the regulator.
2. Development of tools for gathering data for interruption statistics and for presenting the interruption data to the customers.
3. Processing of reliability worth estimates and the modelling of interruption costs.
4. Assessment of the use of interruption costs in distribution business regulation.
5. Utilisation of interruption costs in the strategic network planning.

The research problem of the thesis is examined in a Finnish electricity distribution business environment with an approach akin to case-study. The research methods utilised are a questionnaire and analysis of the result, simulation, and development of information technology solutions and methods to demonstrate operational processes. Despite being implemented in Finnish operational environment, the main target and approach of the thesis is generic and the methods can be adapted as such regardless of the country, except for the issues associated with the regulation model which is Finland-specific.

1.2 Summary of the attached publications

The research work behind this thesis has evolved from development of interruption statistics and determining the customer valuation of electricity distribution interruptions. Essentially, the application of these in the distribution business regulation and network analysis is addressed. The publications concerning these subjects are included in this thesis. The publications have not been used elsewhere as parts of a doctoral thesis.

The author of this thesis is the corresponding author of all eight original publications. The author has contributed in the publications in the form of literature surveys, calculations, modelling, analysis, software implementation and reporting together with the co-authors as described in more detail in the following list.

The thesis includes eight international publications:

- Publication [P1] presents a general overview of the distribution management system interruption database and introduces a web-based application for presenting the interruption data to customers and supports sub-targets 1 and 2 of this thesis. In [P1] the author of this thesis was responsible for the development of the web application for presenting customers the interruption data.

- Publication [P2] defines the reliability worth parameters and interruption cost model used for distribution business regulation. It also presents some reliability analysis results (e.g. the importance of short interruptions in the calculation of total interruption costs) and recognises the need for the updating of the reliability worth values. In [P2] the author participated in the definition of the interruption cost model and parameters, and performed the example calculations. [P2] supports sub-targets 3 and 4 of this thesis.

- Publication [P3] focuses on the development work and guidelines of the national interruption statistics that will contribute reliability-based network design and distribution business regulation. It also includes analysis of different weighting methods in the calculation of interruption indices. The author had principal responsibility of the above analysis work. The guidelines were defined in co-operation within the working group. This publication supports sub-target 1 of this thesis.

- Publication [P4] contains an international point of view. It compares the interruption statistics and their use e.g. for regulation purposes in the Nordic countries. In [P4] the author was responsible for the publication as a whole. The texts concerning other countries were written by the co-authors from Norway and Sweden. [P4] supports sub-targets 1 and 4 of this thesis.

- Publication [P5] proposes a simplified and comprehensive model for the collection of interruption data in addition to the general framework. It introduces a software application that is suitable for the compilation of interruption statistics in small distribution network companies. In [P5] the author was responsible for the development of the models and the software applications for compiling interruption statistics based on the specifications presented in [P3]. [P5] supports sub-targets 1 and 2 of this thesis.

- Publication [P6] presents the analysis methods and the results of the latest Finnish reliability worth study, and supports sub-target 3 of this thesis. In [P6] the role of the author was connected to both the analysis methods and the calculation of the results. The study as a whole was conducted by the research group.

- Publication [P7] focuses on data analysis and a thorough comparison of the strategic response elimination methods used in the reliability worth study. In [P7] the author was particularly responsible for the statistical analysis of the correlation of the results and calculations. Development of the analysis and the elimination methods was made within the research group. This publication supports sub-target 3 of this thesis.

- Publication [P8] presents the use of both reliability worth and indices in network analysis and design. It presents the results of the reliability analysis where different measures are assessed. In [P8] the author was responsible for the definition of the reliability worth parameters and the auto-reclosing accumulation study, and participated in the reliability evaluation studies and calculations. The analysis method development and software parameterisation as a whole were made in co-operation with the research group. [P8] supports sub-target 5 of this thesis.

1.3 Structure of the thesis

Chapter 2 presents the basic aspects of electricity distribution reliability. It shortly introduces the origin of interruptions, basics of the Finnish interruption statistics and the most commonly used reliability indices. Chapter 3 discusses aspects concerning reliability worth. It presents the commonly used reliability worth study methods, reliability worth study results around the world and methods to model interruption costs in e.g. reliability-based network analysis. Chapter 4 concentrates on reliability-based network analysis. It presents the simulation models commonly used in reliability-based network analysis and the reliability evaluation software that was used in the calculation of the results presented in this thesis. Chapter 5 presents the regulation model currently in use in Finland. The regulation model is presented because at the time the research work for this thesis was carried out, the regulation model was somewhat different. On the other hand, the work and results presented in this thesis have partly influenced the regulation model’s development into its present form. In the ends of Chapters 2-5, there is a summarasing section which shortly discusses the publications associated with the chapter.

Chapter 6 draws a summary and concludes the content of this thesis.

1.4 Definitions

Interruptions

According to SFS-EN 50160 [SFS00] supply interruption is a condition in which the voltage at the supply terminals is lower than 1 % of the declared voltage U_c.

There is a need to make a difference between the terms interruption and outage. Interruption refers to the loss of service to one or more customers. Interruption is a result of one or more component outages, depending on system configuration. Outage refers to the state of a component when it is not available to perform its intended function due to some event directly associated with that component. An outage may or may not cause an interruption of service to customers, depending on system configuration. [IEEE01]

Momentary interruption refers to the operation of an interrupting device that results in a voltage zero [IEEE01]. This definition also includes all reclosing operations that do not normally exceed the duration of 3 min. Sustained interruption refers to any interruption not classified as a momentary interruption, i.e. any interruption longer than 3 min.

Scheduled interruption refers to a loss of electric power that results when a component is deliberately taken out of service at a selected time, usually for the purposes of construction, preventative maintenance, or repair. They result from scheduled outage, i.e. an outage that results when a component is deliberately taken out of service at a selected time [Bi70].

Forced interruption refers to an interruption caused by a forced outage that results from emergency conditions directly associated with a component requiring that component be taken out of service immediately [Bi70]. The key test to determine if an interruption should be classified as forced or scheduled is as follows. If it is possible to defer the interruption when such deferment is desirable, the interruption is a scheduled interruption; otherwise, the interruption is a forced interruption. Deferring an interruption may be desirable, for example, to prevent overload of facilities or interruption of service to customers. [IEEE01]

In this thesis, scheduled interruptions are also referred to as planned interruptions, and forced interruptions are referred to as unexpected interruptions. SFS-EN 50160 defines these as prearranged and accidental interruptions. In this thesis, momentary interruptions are also referred to as short interruptions and sustained interruptions to as long interruptions which complies with the definition of SFS-EN 50160 [SFS00].

Interruption statistics

The purpose of statistics is to convey information. Statistics present, with the help of numbers and figures, the condition and development of certain parameters in society. Interruption statistics can be defined as the collecting and presenting of specified data concerning disruptions in customer electricity supply. Interruption statistics are used e.g. for reliability evaluations, regulation and reporting purposes. The difference between interruption statistics and fault statistics is that fault statistics normally present data concerning component failures, and the impacts on the customers are not of great interest in fault statistics.

Interruption and fault statistics comprise two activities:

- Collection of field data by operations and maintenance personnel documenting the details of faults and interruptions together with the associated fault and interruption durations.
- Analysis of the data to create statistical indices and figures.

Reliability of supply

The reliability of an electricity system reflects its ability to maintain service continuity. Reliability of electricity supply is primarily concerned with the duration and frequency of supply interruptions. Thus, reliability of supply is a customer-oriented quantity that does not consider the origin of the causes of interruptions. The reliability of supply depends on the performance of generation, transmission and distribution. [BiAl92]

It should be noted that the term reliability has a very wide range of meanings and cannot be associated with a single specific definition. It is therefore necessary to recognise its extreme generality and to use it to indicate, in a general rather than specific sense, the overall ability of the system to perform its function. Therefore, the ability of a power system to provide adequate and secure supply of electrical energy at any point in time is referred to as the reliability of a system. In this definition, 'adequacy' refers to the static system conditions and the existence of sufficient facilities within the system to meet the system load demand while 'security' is associated with the dynamic response of the system to perturbations to which it is subjected [BiAl84], [KaAl96b].

Reliability worth

Reliability cost refers to the investment needed to achieve a certain level of adequacy. Reliability worth is the benefit derived by the DSO, customer and society as a result of the higher level of reliability. Reliability worth is difficult to measure directly. An indirect measurement of reliability worth can be obtained by evaluating the impacts and the monetary losses incurred by customers due to electric power supply failures [BiAl96], [Wa98]. Customer interruption costs provide a valuable surrogate for the actual worth of electric power supply reliability [WaBi89].

Electricity distribution system

Electricity distribution system is that portion of an electric system that delivers electric energy from transformation points on the transmission system to the customer [IEEE01]. In this thesis, electricity distribution system refers to a 0,4..20 kV network, i.e. the network between the main transformer at the primary substation and the customer.

The Finnish distribution system consists of a medium-voltage network that usually is operated at 20 kV voltage level, and a low-voltage network that usually is operated at 0,4 kV voltage level. Also 1 kV networks between 20 kV and 0,4 kV voltage levels have been built in recent years. In sparsely populated areas, medium-voltage networks usually consist of overhead lines, and in the cities underground cables are used. Low-voltage networks are usually implemented with aerial or underground cables. A majority (up to 80 % or over) of supply interruptions are originated in the medium-voltage network.

2 ELECTRICITY DISTRIBUTION RELIABILITY

Reliability is an essential factor when considering quality of supply. The main factors in judging reliability of supply to customers are the frequency and duration of interruptions. These factors depend on variables such as the reliability of individual items of equipment, circuit length and loading, network configuration, distribution automation, load profile and available transfer capacity. [LaHo95]

The basic function of a power system is to supply customers with electrical energy as economically as possible and with an acceptable degree of reliability and quality. Modern society, because of its pattern of social and working habits, has come to expect that the supply should be continuously available on demand. This is not possible due to random system failures which are generally not within the range of control of power system engineers. Therefore, it is evident that the economic and reliability constraints can conflict with each other. [BiAl88]

An important target in the design of a distribution network is minimising the total costs during the lifetime of the network. This can be presented in mathematical form (Equation 2.1):

$$C = \sum \left(C_i + C_l + C_m + C_o \right) \tag{2.1}$$

where

C_i = investment costs
C_l = cost of losses
C_m = operation and maintenance costs
C_o = interruption costs

Customer interruption costs are usually calculated to determine the level of investments required to achieve and maintain an adequate level of reliability of supply in power systems.

All supply interruptions, regardless of their cause, constitute a reduction in reliability. With 100 % reliability the costs incurred by customers as a result of supply interruptions would be zero. This would probably lead to unacceptably expensive network constructions from the socio-economic point of view, and it would increase the network tariffs purposelessly, because the network company incurs additional costs as the reliability is improved. Eventually these costs increase dramatically as the 100 % reliability is approached, so achieving total reliability would be economically impracticable, or even impossible. On the contrary, if reliability (or actually unreliability) was not considered as a cost component in network planning, it would lead to a decline in reliability when the profits in the network businesses are maximised. On the basis of total minimum costs to the community, the reasonable and socio-economically feasible level of reliability can be determined.

2.1 Origin of interruptions

Interruptions are divided into unexpected and planned interruptions. Distribution networks contribute significantly to the interruptions experienced by customers.

Planned interruptions are usually caused by maintenance and construction work in the network. Customers are informed about the planned interruptions beforehand and can usually make preparations to avoid the harms caused by the interruption.

Unexpected interruptions are caused by power system faults. Faults are usually the result of adverse weather, environmental reasons and faulty operation or construction. In 2008 in Finland, over 50 % of all interruptions were caused by weather dependent reasons (see Figure 2.2).

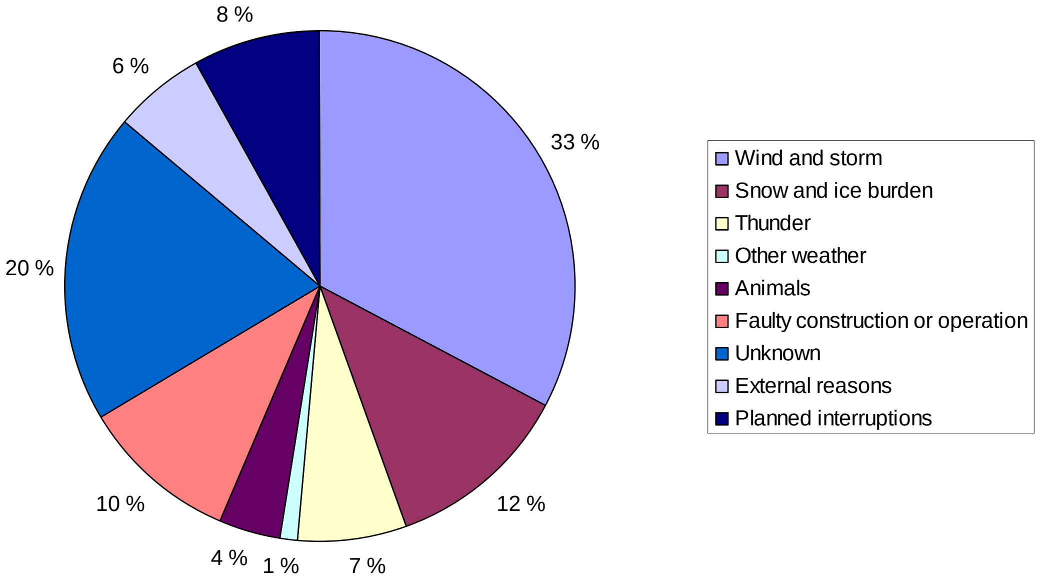


Figure 2.2: Causes of interruptions. [FEI09]

Reducing the number of long interruptions has always been one of the main goals in the planning and operation of power distribution networks. To avoid faults and to diminish their impacts, various suggestions for power system improvements are given. They include e.g. [KTM06]:

- alternative component types
  - underground cables instead of overhead lines
  - covered conductors instead of overhead lines
  - surge arresters instead of spark gaps
  - 1 kV distribution system
- strict policy for maintenance and inspection

- careful tree trimming
- arc suppression coils
- constructing lines on roadsides
- network automation
    - remotely controlled disconnectors
    - fault location
    - distributed protection (e.g. pole-mounted circuit breakers)

2.2 Interruption and fault statistics

Nowadays, interruption statistics in most Finnish distribution companies are collected by data systems, e.g. Distribution Management System (DMS). Many functions that are included in interruption statistics are carried out automatically and automatic functions can be supplemented with manual functions. The basis for interruption data, i.e. the operating times of switching devices, is produced and gathered by SCADA. This data is supplemented by entering the interruption types, causes, locations etc. and the data is stored to DMS database.

The electricity distribution sector in Finland has collected national interruption statistics over several decades to gather information e.g. for benchmarking and system reliability evaluation. An annual report containing a summary has been published by the Finnish Energy Industries association (ET) (formerly Finnish Electricity Association (Sener)). Until 2005, the publication “Interruption Statistics” had remained pretty much the same for the past 30 years and did not adequately meet the needs of the distribution network companies anymore. From 2005 on, the compilation of interruption statistics and the publication have changed quite radically. The DSO’s deliver information about each individual medium-voltage interruption event (including different durations within one interruption, i.e. interruption sectors) to the ET. The aim has been to produce more detailed data and enable better classification of interruption causes and locations. Special attention has been paid to determining which part of the network (overhead line, cable etc.) the interruption has originated from. This way the vulnerability of different networks types, and the number and duration of interruptions experienced by customers located in different conditions (densely or sparsely populated area etc.), are obtained in more detail than before. In Finland, the interruption statistics concentrate on the interruptions experienced by customers. Attention has been paid to the structure of the network, i.e. overhead line or cable network, and to the causes of the interruptions. As the reliability indices collected by the regulator were decided to be energy-weighted, in 2005 the Interruption Statistics publication also introduced new energy-weighted statistics.

The statistics show that there has been a slight decreasing trend from the 70's to mid the 90's in the development of interruption times and frequencies (see Figures 2.3 and 2.4). After the mid 90's, the trend has even been slightly increasing. In 2005, the grouping of network environment changed from countryside / densely populated area to countryside / densely populated area / city.

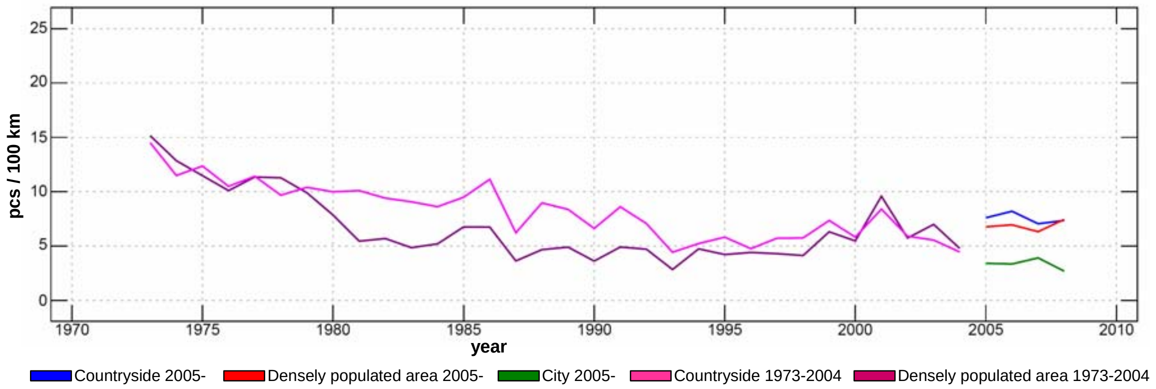


Figure 2.3: The trend of interruption frequency caused by faults in the Finnish medium-voltage network from 1973 to 2008 (reclosings are not included). [FEI09]

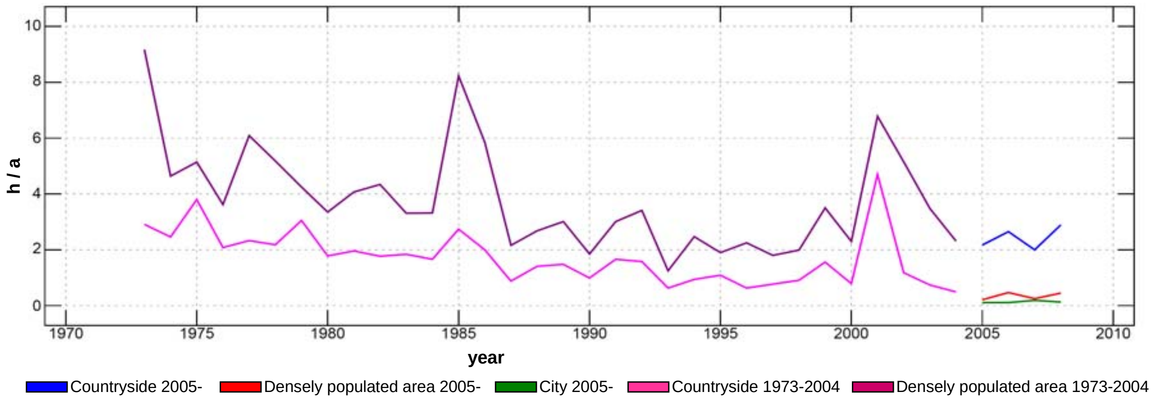


Figure 2.4: The trend of average interruption time caused by faults in the Finnish medium-voltage network from 1973 to 2008 (reclosings are not included). [FEI09]

The approach of e.g. the Nordic fault and interruption statistics [Sin04], [JeEn06] differs a little from the Finnish approach. In the Nordic statistics, the detailing level is higher, i.e. components are divided into several subcomponents, and the statistics concentrate on detailed information about the damaged devices and components.

2.3 Reliability indices

System reliability is usually measured with different reliability indices that are statistics based on interruption data collected from the system. Each reliability index represents a particular aspect of the reliability of a single feeder, a distribution system, or an entire DSO's network. The purpose of these indices is to provide useful information about the system performance and to give historical data for the evaluation of reliability trends. The most commonly used indices are SAIFI (System Average Interruption Frequency Index), SAIDI (System Average Interruption Duration Index) and CAIDI (Customer Average Interruption Duration Index). They can be calculated with Equations 2.2-2.4:

$$SAIFI = \frac{\sum_j n_j}{N_S} \quad (2.2)$$

where

n_j	=	number of interruptions experienced by customer j
N_S	=	total number of customers

$$SAIDI = \frac{\sum_i \sum_j t_{ij}}{N_S} \quad (2.3)$$

where

t_{ij}	=	duration of interruption i at customer
i	=	number of interruptions during the specified reporting period
j	=	number of customers experiencing the interruption
N_S	=	total number of customers

$$CAIDI = \frac{\sum_i \sum_j t_{ij}}{\sum_j n_j} = \frac{SAIDI}{SAIFI} \quad (2.4)$$

where

n_j	=	number of interruptions experienced by customer j during the specified reporting period

[IEEE01] also defines several other reliability indices. These are, for example, ASIFI (average system interruption frequency index) and ASIDI (average system interruption duration index) that are based on the load rather than the number of customers like SAIFI and SAIDI, and ASAI (average system availability index) and MAIFI (momentary average interruption frequency index). Especially in Finland, T-SAIFI and T-SAIDI indices are also used. They differ from SAIDI and SAIFI in that the weighting is made with the number of secondary substations and low-voltage network interruptions are not included. Weighting with power is also used in some European countries [CEER03].

In Finland, it was seen by the regulator that the T-SAIFI and T-SAIDI indices did not treat the DSOs equally and they did not offer sufficient incentives from the investment and operations points of view. Because of that, the regulator decided to start collecting six new energy-weighted reliability indices (e.g. [P5]):

1. Customers' average annual interruption time caused by unexpected interruptions
2. Customers' average annual number of interruption caused by unexpected interruptions
3. Customers' average annual interruption time caused by planned interruptions

4. Customers' average annual number of interruption caused by planned interruptions
5. Customers' average annual number of interruption caused by delayed auto-reclosings
6. Customers' average annual number of interruption caused by high-speed auto-reclosings

In addition to these, the regulator decided to collect two indices that are not weighted with energy:

7. Number of unexpected interruptions in low-voltage network
8. Number of unexpected interruptions in medium-voltage network

The first six indices can be calculated with Equations 2.5 and 2.6:

$$t = \frac{1}{W_{tot}} * \sum_{l=1}^{m} \left\{ W_{mp}(l) * \left(\sum_{i=1}^{n} ka_{mp}(i,l) \right) \right\} \tag{2.5}$$

$$k = \frac{1}{W_{tot}} * \left\{ \sum_{l=1}^{m} \left(W_{mp}(l) * k(l) \right) \right\} \tag{2.6}$$

where

t	=	average annual interruption time
k	=	average annual number of interruptions
$ka_{mp}(i,l)$	=	interruption duration caused by interruption i to distribution substation l
$k(l)$	=	number of interruptions at distribution substation l
n	=	number of interruptions
m	=	number of distribution substations
$W_{mp}(l)$	=	annual energy of distribution substation l
W_{tot}	=	total annual energy of the distribution network

2.4 Reference to related own publications

Issues concerning Chapter 2 are discussed mainly in [P1], [P3], [P4] and [P5]. [P1] recognises the diverse needs of different interest groups for interruption statistics and presents novel methods for informing the customers about their supply interruptions. [P3] discusses the work done to renew the Finnish interruption statistics and it presents the main advantages of the renewed statistics. The aim has been to present more detailed data based on interruption sectors, and enable better classification of interruption causes and locations to be used as input data in reliability-based network analysis. [P4] compares the use of interruption statistics in the Nordic countries (Finland, Sweden and Norway). [P5] presents the new reliability indices that the Finnish Energy Market Authority has decided to collect.

It also introduces different methods for gathering interruption data and meeting the requirements of the regulator.

3 RELIABILITY WORTH

The function of a modern electricity supply system is to provide electric power to customers at reasonable costs and an acceptable level of reliability. The customers' dependence on electricity supply, the use of interruption costs in network business regulation and the tendency of the DSOs to reduce costs associated with maintenance etc. have resulted in the need for a more rational and consistent approach to determining acceptable reliability levels. A major aspect is the attempt to assess the worth of power system reliability in order to be able to compare it with the costs of obtaining that reliability [WaWo80]. Since worth or benefit of reliability cannot be evaluated directly interruption costs are used as a measure of reliability worth.

3.1 Character of the harm caused by interruptions

Among other things, the character of the interruption, the occurrence time of the interruption and the character of the customer's use of electricity affect the harm and costs caused to the customer by the interruptions in electricity distribution.

The character of the interruption: Advance notice about the duration of the interruption and information about the interruption duration directly after it has begun affect the harm produced by the interruption. On the other hand, for example for a large industrial customer, there will not necessarily be any difference in the costs when the duration varies from a voltage dip to a one-hour interruption, if the costs result from spoiled materials and the restarting of the process. It has been stated that advance notice will reduce costs caused by the interruption as much as over 40 % [LeLe94]. On the other hand, if there is information available about the interruption duration immediately after the beginning of the interruption the interruption costs can be up to 6 – 16 % smaller [KaAl96a]. Some studies (e.g. [CaMa04]) also show that uncertainty about the duration of interruption increases the harm caused by the interruption. Thus, this would suggest that the "real" interruption costs would be higher since in a real-life situation the duration of the interruption is not usually known beforehand, or, reversely e.g. in the case of a thunderstorm, the costs should be lower because interruptions can be expected.

The occurrence time of the interruption: The customers' needs and actions and their demand for electricity vary depending on the season, time of week and time of day. Also holidays, such as Christmas, affect the demand for electricity and the criticalness of the interruptions. Therefore the interruption costs also depend on the occurrence time of the interruption.

The character of the customer's use of electricity: In the studies, the electricity users have usually been divided into customer groups which contain similar customers. Questionnaire surveys have been conducted and the interruption costs calculated to each separate group. The customer groups that have generally been used in Finland, and also in some other countries ([Ci01], [LeLe94]) are: residential, agricultural, public sector, commercial and industry. Within the groups, the customers' purposes for the use of electricity can also differ significantly. For example, with respect to agricultural customers' electricity use, livestock farms and greenhouse farms correspond mainly to industry today whereas, except for relatively short times, the electricity use of crop farms is almost like the residential sector's electricity use. Furthermore, different subsidiary businesses can change the character of the electricity use in farms. In industry, for example, shift work also affects the significance of the occurrence time of the interruption.

The harm caused by electricity distribution interruptions can be divided into direct and indirect harm, into economic and social harm and into short term and long term harm. Direct harm is directly caused as a consequence of the interruption whereas the indirect harm results from events that start as a consequence of the interruption. The direct economic harm include, for example, lost production, spoiled materials, paid salaries, starting expenses of the process and broken devices. The types of direct social harm are, for example, loss of leisure time, unpleasant temperature in the building or fear caused by the interruption. It can be difficult to classify indirect harm into economical and social harm. [WaBi89]

3.2 Reliability worth study methods

It is difficult to specify the monetary value of electricity distribution interruptions, e.g. due to differences in the purpose of the use of electricity in the case of different customer types. For an economist, the value of a product means the market price of a product. In the case of electricity distribution, the interpretation cannot be this simple, because when the social significance of electricity has increased, it has become a commodity of necessity, or almost a civil right. When asking about interruption costs from the respondents directly, the respondents' consciousness of what the results are used for may direct the respondents' answers more than the desire to tell about the real monetary losses caused by the interruptions. Therefore different indirect questionnaire methods have also been adapted in many countries for clarifying reliability worth.

Other viewpoints are also connected to clarifying the value of electricity distribution reliability. First of all, a clear difference must be made between the value of the reliability of the service and the value of the service (e.g. electricity distribution) itself. On the other hand, the value of the reliability of the service depends on the reliability of the service. In other words, one cannot suppose that the harm caused by interruptions is the same in the countryside and in densely populated areas, even if the purpose of the use of electricity were of the same type. Maybe the most important issue to define is what are the factors reliable electricity distribution consists of. [WaBi89]

The idea of the economic evaluation of electricity distribution interruptions is not always self-evident or easily explained. For people who have little experience in electricity distribution interruptions, it may be difficult to comprehend a situation described in the questionnaire in which the electricity distribution has been interrupted for a certain period of time. Because of this, it is important to be able to describe the interruption situation and the harm caused by it as illustratively as possible. In fact, the surveys that have been made in areas of fairly many interruptions may produce more significant information about the electricity distribution interruptions than the studies made in areas with extremely high reliability. [GaWa95]

The majority of approaches used to assess reliability worth are based on a determination of the impacts of interruptions, i.e. the cost of unreliability [WaWo80]. In turn, the evaluation of interruption impacts by means of customer surveys is considered to yield relatively definitive results, and such surveys are normally undertaken for each of the various customer groups, e.g. commercial, industrial, residential etc [BiAl88].

Usually the harm caused by electricity distribution interruptions is estimated, however, with fairly direct questions. Yet less straight methods must be used especially in the case of residential customer sector, and the questions can be connected to the respondents' willingness to pay for better reliability (Willingness To Pay, WTP) or to the compensations they want for experiencing more interruptions (Willingness To Accept, WTA). The purpose of these studies is to clarify a monetary value for an interruption taking place in a certain location in the distribution network at a certain time. [GaWa95]

Numerous methods exist for the evaluation of the harm caused to the customer by the interruptions. These can be divided into three more general classes [Ci01]:

- *Indirect analytical methods;* these estimate interruption costs by drawing conclusions from the value of lost production or lost leisure time, or from other indicators or variables, such as transmission prices.
- *Case studies;* studies of this type can be carried out after a real interruption situation, mainly a wider disturbance, focusing on the real harm the interruptions have caused.
- *Customer surveys;* in these the customers are asked to estimate the costs caused by the electricity distribution interruptions when interruptions of different lengths take place at a certain time of year and day.

The strength of indirect analytic methods lies in the fact that they are easy to carry out because the information required for them is usually already available from other sources. The results of these methods are usually fairly general, and with these very exact results cannot be achieved. Case studies, however, estimate the harm caused by interruptions based on a real situation, but they can be carried out rather seldom because they are suitable mainly for the examination of the effects of a large-scale disturbance. The fact that the customers probably know best the harm caused by the interruptions can be considered as the advantage of customer surveys. However, customer surveys are very laborious and the customers' responses, depending on the purpose of use of the interruption costs, can be purposeful [SaKj03].

Principally, the research methods used in the customer surveys can be divided into three groups [KaAl96a]:

- *Direct evaluation of costs (direct costing).*

- *Preparatory actions taken to avoid the harm of interruption (preparatory action method, PAM).* In this method the respondents are usually asked to choose from a list actions they would take in order to relieve harm caused by a certain interruption in given conditions.
- *Price proportional methods (rate-related methods, RRM).* These methods include, among others, willingness to pay (WTP) and willingness to accept (WTA) methods. In WTP the respondents are asked to estimate how much they would be willing to pay for more reliable electricity distribution or to avoid a certain kind of interruption. Correspondingly, in WTA the respondents estimate how big a compensation they would like to receive if the reliability of electricity distribution was worse.

The basis of WTP and WTA approach is that willingness to pay and willingness to accept constitute a valuation of corresponding marginal increment or decrement in reliability. In an ideal situation the WTP and WTA methods should give a similar value for the harm caused by interruptions. However, actual valuations consistently yield WTP values significantly lower than WTA values. This result is believed to support the argument that electric service and its reliability do not perform as normal “markets”. [BiAl96].

In many cases, a large share of respondents state a zero value for WTP. This in turns means that the distribution of the WTP values is skewed and that the median is much lower than the mean, and for many of the interruption durations the median WTP is zero. One could perhaps argue that the share of respondents with zero WTP is usually too high. There are two possible explanations for the high share of zero WTP values. The respondents are either protesting against the scenario itself or against the principle that they should pay for something that they feel they are entitled to [CaMa04]. The same kind of tendency can also be seen in the cases of direct cost evaluation and WTA.

The biggest reliability worth values are typically obtained with the direct evaluation of costs, the second biggest ones with the WTA method and the smallest ones with the WTP method. In other words, it is said that interruptions cause a lot of harm, but the respondents are not ready to pay very much for better reliability of electricity distribution. Particularly in the case of residential sector customers the harm caused by interruptions is discomfort or postponing certain housekeeping tasks to another time, and it is difficult to give a monetary value for this kind of discomfort [WaBi89].

Every customer group has its own special characteristics which prevent the use of the same questionnaire with all customer groups. However, the essential information to be collected is the same within all the groups. This includes, for example [GaWa95]:
- frequency of electricity distribution interruptions
- the character of the customer’s use of electricity
- costs caused by interruptions of different duration
- the effect of the occurrence time of interruption (monthly, weekly and hourly variations)
- the effect of advance notice on the harm caused by the interruption
- the effect of knowing the duration of the interruption

3.3 Overview of interruption cost models

Actual and expected customer outage costs are calculated by combining reliability indices with a suitable cost model. Customer surveys are the preferred method to assess direct short-term customer interruption costs. The application of raw surveyed data requires transformation into usable cost model. The following sections describe some of the cost models.

Useful notations for reliability worth estimates are, for example, €/interruption, €/kW (maximum power), and €/kWh (annual energy or energy not supplied). The information received with the help of customer surveys is the raw data which is in the form €/interruption for interruptions of different lengths and different types. From this data the averaged or aggregated values are calculated with normalising factors. In the averaging process the raw interruption costs are divided by the normalising factor, which is usually the customer's maximum power (kW) or the customer's annual energy (kWh). After this the average values are calculated from these normalised values. In the aggregating process the customer’s raw interruption costs are summed up and then divided by the sum of the normalising factors. The aggregating process usually gives slightly smaller values than the averaging process. Different normalising methods cause differences in the interruption costs even if the raw data collected with the surveys is similar. This must be kept in mind when comparing different studies. [Ci01] On the other hand, for example normalising with the maximum power also causes the assumption that interruptions occurring at the time of maximum power are the most harmful, which is not always true [WaBi89].

3.3.1 Customer Damage Function Cost Model

Customer interruption costs can be used as an estimate of the worth of reliable electric service. Customer survey approach is the most practical and reliable process to obtain these costs. Customer interruption costs are a function of both interruption and user characteristics. The costs incurred due to power supply interruptions can be presented as a function of interruption duration, and when expressed in this form known as a customer damage function (CDF). The CDF can be determined for a group of customers belonging to a particular customer group. [SaWa99]

The CDFs exhibit piecewise linearly increasing relationships in which a segment between any two successive studied interruption durations is described by a straight line equation. The average interruption cost at any possible intermediate duration can be determined by using linear interpolation [BiCh94]. The CDFs can be combined into a representative cost function for that sector designated as a sector customer damage function (SCDF). The costs can be calculated in various ways, but demand normalised (€/kW) values calculated on an aggregated basis are the most common indices [SaWa99]. Another commonly used approach is to calculate the average value of the annual energy or peak demand normalised costs.

The composite customer damage function (CCDF) is an estimate of the cost associated with power supply interruptions as a function of the interruption duration for the customer mix in the service area of interest. Each customer or type of customer has a different cost for a particular interruption duration and the method for combining the individual costs is to perform a weighted average according to the annual energy consumption of the individual customers or customer groups. [BiAl88]

In [KaAl96b] the interpretation of CDF's, SCDF's and CCDF's are presented thoroughly. A consistent and coherent method is presented for evaluating customer outage costs (COC) for any network, using the perceived customer interruption costs (CIC) provided by customer surveys. Therefore, an understanding of the perceived customer interruption costs (CIC) and the customer outage costs (COC) is required. These are defined as follows [KaAl96b]:

> CIC: The perceived individual customer or average sector customer costs resulting from electricity interruptions. They are therefore *system independent.*
>
> COC: The expected total costs incurred by *all* the customers connected to a particular network or service area. They are calculated from the CIC and take into consideration the network performance data and loading information. They are therefore *system dependent.*

Since they are system independent, CIC would neither be suitable for comparing historical or future performance of alternative network configurations nor for cross-utility comparison. In order to make these comparisons on a similar and consistent basis, the CIC per interruption are normalised with respect to either the customers' annual energy consumption or customers peak demand (kW). These normalised costs are given by Equations 3.1 [KaAl96b]:

$$C_{L,x} = \frac{CIC_x(r_i)}{L_x} \tag{3.1}$$

where $CIC_x(r_i)$ are the costs incurred by customer x per interruption of duration r_i and L_x is the customer's peak demand.

After normalising the CIC values, averaged values are calculated for customer sub-sectors. For a general customer group k with n customers $C_{L,k}(r_i)$ is given by [KaAl96b]:

$$C_{L,k}(r_i) = \frac{\sum_{x \in k} C_{L,x}}{n} \tag{3.2}$$

Then, the sub-sector normalised costs are appropriately weighted to yield a composite value for the overall sector (or e.g. for a certain feeder or area), $C_{L,y}(r_i)$, i.e. the SCDF. Equation 3.3 shows the calculation of sector normalised costs for a general sector y consisting of ns sub-sector with weighting with respect to the peak demand [KaAl96b]:

$$C_{L,y}(r_i) = \frac{\sum_{k \in ns} C_{L,k}(r_i) L_k}{\sum_{k \in ns} L_k} \tag{3.3}$$

[KaAl96b] also suggests that there is an approximately constant ratio between the annual energy normalised and peak demand normalised SCDF values for each sector, i.e. between $C_{E,y}(r_i)$, and $C_{L,y}(r_i)$. $C_{E,y}(r_i)$ is calculated similarly as $C_{L,y}(r_i)$ but customers' peak demand is replaced with customers' annual energy. This suggests a relationship between the two types of SCDFs. For any sector y, this relationship can be shown to be empirically expressed by Equation 3.4 [KaAl96b]:

$$C_{E,y} = \frac{C_{L,y}}{LF_y \cdot 8.76} \tag{3.4}$$

where LF_y is the load factor for sector y. This relationship is important because it enables the derivation of a single cost model rather than the pair that would be expected from the two SCDFs. In addition to this, e.g. customers in residential sector are not usually monitored for peak demand and [WaWo83] reports that a load factor of 0.23 was assumed in order to convert the energy requirements into peak load demand.

There are two basic procedures for deriving CDF, i.e. averaging and aggregating procedure. The averaging procedure, which was presented above, evaluates the average of the normalised customer cost functions. The aggregating procedure summates the raw cost data and the normalising factors first and then proceeds to divide the sums (see Equation 3.5).

$$C_{L,k}(r_i) = \frac{\sum_{x \in k} CIC_x(r_i)}{\sum_{x \in k} L_x} \tag{3.5}$$

The aggregating procedure usually gives lower CDF estimates as it reduces the effects of customers that have relatively low consumption and high interruption costs [Bo00], [SiHe05].

The use of CDF normalised with respect to the peak demand would give correct cost estimates for the demand interrupted only if the surveyed costs occur when the customer load is at its annual peak [Bo00], i.e. it makes an assumption that the time of peak demand is the most harmful time and the interruption costs depend linearly on the load.

3.3.2 Energy Not Supplied Cost Models

The basic idea of the cost of *energy not supplied* (CENS) approach is to model interruption costs as a function of the unsupplied energy, regardless of the interruption duration and frequency. The physical nature of CENS is that it represents the average cost over the interruption duration interval. This cost model implies that the cost function is a straight line that passes through the origin, as is shown in Figure 3.1. There are several ways to calculate the cost of unsupplied energy, some of which have got specific names in literature: *Cost of Energy Not Supplied, Interrupted Energy Assessment Rate* (IEAR) [BiOt87], [OtBi89] and *Value of Lost Load* (VOLL) [KaAl96b], [Go98]. CENS, IEAR and VOLL cost models are three variants of the basic idea to represent the interruption costs as a function of unsupplied energy.

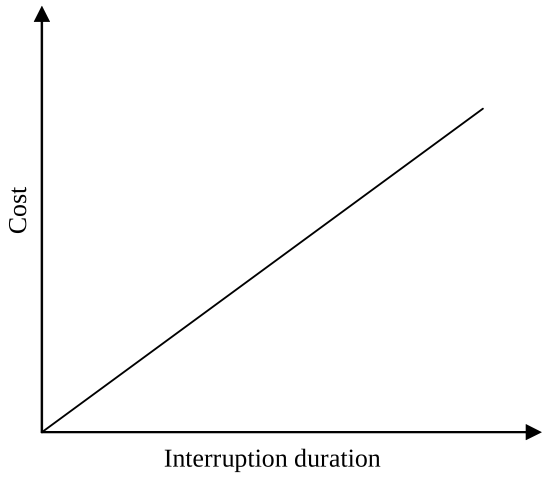


Figure 3.1: Interruption cost functions implied in the energy not supplied model.

Starting from the annual peak demand normalised CDF, CENS could be calculated using Equation 3.6, as the average cost over the interruption duration interval *D*, for each $d_i \in D$ [Bo00]:

$$CENS = \frac{1}{n}\sum_{d_i=1}^{n}\frac{CDF(d_i)}{LF \times d_i} \qquad (3.6)$$

The following variables are defined for each specific interruption *i*, the duration of which is d_i. $CDF(d_i)$ is the cost from the ordinate of the CDF curve; *LF* designates the load factor of the customer mix considered; *n* is the number of interruptions.

3.3.3 Combined Cost Model

The basic idea of the *combined cost model* (CCM) approach is to model interruption costs as a sum of two components: one is a function of the interrupted load demand, another is a function of the unsupplied energy. The inclusion of the interrupted demand term in the cost model takes into account the significant cost that most users experience for even very short, momentary, interruptions. This term is proportional to the frequency of interruptions, which makes the use of this cost model suitable when the frequency and duration reliability indices are calculated. The physical nature of CCM is that it represents the average cost over the interruption duration interval. The CCM assumes that the interruption cost versus time curve is a straight line which does not pass through the origin, as is shown in Figure 3.2.

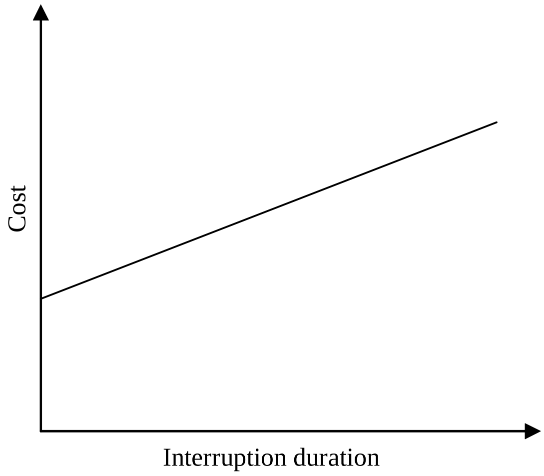


Figure 3.2: Interruption cost functions implied in the combined cost model.

The combined cost model has two parameters that ascribe a cost to the interrupted demand, CD (€/kW interrupted), and to the unsupplied energy, CENS (€/kWh unsupplied), as it is shown in Equation 3.7 [Bo00].

$$COST = CD \times Load\ interrupted + CENS \times EENS \qquad (3.7)$$

The first parameter, CD, determines the intersection of the cost curve with the ordinate, while the second, CENS, determines its slope. EENS is Expected Energy Not Supplied.

Starting from the annual peak demand normalised CDF, the cost of the interrupted demand, CD, could be determined from the intersection of the CDF curve with the ordinate, as is shown in Equation 3.8 [Bo00]:

$$CD = CDF(0) \qquad (3.8)$$

It is important to note that this equation will give the correct value for CD only if the surveyed costs occur when the customer load is at its annual peak. Only then the interrupted demand and that used for normalisation are the same. Otherwise the acquired cost estimates are lower for the demand interrupted than the true ones. The estimation of correct values requires knowledge of the particular survey and reconstitution of the relevant information lost during the process of normalisation, averaging and aggregating.

3.4 Reliability worth studies around the world

The oldest results concerning costs associated with electricity supply interruptions are available from the Swedish survey in 1969 [Swe69]. After that there have been plenty of similar surveys around the world. More recent surveys are introduced in [Ci01]. These studies show that, although trends are similar in virtually all cases, the costs vary over a wide range and depend on the country of origin and the type of customer. On the other hand, interruption costs are likely to vary with the level of reliability.

Form and time distribution of the surveys and the methods used in the further handling (normalising, aggregated or averaged values etc.) of the results differ a little. Table 3.1 presents a summary of the studies and research methods made around the world.

Table 3.1: Reliability worth surveys around the world [Ci01].

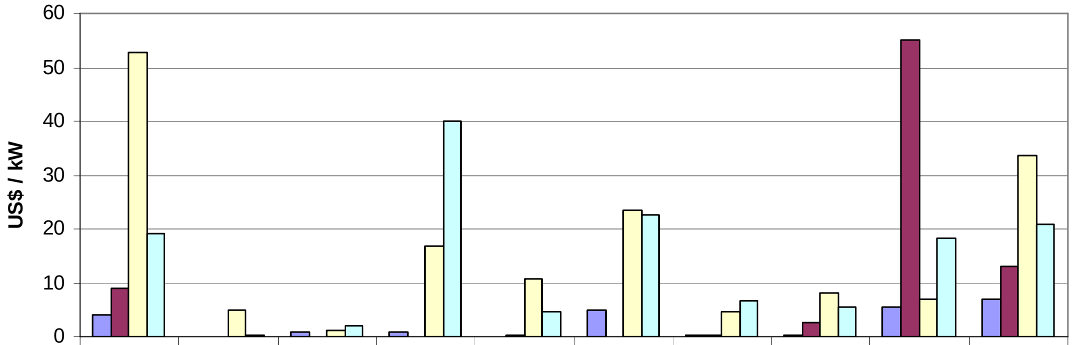
Country	Customer groups	Interruption durations	Normalization	Year of survey
Australia	A, C, I, L, R	2 s - 48 h	Annual energy	1996 - 1997
Canada	A, C, I, O, R	2 s - 24 h	Annual energy Peak demand	1985 - 1995
Denmark	A, C, I, O, R	1 s - 8 h	Peak demand	1993-1994
Great Britain	C, I, L, R	Momentary - 24 h	Annual energy Peak demand	1993
Greece	C, I	Momentary - 24 h	Peak demand	1997 - 1998
Iran	C, I, R	2 s - 2 h	Peak demand	1995
Nepal	C, I, R	1 min - 48 h	Annual energy Peak demand	1996
New Zealand	C, I, R	< 2 h		1987
Norway	A, C, I, R	1 min - 8 h	Peak demand	1989 - 1991
Portugal	C, I, R	1 min - 6 h	Annual energy	1997 - 1998
Saudi Arabia	C, I, R	20 min - 8 h	Annual energy Peak demand	1988 - 1991
Sweden	A, C, I, R	2 min - 8 h	Peak demand	1994
USA	A, C, I, R	Momentary - 4 h	Energy not supplied	1986 - 1993
Norway*	R, A, C, I, L, O	Momentary - 24 h	Energy not supplied	2000 - 2002
USA*	I and Digital economy	1 s - 1 h	Annual energy	2001
Finland**	R, A, C, I, O	1 s - 36 h	Peak demand	2005

* from reference [SaSi03]
** from [P6]

Explanations of the abbreviations in the table are:

R – Residential A – Agricultural
C – Commercial O – Office (including public sector)
I – Industry L – Large users

Figure 3.3 shows reliability worth values from different studies. The results have been converted into US dollars from the national currency of each country using the exchange rates of the research year, except for Finland in which case 1,22 € = 1 US$ has been used. The inflation adjustments etc. have been made here neither to the values that have been presented in report [Ci01] nor to the values for Finland, which have been taken from [P6].



	USA 1986	Nepal 1996	Iran 1995	Great Britain 1993	Canada 1987	New Zealand 1987	Norway 1991	Sweden 1994	Denmark 1994	Finland 2005
Residential	3.97	0.14	0.79	0.86	0.12	4.91	0.29	0.31	5.42	7.07
Agricultural	8.93				0.24		0.15	2.71	55.02	12.93
Commercial	52.61	5.02	1.21	16.90	10.78	23.55	4.73	8.00	7.04	33.66
Industry	19.14	0.37	1.92	40.10	4.67	22.69	6.79	5.46	18.24	20.73

Figure 3.3: Reliability worth values for 1 h unexpected interruption [Ci01], [SaSi03], [P6].

Figure 3.3 shows that the reliability worth estimates vary over a wide range. When results are interpreted, it is worth remembering that different normalising methods (see Table 3.1) have been used in the studies. The time when the study was made (year and season) also affects the results. A common trend, however, is that reliability worth estimates have been growing over time. This was seen e.g. in the latest Finnish study [SiHe05] which showed that reliability worth was doubled during ten years.

3.5 Reference to related own publications

Reliability worth related issues are discussed in [P6] and [P7]. [P6] introduces the results of the reliability worth study made in Finland in 2004-2005. It also presents the basics of the calculation methods (i.e. averaging and aggregating processes) and the methods for eliminating the strategic answers. [P7] makes a thorough comparison between different methods to eliminate the strategic answers. It also presents a correlation study that shows how the harm caused by the interruptions depends on the size of the customer.

In the Finnish study both averaged and aggregated values were calculated. These first two steps (Equations 3.1 and 3.2) of the CDF process presented above correspond to the Finnish study, if the averaging process calculation method is used. In the Finnish study, the actual peak demand of the respondents was not known, and therefore it was estimated from the measured energy consumption of the respondent and the estimated average utilisation time of the customer group in question. The formula for customer group k with n customers can now be given:

$$C_{averaged,k}(r_i) = \frac{\sum_{x \in k} \frac{CIC_x(r_i)}{L_x}}{n} = \frac{\sum_{x \in k} \frac{\frac{CIC_x(r_i)}{W_x(r_i)}}{t_k}}{n} \tag{3.10}$$

where $CIC_x(r_i)$ are the costs incurred by customer x per interruption of duration r_i, L_x is the customer's peak demand, $W_x(r_i)$ is the annual energy consumption of customer x and t_k is the utilisation time of customer group k.

On the other hand, the last step presented in Equation 3.3 corresponds to the Finnish study, if the aggregating process calculation method is used, with the assumption that each customer forms its own sub-sector, i.e. in Equation 3.2 $n=1$. In this case the following formula can be given:

$$C_{aggregated,k}(r_i) = \frac{\sum_{x \in k} CIC_x(r_i)}{\sum_{x \in k} L_x} = \frac{\sum_{x \in k} CIC_x(r_i)}{\sum_{x \in k} \frac{W_x(r_i)}{t_k}} \tag{3.11}$$

The utilisation time applied in the study was 3100 hours for agriculture, and 3000 hours for other customer groups. These are the same utilisation times that were used in the previous study [LeLe94] and they are based on the Finnish metering study made to define load curves for customer groups [SLY92].

The reliability worth estimates presented in the publications are principally calculated with the aggregating process. The reliability evaluation software presented in Chapter 4.2 implements the combined cost model to evaluate the customer interruption costs.

4 RELIABILITY-BASED NETWORK ANALYSIS

Historical assessment and predictive assessment are the two frequently used approaches to reliability evaluation of power distribution systems. Historical reliability assessment involves the collection and analysis of an electric system's outage and interruption data. It is essential for DSOs to measure actual distribution system reliability levels and define performance indicators in order to assess their basic functions of providing a cost-effective and reliable power supply to all sectors of society [ChKo98]. Historical assessment generally analyses discrete interruption events occurring at specific locations over specific time periods, whereas predictive assessment determines the long-term behaviour of systems by combining component failure rates and the duration of repair, restoration, switching, and isolation activities that describe the central tendency of an entire DSO's distribution system of the possible values for given network configurations.

Historical system performance can be monitored because knowledge of the characteristics is available, i.e. the data concerning faults and interruptions are stored in the databases. However, it is extremely difficult to predict the future system performance with a high degree of confidence because it contains considerable uncertainties associated with the predicted system requirements (due to e.g. load growth). The models (e.g. failure models) used are also usually approximations of the system behaviour. Therefore uncertainties are embedded in the indices concerning the predicted supply reliability. [BiAl92]

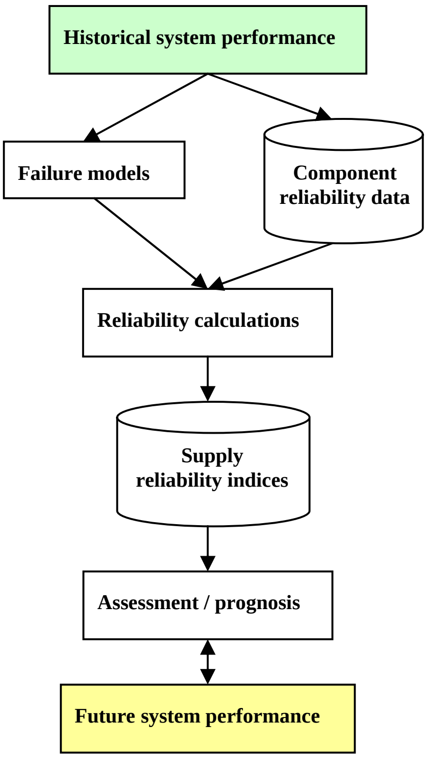


Figure 4.1: Schematic sequence of reliability analysis.

It is not easy to identify when the development of predictive reliability evaluation of distribution systems has started. [GaMo64] presents probably the first comprehensive technique based on approximate equations for evaluating the rate and duration of outages. This technique has formed the basis and starting point of most of the later and more modern developments [BiAl96].

The simplest approach which can be used to relate economics with reliability is to consider the investment cost only. In this approach, the increase in reliability due to the various alternative reinforcement or expansion schemes are evaluated together with the investment cost associated with each scheme. Dividing this cost by the increase in reliability gives the incremental cost of reliability, i.e. how much it will cost for a per unit increase in reliability. This is a significant step forward compared with assessing alternatives and making major capital investment decisions using deterministic techniques. [BiAl88] The weakness of this approach is that it is not related to either the likely return on investment or the real benefit accruing to the customer, DSO and society. In order to make a consistent appraisal of reliability and economics, it is necessary to compare the reliability cost (the investment cost needed to achieve a certain level of reliability) with reliability worth (the benefit derived by the DSO, customer and society).

Reliability of a distribution system is usually assessed at the customer end, i.e. at the load points. The basic indices normally used to evaluate the reliability of a distribution system are e.g. load point failure rate and average interruption duration. The basic indices are important from the customer's point of view but they do not provide an overall appreciation of the system performance. An additional set of indices can be calculated using the basic load point indices and the number of customers or load connected at each load point. Most commonly used system indices are System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), Average Service Availability Index (ASAI) and Energy Not Supplied (ENS). Reliability indices are discussed in more detail in Chapter 2.3. Load point indices, as well as system indices, are dependent on component outages, system configurations and restoration activities.

The criteria and techniques first used in practical reliability evaluation applications were all deterministically based. A typical deterministic criterion is e.g. the (n-1) criterion to construct, depending on the amount of redundancy, a minimal number of circuits to a load group. Many of these deterministic criteria and techniques are still in use today. The essential weakness of deterministic criteria is that they do not respond to nor do they reflect the probabilistic or stochastic system behavior, of customer demands or of component failures [BiAl88]. Typical probabilistic aspect is e.g. that the failure rate of an overhead line is a function of length, design, location and environment.

The reliability evaluation model utilised in this thesis considers the overall life-cycle costs of the network as presented later in this chapter and in e.g. [P8].

4.1 Analytical and simulation based power system reliability assessment

Power system reliability indices can be calculated using a variety of methods. The two main approaches are analytical and simulation. The vast majority of techniques are analytically based and simulation techniques have taken a minor role in specialised applications [BiAl96].

Analytical techniques represent the system by a mathematical model and evaluate the reliability indices from this model using direct numerical solutions. They generally provide expectation indices in a relatively short computing time. The long-term performance of the system is analysed through average values and the calculated reliability indices are average or expected values. However, assumptions are usually required to in order to simplify the problem and produce an analytical model of the system.

Simulation techniques represent the system by simulating stochastic behavior of its components and deterministic events in basic intervals of time. Their generic name is Monte Carlo simulations. A Monte Carlo simulation is a repeated chronological simulation of the power system. During each simulation, faults will be introduced randomly, as in real life, and the reactions of the system to these faults are simulated chronologically. The performance of the system is then monitored during the simulations. [Ca03]

Simulation methods estimate the reliability indices by simulating the actual process and random behavior of the system. The method therefore treats the problem as a series of real experiments. Simulation techniques can take into account several aspects, like random events such as outages and repairs of components represented by general probability distributions, dependent events and components' behavior as well as different types of operating policies.

Reliability indices of a distribution system are functions of component failures, repairs and restoration times which are random by nature. The calculated indices are therefore random variables and can be described by probability distributions. Conventional reliability analyses are normally concerned with the expected or average value of the particular measure of reliability. The mean values are extremely useful and are primary indices of load point reliability. Little consideration has been given in the past to the variation of that measure about its mean. [BiAl88]

It is important to realise that most of the probabilistic techniques for reliability evaluation are in the domain of adequacy assessment. Consequently most of the evaluated indices are adequacy indices and not overall reliability indices. [BiAl88]

Considerable research has been done on generation and transmission system reliability valuation, and service interruption cost applications. Both analytical and simulation methods are used in these areas. Relatively little work has been done in the area of distribution systems. [BiWa98] Generally simulations require a large amount of computing time and they are not used extensively if alternative analytical methods are available

[BiAl92]. Analytical models and techniques have usually been sufficient to provide the results needed to make objective decisions.

4.2 Reliability evaluation software utilised in the thesis

In quantitative reliability analysis of a distribution system, the most important factors are the expected failure rates and outage durations. The distribution system consists of a variety of components, such as lines, cables, transformers, circuit breakers, disconnectors, etc. The solution is aimed primarily at estimating the influence of the unavailability of each component on the supply interruptions at each customer. Both the reliability data for the components and their location in relation to the paths from the feeding points to the customer must be taken into account [MäPa90].

The reliability requirements for an electrical distribution system can be taken into account in several ways. One is to state certain specific engineering recommendations, e.g. that each distribution substation or group of substations must have at least two feeding cables in urban areas. Another is to find the most critical customers and determine the maximum expected outage rate and/or outage time allowed. Both of these criteria can be based on experience, and very subjective aspects are sometimes considered. [MäPa90]

In a radial distribution system, quite simple formulae can be used to calculate the reliability indices. The calculation of reliability indices involves a system consisting of series components from source to load. The basic techniques to evaluate the average values of distribution system indices can be effectively utilised to investigate the effect on the system performance of varying the component performance parameters, system restoration times, operation strategy, system configuration etc [BiAl88]. Deterministic data is required at both the system and at the actual component level. The component data includes known parameters such as line impedances and other similar factors normally utilised in conventional load flow studies. One significant assumption frequently made in the reliability evaluation of all systems is that the behaviour of any component is quite independent of the behaviour of any other component.

In the reliability analysis, the main approach is to discover the closed and the normally open paths from each load point to the feeding points. Based on these and on further information regarding the network configuration and component characteristics, the influence of the unavailability of each network component on the unavailability at each load point is calculated [MäPa90]. In radial networks this is quite straightforward, because the network consists of components in series between the feeding point and the load point. Hence, a failure in any component between feeding point and load point, and a failure in any other component belonging to the same protection area as the load point, leads to supply interruption.

Enhanced reliability-based network modelling methods and algorithms (i.e. LuoVa software) have been developed as part of reliability-based network analysis [VePy05].

These enhanced methods have emphasis on component modelling, but they also involve other modelling such as radial network reliability analysis and interruption cost modelling (see Figure 4.2).

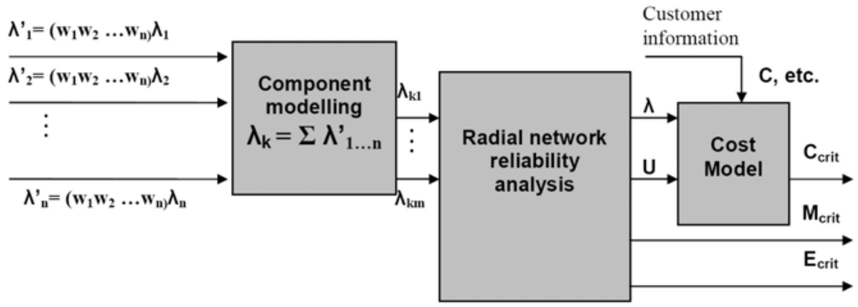


Figure 4.2: Enhanced reliability-based network analysis [PyVe05].

The following chapters present shortly the models used in the developed software [VePy05]. These methods are utilised in the analysis presented in [P8].

4.2.1 Component modelling and failure rates

Traditionally, component failure models used in reliability calculations are based on constant failure rates. However, the constant failure rate is an inadequate approach if the effects of the component type and surroundings are to be analysed [PyVe05]. For example, some line types (overhead line, covered overhead line) are more vulnerable to environmental faults than others (e.g. underground or aerial cables). On the other hand, it is found in practice that the failure rate of most components is a function of the environment to which they are exposed.

According to [PyVe05], the main requirement the method had to meet to be implemented in LuoVa was to have estimates of failure rates that take into consideration the main stress factors affecting the failure rate. Another requirement was the possibility to have first estimates from incomplete data and to update the values when better data is available.

The network consists of several components whose failure rates depend on different factors. Components are modelled in certain entities such as overhead lines, cables and transformers. The basic principle in component failure rate modelling has been to utilise different failure rate factors for different components. Failure rates consist of several partial failure rates. Failure causes (e.g. wind, snow, lightning, animals) and stress class factors (e.g. location on forest, roadside, field) are defined for different components. The total failure rate can be formed as a sum of partial failure rate factors weighted with stress class factors, as depicted in Equation 4.1 [PyJä04]:

$$\lambda_{TOT} = w_{1\_1} \times ... \times w_{n\_1} \times \lambda_1 + w_{1\_2} \times ... \times w_{n\_2} \times \lambda_2 + ... + w_{1\_n} \times ... \times w_{n\_n} \times \lambda_n \qquad (4.1)$$

where

λ_{TOT} = total failure rate of the component
$\lambda_1 \ldots \lambda_n$ = partial failure rates of the component
$w_{1\_i} \ldots$ = weights for i:th stress class of partial failure rate

General default values for failure rates and weight coefficients are defined with the help of fault statistics and engineering judgement. However, it was found that present fault statistics are incomplete from the advanced component modelling point of view. Parameters can be adjusted further with improved statistics [PyJä04].

4.2.2 Radial network reliability analysis

Component information and network topology are used as basic input data for reliability analysis. The network is analysed one feeder at a time, and each feeder is divided into zones. A zone comprises of the part of the feeder that can be isolated with switches, either locally or remotely. The expected failure rate of a zone is calculated using Equation 4.2 [PyJä04]:

$$\lambda_{zone} = \sum_{i \in I} \lambda_i \tag{4.2}$$

where

λ_{zone} = annual failure rate of the zone
λ_i = annual failure rate of component i
I = set of components in the zone

In the reliability analysis, an expected amount of sustained and temporary failures in a zone is calculated as a sum of the individual network component failures. In the case of a sustained fault, the determination of the repair time is made by analysing the possibilities to isolate load points from the faulted part of the feeder. Supply for the majority of the load points can usually be restored with locally or remotely operated disconnectors, while the load points in the faulted zone experience an interruption of the length of the repair time. In the case of auto-reclosings, the whole feeder experiences the same interruption. For example, the following restoration times can be used depending on the switch type and faulted component:

- remote fault isolation and restoration
- local fault isolation, remote restoration
- local restoration
- fault repair time
- transformer change time
- cable replacement with temporary backup cable or aggregate

A more thorough presentation of the radial network reliability analysis is depicted in [MäPa90].

4.2.3 Interruption cost modelling

Interruption cost evaluation involves the modelling of the costs incurred by both DSO and customers. The value of DSO costs comprises of the cost of energy not supplied and the fault repair costs. Customer interruption costs are evaluated using the interruption durations and numbers of different interruption types, gathered from the reliability analysis, and reliability worth estimates based on studies (e.g. [LeLe94], [SiHe05]). The expected annual interruption costs are defined using Equation 4.3 [PyVe05]:

$$C = \sum_{j \in J} \sum_{i \in I} \lambda_{zone} (a_i + b_i t_j) P_{ij} n_{ij} \tag{4.3}$$

where

J	=	set of load points to which fault in zone causes an interruption
I	=	set of customer groups
λ_{zone}	=	sum of the individual component failures in the zone per year
a_i	=	load dependent interruption cost parameter for customer group i [€/kW]
b_i	=	time (energy) dependent interruption cost parameter for customer group i [€/kWh]
t_j	=	expected interruption duration of load point j [h]
n_{ij}	=	number of customers of group i in load point j
P_{ij}	=	power of average customer of group i in load point j [kW]

4.3 Interruption costs in network planning

The interruption costs consist of two parts: the costs seen by the DSO and the costs seen by society or customers. The former is normally composed of the value of energy not supplied and the extra costs caused by network reparations. The latter is formed of the value of lost production, spoiled materials, etc. The costs seen by the customers form the main part of the total interruption costs and the DSO's interruption costs are usually much smaller. Hence, the customer expectations of network reliability should direct the actions of the DSOs.

The use of interruption costs is very practical in network planning. The approach involves the estimation of the outage periods and loads for each customer and assessing of these from either the DSO's or the customer's point of view. This way, the value of the customer costs associated with interruptions can be treated as a cost component, like the values of power and energy losses or annuities of investments. Thus the quality of the supply can be judged quantitatively and related to the economics of the whole system. This tends to result in better design and smaller overall costs than when only qualitative criteria are applied. [MäPa90]

The planning of electricity distribution systems is a technical and economic optimisation problem in which the long-term total costs must be minimised whilst taking into account the technical, environmental and other constraints. Thus, the optimal reliability level is reached by considering the costs associated with interruptions as a cost component. For the reliability and cost analysis, the use of interruption costs offers a tool for evaluating e.g. which load points have the largest interruption durations or which components cause the largest interruption costs.

The basic function of the reliability analysis tool is the analysis of an existing network in for example a one year period. As a result of this analysis, the following results are gained which can be divided into different interruption types:

For each load point:

- the number of interruptions
- the duration of interruptions
- the total interruption costs

For each component:

- the interruption costs due to one failure
- the total interruption costs caused by the failures of the component
- the number of temporary faults caused by the component

For the whole network:

- general indices (SAIFI, SAIDI, CAIDI)
- total interruption costs
- list of the load points with the largest interruption costs
- list of the components causing the largest interruption costs

The results of the current network analysis can be utilised to select the future network structure in order to optimise the level of security and reliability of the network. Network planning is an interactive process, where different future network possibilities are studied. As a result of the network analysis of the existing network the most critical components can he identified [PyJä04].

One practical example of using interruption costs in network planning is the routing of the aerial line. While considering different alternatives, quite many planning aspects must be taken into account. For example, interruption costs caused by the line varies depending on the selected route. This means that if the aerial line is situated in a forest, the failure rates and interruption costs are higher than if the line is placed by the roadside. However, if the length of the line is much shorter if placed in the forest, it could still be the most economical routing option. In the analysis, it is also important to determine if it is more economical to use a covered conductor line instead of an overhead line. Even if a covered conductor line is more expensive, sometimes the total costs are lower in comparison to the overhead line. The interactive analysis will point out the most economical way to achieve the optimal network structure for the problem studied. In the future, underground cables may also become a cost effective alternative even in sparsely populated areas if the reliability worth estimates still increase.

As e.g. [P2] points out, up to 50 % of the customer interruption costs may be originated by high-speed and delayed auto-reclosings, which are used to avoid long interruptions. Another practical example is the use of arc suppression coils in order to decrease the amount of short interruptions and the costs associated with them. The effect of arc suppression coils and the profitability of the investment can be evaluated with the reliability evaluation software.

4.4 Reference to related own publications

Chapter 4 discusses reliability-based network analysis related issues and presents the analytical model used in the reliability evaluation software to simulate distribution system reliability. Chapter 4 presents the basics of the simulation models in general and introduces the reliability analysis software used in this thesis. These issues are discussed in [P2] and [P8]. [P2] presents results of some basic reliability calculations. [P8] depicts the definition of reliability worth parameters and the parameterisation of the reliability analysis software. It also presents thoroughly the results of the life-cycle cost analysis for network alternatives in the cases where different reliability parameters were optimised.

However, the life-cycle cost minimisation approach adopted in this thesis is quite hypothetical and limited as it relies on optimising one reliability parameter at a time. Subjective choices may also affect the investment cost of each network alternative as there were several options to achieve the goal of halving a certain reliability parameter. On the other hand, almost every investment made to decrease one reliability parameter will probably decrease the others, too. The part of the thesis presenting life-cycle cost evaluation results is applicable to that distribution network and the alternatives presented are not exclusive, but otherwise the approach is generalisable.

The reliability evaluation software used in this thesis utilises the combined cost model presented in Chapter 3.3.3.

5 RELIABILITY IN NETWORK BUSINESS REGULATION

The restructuring process of the electricity supply industry has led the business to significant changes. Generation and sale of electricity have been deregulated and they are opened to free competition. Regulation has been introduced in the field of electricity distribution and transmission, where monopolies have been considered the most efficient option. In almost all European countries the basic reliability indices (such as SAIFI and SAIDI) are reported to regulators and reliability aspects are considered somehow in the regulation of distribution businesses [CEER08]. Usually incentive/penalty schemes affect revenues earned by distribution companies. The economic effects are typically directly proportional to the difference between the actual value of the regulated indicator and the target [CEER05].

The regulation of distribution system operators (DSO) in Finland is based on the Electricity Market Act [Fi95]. Energy Market Authority has carried out the regulation ever since the Electricity Market Act came into force in 1995. In the beginning, there was no ready-to-use regulatory model, and therefore the regulation was done with a case-by-case practice. In the end of the 90's, the regulation model was developed to be a common model. It was still clearly an ex-post regulation and it covered only a few of the DSOs operating in Finland. From 2005 on, following the EU legislation (European Commission Directive (2003/54/EC)), the Energy Market Authority adopted a systematic ex-ante regulation practise, which covers all the DSOs operating in Finland.

Before 2005, power quality was included in the economic regulation as a part of efficiency evaluation. Total interruption time was an input parameter in the DEA model. It was, however, noticed that the quality input did not depict the power quality experienced by the customers in the best possible way and its directing effects were questionable. In 2005-2007 individual efficiency requirement was not included in the regulation model, so power quality did not have any economic effects in the regulation model.

Publications [P1]-[P7] in this thesis are written before the first regulation period in 2005-2007 or during it. After that, there have been some modifications in the regulation model. The work and results presented in this thesis have partly influenced the regulation model's development into its present form. The biggest change made to the second regulation period 2008-2011 is that a power quality incentive has been added in the regulation model. The first regulation period did not include a power quality incentive, but the need for it was already recognised during the first regulation period [Ki08].

Incentives will have effects on the behaviour of the regulated entities. The aim of the power quality incentive is to motivate the DSOs to aspire after as good power quality as possible without neglecting network maintenance and reinforcements. The quality incentive is included in the regulation in the form of disutility of interruptions (DOI) [Ki08], which is the monetary value of the harms caused by interruptions to the customers, i.e. interruption costs.

5.1 Overview of the Finnish regulation model 2008-2011

The current regulation scheme in Finland can be described as being an incentive-based rate of return regulation with some price-cap characteristics in it. This means that in Finland the regulator determines the allowed profit for DSOs and then calculates whether the actual (adjusted) profit has been reasonable or not [Ki08]. A simplified illstration of the regulation model is presented in Figure 5.1.

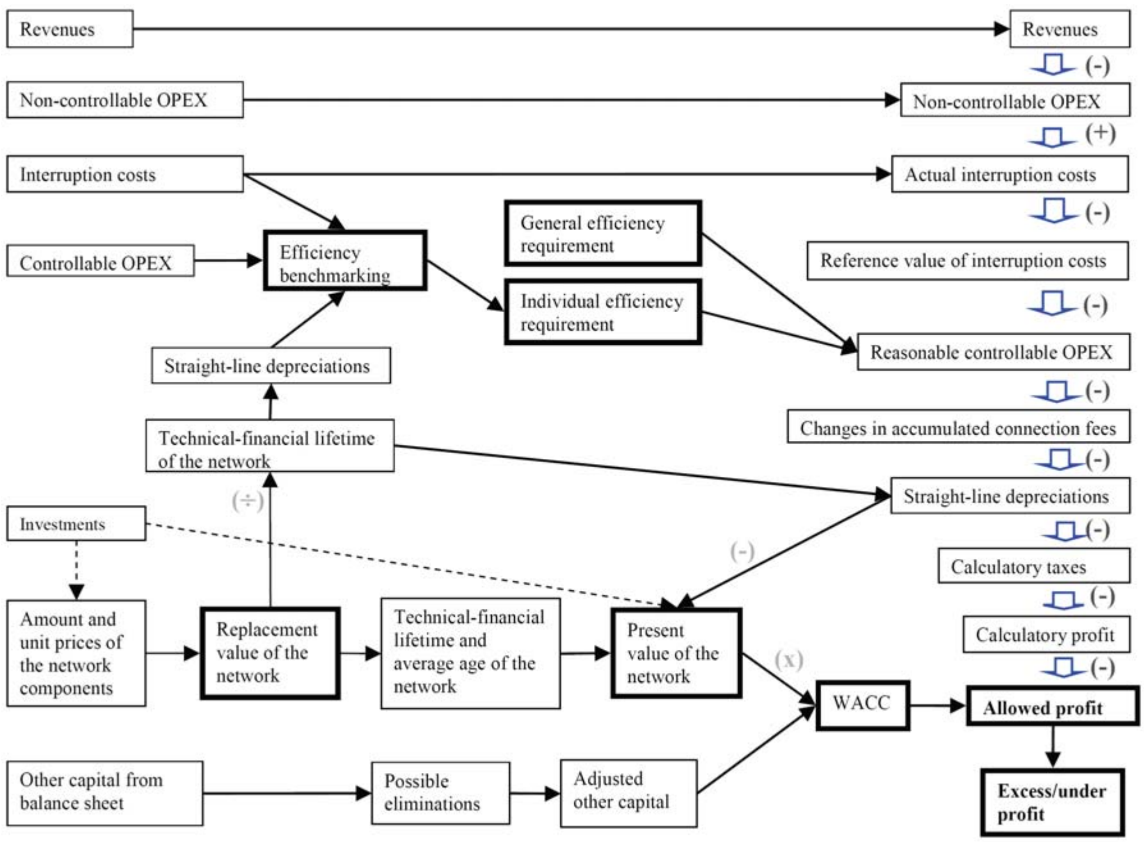


Figure 5.1: Simplified illustration of the regulation model in Finland between 2008 and 2011 [Ho08].

The allowed profit is defined based on the present value of the network. Straight-line depreciations are used to define the reasonable level of depreciations. They are calculated with the repurchase value of the network and the technical-economic lifetimes of network components. The repurchase value of the network is calculated based on the unit costs and the amount of different network components. The unit costs are set by the regulator and they are based on national statistics about the prices of network components.

The present value of the network is defined based on the repurchase value, lifetime and the age of the network. It is adjusted yearly by annual investments and depreciations, as well as changes in the Building Cost Index (BCI).

5.1.1 Efficiency benchmarking

In the DEA model used during the second regulation period, the input parameter is the sum of operational costs, straight-line depreciations and interruption costs. Other parameters are the value of delivered energy, total length of the network and the number of customers (see Equation 5.1) [Ho08].

$$DEA_i = \frac{u_1 \times energy_i + u_2 \times network_i + u_3 \times customers_i - u_0}{v_1 (OPEX_i + SLD_i + IC_i)} \qquad (5.1)$$

where

DEA_i	=	the DEA-score of company *i*
$energy_i$	=	value of delivered energy of company *i*
$network_i$	=	total network length of company *i*
$customers_i$	=	number of customers of company *i*
IC_i	=	interruption costs of company *i*
$OPEX_i$	=	controllable operational costs of company *i*
SLD_i	=	straight-line depreciations of company *i*
$u_{1..3}$	=	weight of output parameters
v_1	=	weight of input parameter
u_0	=	non-positive constraint defining the non-decreasing returns to scale

In addition to the DEA model, a parallel efficiency benchmarking based on the SFA method [SyBo06] was also introduced for the second regulation period [EMA07]. The parameters in the SFA model are the same as in the DEA model, except the network length in SFA is divided into underground cables and other network. DEA and SFA methods are used together, and the average of these two efficiency scores is calculated for each company.

5.1.2 Continuity of supply regulation

Continuity of supply or network reliability has several incentive mechanisms in the Finnish regulation model. Interruption costs affect in the input parameter of the efficiency benchmarking. In addition to this, actual interruption costs are compared with the reference level of interruption costs. The reference level of interruption costs is determined as the average of the interruption costs from 2005-2008 [EMA07]. Half of the difference between actual interruption costs and the reference level adjust the allowed incomes, and the effect of the adjustment is limited to 10 % of the allowed income (see Figure 5.2).

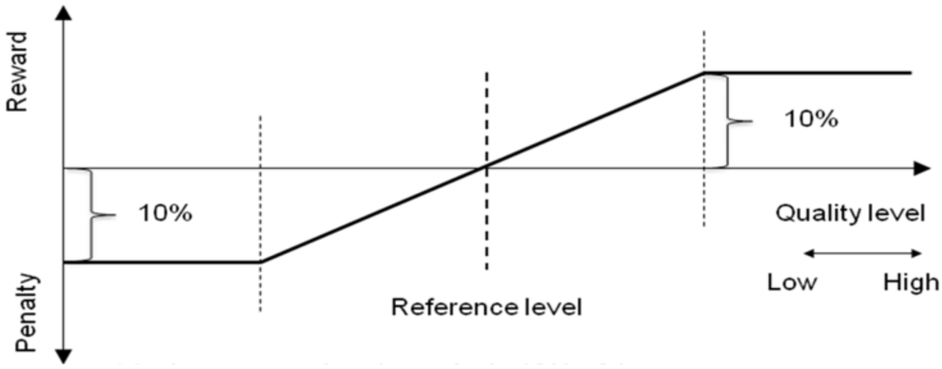


Figure 5.2: Power quality incentive applied in Finnish regulation [Ki08].

According to [Ki08], by adjusting the allowed income by the half of the difference between actual interruption costs and the reference level of interruption costs, the risk of interruptions is divided between the DSO and its customers. On the other hand, both the DSO and its customers will benefit from improved reliability.

The calculation of interruption costs involves the collection of different interruption indices (e.g. [EMA07], [P3], [P5]). Since the interruption indices are not divided into customer groups, the customer group-specific reliability worth parameters cannot be used. Hence, to cover all the customer groups, the reliability worth parameters are combined [HoTa07] as one parameter per interruption type (see Table 5.1).

Table 5.1: Reliability worth parameters used by the Finnish regulator [EMA07].

Unexpected interruption		Planned interruption		High-speed autoreclosing	Delayed autoreclosing
€/kW	€/kWh	€/kW	€/kWh	€/kW	€/kW
1,1	11,0	0,5	6,8	0,55	1,1

The actual interruption costs are calculated by multiplying the annual interruption indices (number and duration of interruptions) with the corresponding reliability worth parameter. The interruption costs of different interruption types are then summed to gather the overall interruption costs (see Equation 5.2) [EMA07].

$$IC_t = \begin{pmatrix} ID_{unex,t} \times c_{E,unex} + IN_{unex,t} \times c_{P,unex} + \\ ID_{plan,t} \times c_{E,plan} + IN_{plan,t} \times c_{P,plan} + \\ DAR_t \times c_{DAR} + HSAR_t \times c_{HSAR} \end{pmatrix} \times \left(\frac{W_t}{T_t} \right) \tag{5.2}$$

where

IC_t = Interruption costs in year t
$ID_{unex,t}$ = Duration of unexpected interruptions, weighted by annual energy, in year t
$c_{E,unex}$ = Reliability worth for unexpected interruptions [€/kWh]
$IN_{unex,t}$ = Number of unexpected interruptions, weighted by annual energy, in year t
$c_{P,unex}$ = Reliability worth for unexpected interruptions [€/kW]

$ID_{plan,t}$	=	Duration of planned interruptions, weighted by annual energy, in year *t*
$c_{E,plan}$	=	Reliability worth for planned interruptions [€/kWh]
$IN_{plan,t}$	=	Number of planned interruptions, weighted by annual energy, in year *t*
$c_{P,plan}$	=	Reliability worth for planned interruptions [€/kW]
DAR_t	=	Number of delayed auto-reclosings, weighted by annual energy, in year *t*
c_{DAR}	=	Reliability worth for delayed auto-reclosings [€/kW]
$HSAR_t$	=	Number of high-speed auto-reclosings, weighted by annual energy, in year *t*
c_{HSAR}	=	Reliability worth for high-speed auto-reclosings [€/kW]
W_t	=	Total annual energy transferred in DSO's network in year *t*
T_t	=	Number of hours on year *t*

The interruption costs for the reference years are calculated similarly to gather the reference level of interruption costs as an average of these. The interruption costs are adjusted annually by the change in Building Cost Index (BCI).

5.2 Directing signals of the continuity of supply regulation in Finland

Major changes in the regulation model of the second period, compared with the one used in the first period, are related to the role of the power quality and efficiency benchmarking, while the basic principles, such as determining the allowed profit, remain the same [Ho08]. Continuity of supply (i.e. interruption costs) has a sort of duplicate role: it affects the allowed profit directly, and it is a part of the input parameter in efficiency benchmarking. Hence, it is obvious that continuity of supply will direct the behaviour of the network companies.

On the contrary, straight-line depreciations and operational costs are also parts of the input parameters in the efficiency benchmarking. Therefore, efficiency benchmarking provides companies with incentives to optimise their total costs, and not only operational cots. However, the efficiency requirement focuses only on the operational costs. Thus, the directing signals of the regulation are somewhat unclear, since the efficiency of the total costs are benchmarked, but the decreasing requirement focuses on the operational costs only [Ho08].

New reliability indices that are used in the calculation of interruption costs have been collected since 2005. Therefore, the period for calculating the reference value for interruption costs was very short. However, interruptions are random events, and there are significant annual variations in the occurrence of them. A short reference period may contain a remarkable amount of random errors, and does not necessarily reflect the typical reliability level of the company.

Incentive regulation often tends to encourage both cost and quality reductions unless the quality issue is specifically addressed. In the regulatory model with efficiency requirements directed towards the operational costs, there is also a concealed danger of neglecting e.g.

network maintenance. While savings in operational costs affect the profit instantly, the omission of maintenance probably affects with several years' delay.

5.3 Reference to related own publications

Chapter 5 presents a summary of the regulation model in use in Finland on 2008-2011. Reliability regulation is discussed in [P2] and [P5]. [P2] presents the definition of reliability worth parameters for regulation purposes and the results of reliability calculations. It introduces shortly the Finnish regulation model. [P2] also presents a proposed equation, similar to Equation 5.2, to calculate the interruption costs for regulation. These formulae implement the Combined Cost Model as presented in Chapter 3.3.3. [P5] discusses the reliability regulation issues in Nordic countries. It also introduces the reliability indices that the Finnish regulator has decided to collect and presents different methods for DSOs to formulate these indices.

However, the regulation model that was in use at the time the publications were written was somewhat different. Thus, the regulation model in use at present is depicted in chapter 5. On the other hand, the work conducted for this thesis has partly influenced the regulation model to develop into its current form. The reliability worth study presented in [P6] and [P7] has been the basis for the reliability worth estimates used in the current regulation model. The reliability indices and interruption statistics presented in [P3], [P4] and [P5] have enabled the acquiring of more accurate reliability data and the use of interruption costs in the regulation.

6 CONCLUSIONS

Severe weather conditions will become more common due to the climate change. Concurrently, customer expectations on reliable electricity distribution are increasing. This presents a need for the utilisation of more reliable, and usually also more expensive, network designs. At the same time, the regulatory model involves an obligation to decrease costs and the DSOs' shareholders demand higher profits. The general principle of network design is minimising total societal costs, i.e. the sum of DSO costs and customer interruption costs, of the electricity distribution during the lifetime of the distribution network. Solving this equation is a challenging task for the DSOs, especially when reliable and cost-efficient electricity distribution is a more vital element in society than ever. *This thesis presents an overview of different aspects associated with this minimising task.*

Modern data systems enable the gathering of more accurate data about faults and interruptions. Therefore, it is possible to share this data also to customers and use it in the network business regulation. In addition to this, fault and interruption statistics also form a basis for the component modeling and reliability-based network analysis. *One contribution of this thesis is the development of modelling and compilation of the interruption statistics taking into account the needs of different interest groups, i.e. the DSO, its customers and the regulator.*

Renewing interruption statistics and more comprehensive use of reliability data also present new requirements for the data systems of the distribution companies. It is not self-evident that all distribution companies have sufficient tools for the compilation of the obligatory fault and interruption statistics. DSOs are in different situation when compared to each other. Some companies are able to meet the new requirements immediately while others still have some work to do with their data systems. From the viewpoint of the less progressive companies, *the development of the tools for gathering the data for interruption statistics (i.e. Interruption Manager software application) has been one contribution of this thesis.*

This thesis presents the results of a reliability worth study, the definition reliability worth estimates and the modelling of interruption costs applicable both in network planning and regulation purposes. In the context of reliability worth studies in the area of regulated electricity distribution business, the respondents' awareness of the purpose of use of the results may direct their responses, i.e. they may resort to so called strategic responses. There have also been arguments that averaged or aggregated values were not suitable for reliability worth estimate calculation as the distribution of the responses deviates from normal distribution. It is said that in these cases median values should be used. Traditionally the averaged or aggregated values have been used, and, on the other hand, the right type of elimination method can also improve the situation both in the case of strategic responses and skewed distribution of the responses.

In general, a questionnaire as a reliability worth study method is widely used. Despite that, the methods to eliminate the strategic responses are not so widely discussed. However, some kind of filtering may have been done to the responses. In reliability worth study, the selection of respondents, despite being randomly chosen, may also affect the results. Probably only the most aware individuals will respond to the questionnaire which may result in the data being biased. In the utilisation of reliability estimates, it should be considered which respondents are the most deviating and why. As suggested in [P7], individual reliability worth estimates could be used for these respondents and they could thus be managed separately in reliability analysis. In this field further research should also be carried out, and it should be assessed why some respondents have such deviating responses.

There are various purposes of use for the reliability worth estimates. Among other contributions, *this thesis presents analysis of the use of interruption costs in distribution business regulation.* If the directing signals of the regulation, especially the effects on reliability, are not analysed with a whole understanding, regulation may have unintended incentives for network operation, maintenance and investments. On the other hand, reliability must be regulated. Otherwise, there is a temptation to e.g. neglect maintenance. Neglecting maintenance would probably not have serious immediate effects, but, would damage reliability in the long run. The DSOs should also be aware of and understand the desired directing signals, but perhaps some DSOs respond to them with a few years' delay.

In this thesis, *one of the contributions has been the utilisation of interruption costs in strategic network planning which leads to network solutions that assure a reasonable level of reliability in normal operation conditions.* These network solutions do not, however, prevent large blackouts experienced in the cases of natural catastrophes. Of course, the effects of these have decreased, but as long as the network includes overhead lines it is vulnerable to natural phenomena. For example, some further research and development should be carried out to model the possible effects of major blackouts in reliability analysis.

On the other hand, reliability is affected not only by distribution networks but also by generation and transmission. Reliability analysis made in this thesis assumes that generation and transmission are always available. In the future, this may not be self-evident as intermittent production such as wind turbines become more common and also the market design should be able to respond to varying capacity needs. On the contrary, small scale production can provide possibilities to enhance supply availability in cases of faults in a distribution network.

Customer expectations on electricity supply reliability are reflected in the reliability worth studies. The latest Finnish study reveals that the reliability worth estimates were doubled during the past ten years. Concurrently with increased customer expectations, electricity distribution regulation as well as adverse weather conditions that are becoming more common due to climate change make new network design alternatives attractive from the reliability point of view. Therefore, reliability-based network analysis should be included as one, important element in the distribution system planning. On the other hand, the reliability models are approximations of the real system behaviour. Therefore uncertainties are embedded in the reliability analysis and some extreme events may have such effects on the system that were not considered in the reliability analysis.

In addition to being the biggest investment ever for many DSOs, the utilisation of automatic meter reading provides an excellent opportunity to develop functions. With the help of real-time communication, network control can be expanded to also cover the low-voltage network [JäMä07]. Automatic meter reading also provides possibilities to share more accurate information to customers and to produce more detailed interruption statistics. Utilising automatic meter reading and constitution of smart grids offers challenging tasks also for research and development.

To summarise the most important contributions with scientific novelty value presented in this thesis:

- Definition of interruption statistics so that interruption data can better be utilised in network planning and regulation, and also shared to customers. This has included the definition of row-based data collection (e.g. [P3]) and energy-weighted indices (e.g. [P4] and [P5]).
- Development of tools for increasing the customers' awareness about electricity distribution interruptions. This thesis presents a demonstration of a web application for presenting interruption data to customers ([P1]). Today similar systems are widely utilised in distribution network companies.
- Development of methods for composing appropriate reliability worth estimates. This has included the implementation of reliability worth study (e.g. [P6]) and development methods for eliminating strategic responses so that individual deviating responses do not distort the estimates and analysis of the results ([P7]).
- Utilisation of the former results in distribution network life-cycle cost estimation. For this purpose, reliability worth estimates were processed into a suitable form to be used in reliability evaluation software, including the methods for the valuation of auto-reclosings ([P8]).
- Piecing together the entity associated with electricity distribution reliability assessment (see Figure 1.2).

The importance of reliable electricity supply will be emphasised more and more as society's dependence on electricity increases. The main target of this thesis was answering the question: Can interruption statistics be compiled, and electricity distribution reliability worth modelled, so that the methods direct electricity distribution business socio-economically most cost-efficiently? Due to the wide diversity of DSOs and aspects associated with the issue it is a challenging task, but if reliability regulation, including gathering sufficient statistics and reliability worth evaluation, is properly constructed it will provide incentives that lead the network designs, and the business in general, towards a socio-economical optimum.

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