KTH Electrical Engineering

Maintenance Optimization for Power Distribution Systems

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Abstract

Maximum asset performance is one of the major goals for electric power distribution system operators (DSOs). To reach this goal minimal life cycle cost and maintenance optimization become crucial while meeting demands from customers and regulators. One of the fundamental objectives is therefore to relate maintenance and reliability in an efficient and effective way. Furthermore, this necessitates the determination of the optimal balance between preventive and corrective maintenance, which is the main problem addressed in the thesis.

The balance between preventive and corrective maintenance is approached as a multiobjective optimization problem, with the customer interruption costs on one hand and the maintenance budget of the DSO on the other. Solutions are obtained with meta-heuristics, developed for the specific problem, as well as with an Evolutionary Particle Swarm Optimization algorithm. The methods deliver a Pareto border, a set of several solutions, which the operator can choose between, depending on preferences. The optimization is built on component reliability importance indices, developed specifically for power systems. One vital aspect of the indices is that they work with several supply and load points simultaneously, addressing the multistate-reliability of power systems. For the computation of the indices both analytical and simulation based techniques are used. The indices constitute the connection between component reliability performance and system performance and so enable the maintenance optimization.

The developed methods have been tested and improved in two case studies, based on real systems and data, proving the methods' usefulness and showing that they are ready to be applied to power distribution systems. It is in addition noted that the methods could, with some modifications, be applied to other types of infrastructures. However, in order to perform the optimization, a reliability model of the studied power system is required, as well as estimates on effects of maintenance actions (changes in failure rate) and their related costs. Given this, a generally decreased level of total maintenance cost and a better system reliability performance can be given to the DSO and customers respectively. This is achieved by focusing the preventive maintenance to components with a high potential for improvement from system perspective.

Key words:
Reliability Importance Index, Multiobjective Optimization, Maintenance Optimization, Asset Management, Customer Interruption Cost, Reliability Centred Maintenance (RCM), Reliability Centered Asset Management (RCAM), Monte Carlo Simulation, Evolutionary Particle Swarm Optimization.

Preface

This thesis is the summary of the PhD project on "Development of optimization methods for maintenance considering reliability and costs for electric power networks" at the department of Electromagnetic Engineering, School of Electrical Engineering, Royal Institute of Technology.

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List of Papers

I   Monetary Importance of Component Reliability in Electrical Networks for Maintenance Optimization. Patrik Hilber and Lina Bertling. Proceedings 8th International Conference on Probabilistic Methods Applied to Power Systems, PMAPS 2004, Ames, USA.

II Optimizing the replacement of overhead lines in rural distribution systems with respect to reliability and customer value. Patrik Hilber, Bengt Hällgren and Lina Bertling. Proceedings 18th International Conference & Exhibition on Electricity Distribution, CIRED 2005, Turin, Italy.

III A Method for Extracting Reliability Importance Indices from Reliability Simulations of Electrical Networks. Patrik Hilber and Lina Bertling. Proceedings 15th Power Systems Computation Conference, PSCC 2005, Liege, Belgium.

IV Effects of Correlation between Failures and Power Consumption on Customer Interruption Cost. Patrik Hilber, Lina Bertling and Bengt Hällgren. Proceedings 9th International Conference on Probabilistic Methods Applied to Power Systems, PMAPS 2006, Stockholm, Sweden.

V   Multiobjective Optimization Applied to Maintenance Policy for Electrical Networks. Patrik Hilber, Vladimiro Miranda, Manuel Matos and Lina Bertling. IEEE Transactions on Power Systems, Volume 22, No. 4, November 2007.

VI Component Reliability Importance Indices for Electrical Networks. Patrik Hilber and Lina Bertling. Proceedings 8th International Power Engineering Conference, IPEC 2007, Singapore.

VII Multiobjective Maintenance Policy for a Distribution System an Application Study. Patrik Hilber and Lina Bertling. Accepted to the 10th International Conference on Probabilistic Methods Applied to Power Systems, PMAPS 2008, Puerto Rico.

Contents

To my significantly bigger Family

1 Introduction

1.1 Background

Maximum asset performance is one of the major goals for power distribution system managers. To reach this goal maintenance optimization becomes crucial, aiming at the right level of reliability, maintaining the system at a low total cost while meeting demands from customers and regulators. One of the fundamental objectives is consequently to relate maintenance and reliability in an efficient and effective way and further to identify the optimal balance between preventive and corrective maintenance.

The concept of cost efficient maintenance achieved through reliability analysis, for power system networks, was presented already in the 1960's, when reliability models solved with computers were developed, see [1] and [2]. However, new tools and new demands on the electric power systems demand further development of methods, such as maintenance optimization routines. Methods to support cost-effective maintenance policies have been developed for electric power systems as presented in [3], which presents a quantitative method for developing Reliability Centered Maintenance (RCM) plans. The resulting technique involves the comparison of different policies for maintenance and therefore the results provide not the optimal solution but the best solution from the selected policies. A direct extension of the method developed is presented within this thesis, which describes an approach to maintenance optimization that delivers one optimal policy. The optimization is built on methods for component reliability importance methods presented in [4].

The question of finding an optimal maintenance solution is not new, e.g. see [5] and [6]. However, the relation between maintenance, reliability and costs is not completely solved and requirements from owners, authorities and customers, create needs and incentives for still newer methods to handle the maintenance in an effective and efficient way. It becomes important to identify a connection between component and system reliability performance where the system performance is measured for several load and supply points at a time.

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Furthermore, the reregulation has increased the incentives to study the power system performance from a multiobjective approach where the customer's perspective is on one hand and the total maintenance cost of the network on the other. This gives the decision maker a range of solutions to choose between.

1.2 Related research at the School of Electrical Engineering, KTH

The School of Electrical Engineering, KTH, has built up specialist knowledge in the field of reliability modeling of power distribution systems. This has for example resulted in a number of published doctoral theses [3], [7], [8] and [9]. These PhD projects had different inputs, for the evaluation of the system reliability; preventive maintenance of components to reduce system failures, automation of the system to reduce outage times due to component failures, development of new structures in the power system and Monte Carlo simulations. Also related to power system reliability is the research at the department in the fields of diagnostics and condition assessment of power cables [10], [11], [12] and [13].

The present research project together with a project on component reliability modeling, with specific reference to maintenance [14], constitutes a logical continuation of the work. The vision is to establish a comprehensive program in power system asset management, with a special focus on the effects of maintenance on reliability, at both component and system level. A description of the research program on reliability centered asset management (RCAM) is presented in [15]. Currently six PhD projects are in progress within the RCAM program, with a number of publications on the topic of reliability calculations for power systems, e.g. [16], [17], [18], [19] and [20].

1.3 Project objective

The objective of this PhD project has been to develop a useful optimization method for cost-efficient maintenance plans for power distribution systems. A method that can be used as decision support in the search for the right level of reliability, balancing preventive and corrective maintenance. Comprehensive case studies, mainly for distribution systems, using the developed methods have been crucial in achieving the objective.

1.4 Scientific contribution

The main scientific contributions of this thesis is a maintenance optimization framework, presented in paper V, and methods for component reliability importance indices, specifically designed for electric distribution systems, summarized in paper VI.

The maintenance optimization framework, which is built on the component reliability importance indices, is based on the connection between total system reliability performance and the individual components. The developed framework has been applied and proved usable in two different case studies, one in the Stockholm city area (the Birka system) and one in and around the town of Kristinehamn. The first case study is based on the network model and

reliability tools presented in [3]. The second case study was performed in cooperation with Bengt Hällgren, Karlstad University, [21], within the same research program, see paper II and IV. In paper V Patrik Hilber is responsible for the proposed method and the AGEBOM algorithm and some minor modifications to the EPSO algorithm, which is a method developed at INESC Porto, Portugal.

Beside the developed methods a correlation between failures and power consumption is showed in paper IV. One effect of this correlation is that with average values for power consumptions and failure rate the energy not delivered and customer interruption costs are underestimated with approximately 7%, for the studied case.

1.5   Thesis outline

This thesis is organized as an introduction and extended summary of papers I-VII. The next chapter (2) constitutes an introduction to the topic of the thesis, while the two following chapters (3 and 4) constitute the actual summary of paper I-VII. The outline of the thesis is as follows:

Chapter 2 introduces asset management and provides a framework for maintenance optimization. This is performed through a survey of a number of recently published papers. Furthermore, the concept of maintenance optimization of electric power systems is introduced. After a literature review, different kinds of maintenance optimization methods are identified and the maintenance situation of power distribution systems is discussed. The chapter ends by a discussion on some aspects of reliability modeling.

Chapter 3 introduces reliability importance indices and contains a presentation of the proposed importance indices, specifically developed for power systems with results from one case study.

Chapter 4 presents the optimization framework and results from one case study.

Chapter 5 concludes the thesis and outlines ideas for future work.

Reading guidelines:
For those familiar with the topic of the thesis, paper VI followed by paper V is recommended reading. The reader with a background from either power systems or reliability modeling is recommended to start with Chapter 2-5 followed by selected papers of interest.

2 Introduction to asset management of electric power networks

Asset management and maintenance optimization are two related topics. Ultimately maintenance optimization should be viewed as a toolset within the wider concept of asset management. Hence the definition of asset management becomes important. This chapter is mainly an introduction to asset management and the related topic of maintenance optimization and includes some more information on the more specific topic of maintenance of electric power systems. The chapter is ended with a presentation of reliability modeling and analysis of the most common assumptions.

2.1 Asset management

In a company there are several things that can be called an asset, for example:
- Capital
- Equipment and premises (physical assets)
- Employees
- Customer base
- Corporate structure
- Brands

Previous work has shown that asset management literature in the electric power sphere mainly deals with physical assets with a focus towards heavy equipment [4]. This doesn't exclude other assets completely from asset management considerations. Other assets can for example be involved as costs and/or constraints in the work with asset management. The primary assets in this thesis are assumed to be the physical ones. Usually these physical assets have an expected life of more than one year (typical 20-50 years for electric power equipment) and/or represent a big turnover [22]. By a review of [22]-[28], presented in detail in [4], the following definition is established:

If the organization is a company, the goal is maximum profit at an acceptable risk, and asset management becomes a method to achieve this by handling the physical assets.

A number of actions are identified that are closely associated with asset management:

- Acquire
- Maintain
- Dispose
- Replace
- Redesign/Rebuild

These actions are what the asset manager can use to align the assets with the goal fulfillment. This task is not easy; where and when should the actions take place and which of the actions is the best one for every specific component? All the actions are related to each other, for example a replacement consists of a disposal and an acquisition. In the acquisition phase redesign is considered and afterwards the equipment has to be maintained. The studied publications are in general focused on maintenance and/or replacement (intervals). However, some publications bring up a discussion about redesign. In those publications it is more or less directly stated that redesign is always an option to consider. Since it is hard to form any universal rules for redesign it usually stops here (sometimes with examples on redesign).

Risk, here defined as probability for failure multiplied with consequences, is one important aspect of asset management. Asset management methods are often referred to as the way to keep the risk at a constant level while downsizing cost (maximizing profit). This is achieved by a better utilization of the available asset i.e. by performing the best actions at the best possible time. In order to do this, different methods and systems are used.

Despite not much written about the concept of asset management in the studied publications, the concept can be implicitly derived from them, and that is to choose the right profit-risk level. To choose the right level of risk and profit is especially
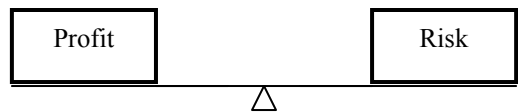
Figure 2.1. Profit versus risk.

significant as a second phase, after a cost minimization at constant risk. Figure 2.1 illustrates the classical problem, profit versus risk, which has to be considered.

By the identification of the goal of asset management; "To handle physical assets in an optimal way in order to fulfill an organizations goal whilst considering risk." and by a brief survey of a number of recently published papers, we have put maintenance in its right context for this thesis. A context that clarifies the need of maintenance optimization and points out that all aspects of asset management has to be considered in the optimization.

2.2 Maintenance optimization, introduction

Maintenance optimization is here defined as a method aimed at finding the optimal balance between preventive and corrective maintenance with respect to objectives. The objectives are assumed to be revenue and satisfied customers. Satisfied customers is important, if not, they will potentially buy their energy from other companies and/or cause increased regulation. The definition of maintenance optimization is in accordance with the definition of asset management. A good maintenance optimization supports asset management.

From a reliability viewpoint the reason for maintenance is quite clear, that is to increase the reliability by means of improving apparatus. Another aspect of maintenance is to reduce risk, usually by inspection, for example; if no cracks are found we can assume that the inspected item will last for some time, in the case of a crack, maintenance actions will be taken. The risk reducing approach can be said to be a subgroup of the main objective (increase reliability), since it is aimed at identifying substandard and/or hazardous equipment. Nevertheless, there are other objectives of maintenance such as appearance and worth of the maintained equipment. Appearance and worth does not necessarily correlate with reliability. Another aspect of maintenance is to make use of existing labor. However, this thesis mainly deals with the reliability objectives, while not diminishing the other aspects of maintenance.

Maintenance optimization can be tracked back to the 1950's when preventive maintenance plans became a popular and a growing concept and to the 1960's when operation research methods was applied to preventive maintenance plans for the first time [29]. In the 1970's condition monitoring improved the effect of the maintenance. With the introduction of cheaper and more available computers in the 1980's, maintenance optimization became more widespread [29]. In the 1990's Reliability Centred Maintenance (RCM, which was originally created in the 1960's for the aircraft industry), became a method for maintenance planning of electric power networks [30].

A description and overview of the current situation of general maintenance optimization is found in [31], [32], and [33]. In [34] a general model for quantitative maintenance optimization is proposed, which is compared to the qualitative approach of RCM. A common problem discussed in the publications above is the gap between research efforts and practitioners of maintenance, where the research is focused on advanced mathematical models while somewhat generalized the most advanced practitioners utilize RCM. However, there are efforts made trying to connect these two worlds, for example [35].

Maintenance optimization of electric power networks, which is the ultimate objective of this thesis, is not a very common topic in the literature. However, there exist a number of publications for example [6], [36], [37], [38], and [39]. In [40] additional publications on maintenance optimization can be found. Paper [6] utilizes the Total Test Time and the Weibull (maximum likelihood fitting of Weibull distributions) methodologies in order to establish failure rates for maintenance interval optimization. A method for prioritization of maintenance activities is presented in [36] the approach is best performance per monetary unit. Performance is measured with an index that is a weighted combination of traditional power reliability indices (SAIDI, SAIFI, etc.). In [37] Petri nets are used for maintenance

optimization of the system operator's costs (cost minimization). In [38] genetic algorithms are used for power system reliability optimization. Multistate systems are used to capture the fact that power systems in general have different task performance levels. A wood pole replacement model with respect to Life Cycle Costs (LCC) is presented in [39].

The above presented methods all answer specific problems of maintenance, in general they focus on components (mostly single or a single sets of components) which are optimized for availability and/or cost. Hence, with the exception of [36] that minimize a weighted reliability index, the methods do not have the focus of total system objective (revenue and customer utility). One of the major contributions of this thesis is to connect component reliability performance to the overall objectives in order to establish the right level of maintenance for every component.

2.3 Classification of maintenance optimization

There are many approaches to maintenance optimization. This subchapter indicates on how the methods can be classified, depending on their objective, time horizon, decision factors and number of components. In [41] references to example methods can be found.

The maintenance optimization is usually performed with one of the objectives presented in Table 2.1. The first two objectives are related to each others in that they utilize constraints regarding the other methods objective (duality). The last incorporates the two previous into one objective.

TABLE 2.1 OBJECTIVE FOR MAINTENANCE OPTIMIZATION

Objective	Description
Reliability	Maximize reliability under given constraints (e.g. cost constraints).
Minimal cost	Minimize cost given constraints (on reliability and/or maintenance requirements).
Minimal total cost	Minimize total cost (of interruptions and maintenance).

The time horizon, for the maintenance optimization, can be divided into three major concepts. The first is performed for one time period as the time horizon. This horizon can be interpreted in two different ways, either as a focus on the coming time period or that the coming time period represents an expected average for several periods. The second concept involves multiple time periods and often uses the net present value, costs of all actions and effects are recalculated to the present value. Net present value approaches do usually have a fixed end point that the analysis is not performed beyond (for example 30 years). The third concept suggests a plan for a relatively long time but is built to adapt to changes due to events in the maintained system. See Table 2.2.

TABLE 2.2 TIME HORIZON FOR MAINTENANCE OPTIMIZATION

Time	Description
One time period	Optimize for an average or next time period (e.g. 1 year).
Multiple time periods	Optimize for a distant time period (for power systems typically 30 years). Often involves lifecycle cost planning.
Adaptive	Methods that based on data revealed during the maintenance process adjust the maintenance.

A number of decision factors for the maintenance optimization are presented in Table 2.3. Such list will never be complete but the most common factors are captured. The decision factors depends on data available and what aspects of the organizations activities that affects the objective.

TABLE 2.3. DECISION FACTORS FOR MAINTENANCE OPTIMIZATION

Decision factor	Description
Interval	Optimal maintenance and/or replacement and/or inspection interval, for example based on failure statistics.
Delay-time	Related to "Interval" but based on the time from a measurable indication of failure to actual failure.
Spare part	Identifies the allocation and number of spare parts.
Opportunity	For equipment that is costly to interrupt or hard to access, opportunity optimization produces schedules for what should be done during planned and/or unplanned interruptions/access to the equipment.
Manpower	Identifies optimal maintenance work force manning, for example how a number of utilities should be manned.
Redundancy	Identifies where it is most profitable (from a reliability view point) to place redundant components.

The number of components that are included in optimization models vary. In this classification the optimization models are divided into two groups, single- and multi-component. The single-component models usually work with one important (expensive) component such as a power generator or with a generic component such as a light bulb. The multi-component models works with several components typically in a network structure with various degrees of redundancy. It is not always a clear distinction between the single- and multi-component models, especially for advanced components, such as the generator, since subcomponents usually are modeled to a certain extent. In Table 2.4 the two groups are presented.

TABLE 2.4. NUMBER OF COMPONENTS

Number of components	Description
Single-component	Solves the optimal maintenance and/or replacement and/or inspection interval for an individual component. In general this is the most frequently used maintenance optimization method.
Multi-component	Solves the optimal maintenance and/or replacement and/or inspection interval for a number of components. These methods can also be aimed at identification of profitable switches of components.

In a model with maximal realism, all of the above mentioned decision factors and objectives would be included. However, in reality most optimization methods involve one or a few of the decision factors and hence derive a sub optimized solution to the question of an optimal maintenance. Nevertheless, this is quite reasonable since it is extremely difficult and complicated to build and solve an optimization model that includes all the factors. Hence it becomes important to choose what should be included within an optimization framework, in order to get as close as possible to the "true" optimum.

2.4   Maintenance of power distribution systems

Maintenance is crucial for distribution system operators both when acquiring new assets (apparatus) and when trying to utilize already existing assets in the best possible manner. The cost of maintenance and consequences of failures can be significantly higher than the cost of the equipment. Hence, it becomes important to study maintenance and its effects in all stages of the lifetime of the asset. In this subchapter the maintenance of electric power networks is introduced. Maintenance actions are performed on the basis of components degradation and potential failures' probabilities, consequences and characteristics. The failures can be grouped into the two following categories [4]:
1. Reoccurring failures (i.e. to some extent possible to predict).
2. Random failures.

Failures can further be divided into the following two groups:
A. Failures with incubation time (possible to detect before they happen).
B. Instant failures (without incubation time).

These two forms of groupings gives us in total four types of component failures, which can be used in the identification of proper maintenance actions. Two important keywords are *predict* and *detect*. Categories 1 and 2 address if it is possible to *predict* a failure, with statistics, e.g. the equipment may for example be close to outworn after a number of cycles or time. Categories A and B address if it is possible to *detect* failures before they occur, this might be accomplished with thermography, dielectric response measuring or vibration monitoring.

Random failures, type 2, may be addressed with diagnostics. But diagnostics might not be suitable for failures that occur instantaneously, type B. However, type B component failures might be prevented by early replacement based on statistics. Components with type 2B failures, i.e. random failures that go directly from functioning to failure, are hard to maintain before a failure occur and hence either has to be handled with corrective maintenance or system redesign. Important to note is that there is no sharp line between these four types of failures and that a specific component can have failures within one or more of the groups. Furthermore, there might be methods to move a type of failure from one category to another, for example by improved failure statistics. A specific failure might belong to type 2B, but with better statistics and new diagnostic methods the failure might potentially be retyped to 1A. It is, moreover, important to note that it is up to the maintenance organization to decide upon whether diagnosis and/or preventive maintenance actions shall be performed or not, it might

for example be better to let the failure occur and then perform corrective maintenance than to put resources on condition monitoring.

Corrective and preventive maintenance are discussed below, followed by a brief overview of the strategies within electric power networks, concerning these two forms of maintenance. Finally a number of problems regarding maintenance of electric power networks are outlined.

2.4.1 Corrective maintenance

Corrective maintenance is performed after fault recognition and is intended to put the component in a state in which it can perform a required function [42]. The component is used until it fails. Corrective maintenance might be considered as a last resort and might intuitively be considered as a failure of the maintenance organization performing it, but that is not necessary the case. Corrective maintenance has its place in a sound maintenance strategy at least in the planning stage (for example in "what happens if …"-scenarios). Corrective maintenance might be the right approach for a component group given that resources are focused on other, possibly more important, assets. For equipment with random occurring instant failures corrective maintenance might be the only option. As mentioned above one might consider redesign of the system for these kinds of failures, but still it is quite likely that these failures might be worth "living with" while focusing on other areas with a better goal fulfillment per monetary unit.

2.4.2 Preventive maintenance

The concept of preventive maintenance is to reduce failure probabilities by maintenance before failure or significant degradation has occurred [42]. This often translates into trying to avoid costs of corrective maintenance and other costs that belong to unexpected failures. Preventive maintenance can be divided into the following groups:

- Periodical maintenance
- Condition based maintenance

Periodical maintenance is as the name inclines performed at regular intervals (not limited to time). This is a good strategy in the case of a well identified ageing process for the component. The time intervals between the maintenance should be based on the expected time to failure with shorter intervals for the maintenance, than for the expected time to failure. Usually the periodic maintenance is based on time intervals from the manufacturer's specifications or company policies. By generalizing it can be stated that the manufacturer is more interested in that the product does not fail during the warranty time than in the maintenance organization's costs. (This can however be addressed with techniques such as Life Cycle Cost analysis in the procurement phase of equipment.) The company policies seldom consider different makes, usage and environment. A potential risk lies within the periodical maintenance if it is performed at these generalized time intervals. To maintain a component unnecessarily often introduces higher maintenance costs and risks for faults introduced by the maintenance activity.[43]

Conditioned based maintenance is performed based on an estimate of the components condition. One of the simpler forms of condition based maintenance is to prolong the first service interval of a periodical maintenance routine, this is based on the assumption that new equipment is in better condition compared to older. Examples of more advanced methods are methods based on measurements (e.g. diagnostics and inspections). Methods based on measurements presents a vide variety of methods, partly depending on the component studied.

When considering preventive maintenance actions and specifically replacement actions the cost of the action might seem high compared to the benefits of the replacement. But under certain circumstances the cost of doing maintenance earlier than necessary can be considered to correspond to the depreciation from the time of maintenance to the point in time considered to necessitate the maintenance activity.

2.4.3 Maintenance strategies in electric power systems

The reregulation has led the distribution system operators to center their attention towards profit optimization. That is a shift from an engineering era, focusing on reliability and "good technical solutions", to a more business and profit orientated regime. This is illustrated with a study performed by Cigré [44] in the late 1990's for circuit breakers, see Fig 2.2. It seems like periodical maintenance is losing ground to condition based maintenance and RCM approaches. This is further illustrated with the distribution of maintenance activities around year 1990 for a large Swedish power company with: 5% corrective maintenance, 90% periodical maintenance, and 5% condition based maintenance, [45]. All of the values presented in this subchapter depend on every company's definition of the maintenance strategies, nevertheless it is possible to identify the trend.
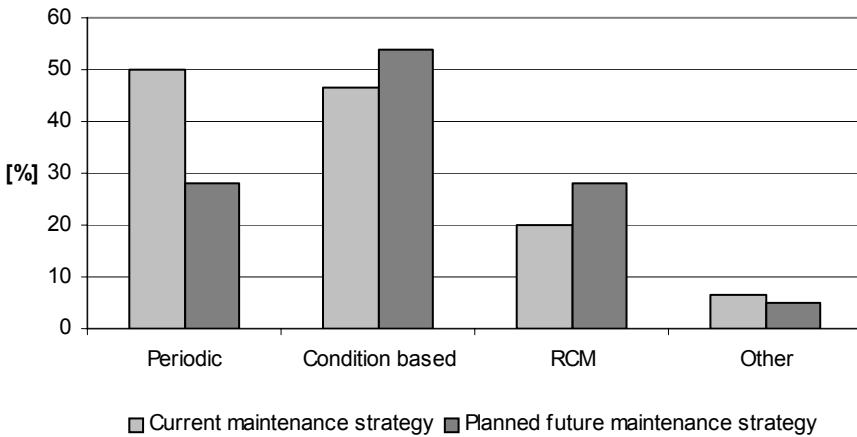

Figure 2.2. Current and planned maintenance strategies for circuit breakers, late 1990's [44].

2.4.4 Common maintenance problems

Some common problems for electric power networks are identified in [43]. Many of these problems have two sides, i.e. it is important to balance between the problem and its solution, which might be expensive and/or include other drawbacks. Below are the problems presented in bullet form:

- Failures are often not analyzed to the extent that similar future failures can be prevented.
- Effective maintenance actions are made but without structure and clear relevance to organization objectives.
- Maintenance induced failures, maintenance is not failure free.
- Periodical preventive maintenance is performed unnecessarily often; maintenance is performed towards technical goals without economical considerations.
- Non-existent reasons for maintenance actions, it is crucial to know why the maintenance action is performed (what will be improved?). Without this knowledge it is hard to estimate the value of the maintenance action.
- Low visibility of maintenance strategy. If the effects of the maintenance activities not are clear for the organization it is hard to motivate the current strategy. (Note: this point is related to the previous bullet, but on a higher level.)
- Accepting manufacturer's recommendations without consideration of specific circumstances of the usage. Does the manufacturer's maintenance goal coincide with the user's?
- Resistance towards new equipment for diagnostics that could improve the maintenance actions impact on system reliability [45], [46]. It is however noteworthy that there is a risk with new equipment for diagnosis as well as with other maintenance actions, the introduced equipment might introduce new failures and will probably need maintenance itself.

For maintenance optimization the presented problems are crucial.

2.5 Reliability assessment techniques

Reliability is the ability to perform a required function under given conditions for a given time or time interval [42], often expressed as a probability. A term that is closely related to reliability is availability. Availability further includes the concepts of maintainability and the maintenance supportability [42] and is generally expressed as the ratio of available time (mean time to repair) divided by total time (mean time to repair plus mean time to failure). One of the fundaments of this thesis is the calculation of reliability and availability. Reliability calculation can be seen as a tool utilized in order to estimate the expected availability of systems as well as other system and/or component measures. Numerous books have been published on the topic and the author would like to specially emphasize on the following books:

- "System Reliability Theory: Models and Statistical Methods (2nd edition)" [47], is a book that deals with general reliability calculations and spans over a wide selection of reliability topics. This book is good for the understanding of general reliability

calculation. Since the book spans over a wide selection of topics it can be useful in a variety of circumstances, even so in calculations for electric power networks.

- "Maintenance, replacement and reliability" [48], is a compact book on general reliability with a focus on maintenance.
- "Reliability Modeling in Electrical Power Systems" [49] is one of the first books to address reliability theory for electric power systems.
- "Reliability evaluation of power systems" [50] provides an introduction to the field and can be considered as a fundament of the reliability evaluation of electric power systems.
- "Probability concepts in electric power systems" [51], is focused on the more theoretical aspects of probability within electric power systems. Furthermore it applies traditional component reliability importance indices to power systems.
- "Electric Power Distribution Reliability" [52] provides as the title indicates an introduction to the field of reliability calculations for power distribution systems. The book introduces the reader to both theoretical techniques as well as more practical issues like animals effect on electric power equipment. Furthermore the book contains economical calculation techniques for electric power systems.

This subchapter briefly addresses a number of reliability measures, both general and more specific for power systems. They are introduced in order to aid a reader, new to the topic, through the thesis. For more detailed analysis, the books mentioned above are recommended.

2.5.1 Measures

One of the most basic measures of reliability performance is the average unavailability, here defined as:

$$U = \frac{r}{1/\lambda + r} \tag{2.1}$$

Since $\lambda r \ll 1$, (2.1) is often approximated to:

$$U = \lambda r \tag{2.2}$$

where U is the unavailability, λ is the failure rate [f/yr] and r [yr/f] the repair time. U is without unit and is usually expressed either as a probability or in the form of hours per year.

More complex measures, developed for electric power network reliability performance are the following indices:

- System Average Interruption Frequency Index (SAIFI) [f/yr,cust]. Total number of customer interruptions per year divided by the total number of customers served.
- System Average Interruption Duration Index (SAIDI) [h/yr,cust]. Sum of customer interruption durations per year divided by the total number of customers.
- Customer Average Interruption Frequency Index (CAIFI) [f/yr,cust]. Total number of customer interruptions divided by total number of customers affected.

- Customer Average Interruption Duration Index (CAIDI) [h/f]. Sum of customer interruption durations per year divided by the total number of customer interruptions per year.
- Average Service Availability Index (ASAI). Customer hours of available service divided by total customer hours demanded.
- Average Energy Not Supplied (AENS) [kWh/yr,cust]. Total energy not supplied divided by total number of customers served.
- Expected Energy Not Supplied (EENS) [kWh/yr]. Total energy not supplied per year.

Formulas for calculation of these indices can be found in [53] and [50]. Note that the above presented indices can be calculated both analytically and with Monte Carlo simulations.

2.5.2 Reliability calculation techniques
There exist many methods to calculate the expected reliability of a network, examples of approaches are; Reliability block diagrams, Markov methods, Petri nets and Monte Carlo Simulations [47]. Below are an analytical reliability block diagram and a Monte Carlo Simulation approach discussed.

2.5.2.1 *Reliability block diagram (analytical modeling)*
One common approach to reliability modeling is the reliability block diagram here called the analytical approach. The analytical approach allows for repeatable results. However the below, in 2.6, mentioned approximations and simplifications are usually employed [35]. Example of a tool that applies analytical models is RADPOW [54].

RADPOW has been used for the case study performed in paper I. The tool utilizes a minimal cut set method on network models and is load point driven. For the load points the following indices are calculated; expected failure rate, average outage duration, annual expected outage time, expected average loss of energy and customer interruption cost. On system-level the indices presented in 2.5.1 are calculated.

2.5.2.2 *Monte Carlo Simulation*
In general, simulation techniques allows for a significantly easier implementation of complex connections and model details compared to the analytical approach [55]. One additional interesting output that usually is obtained from simulations is probability distributions of the results [9]. The probability distributions can be very useful in a risk assessment process.

Computation time is an often mentioned drawback of simulations, i.e. that simulations are costly in terms of computation time. There are techniques for reduction of calculation times without loss of precision, for example the event driven approach of paper III and different variance reduction techniques. Still simulations quite often turn out costly in terms of calculation time. Another issue regarding simulations is their repeatability and consistency. Rare events with high impact can have a huge effect on simulations. However, being aware of these issues regarding simulations, the benefits of simulations must be acknowledged. Simulation based calculations enables us to develop models with higher resolution for larger systems in a more straightforward manner compared to the analytical approach.

2.6 General simplifications and assumptions

In order to create manageable models, simplifications and assumptions often have to be made; the simpler model the easier calculations. Furthermore, assumptions are made when there is little knowledge about the reliability properties of the entity modeled. The modeler has to balance between calculation difficulties, knowledge about the entity and model realism. In this subchapter we study the most commonly performed simplifications in reliability modeling.

2.6.1 Independent probabilities

The assumption of independent failure probabilities and repair times for components is a common simplification in reliability modeling. It is a simplification with high impact on the model behavior. There are many examples where it might prove wrong to assume independence. For example:

- Protection device failure, e.g. relay activated breakers that does not operate when a failure has occurred, makes the failure propagate higher up in the system structure.
- Weather related failures, such as caused by storms and/or heavy snowfall. Since weather is generally affecting a whole area, all components within an area will be influenced.
- Rerouting of energy due to a failure, places a higher load on a "redundant" component, which in turn fails because of the higher load.

These examples highlights that it is important to scrutinize the assumption of independent failure probabilities for components. Nevertheless, having mentioned these counter examples of why an assumption of independent failure probabilities is imperfect, it has to be noted that this assumption leads to relatively simple reliability models.

One method to avoid the simplification of independencies within analytical calculations is to use Markov chains in the modeling; however this will in general limit the size of the modeled system. Within simulations dependencies are in general easier implemented, which promote the use of simulations. Within an analytical approach dependant probabilities can be incorporated by breaking up one case into more cases for example; a case could be broken up into normal, heavy snow, and stormy weather, and assigning proper probabilities and weighing these new cases according to how often they are expected to occur.

2.6.2 Exponential distribution for repair time and time to failure

Exponentially distributed time to failure and repair time are frequently used simplifications. The reasons for making these assumptions are many. One of the reasons is that the aging process of components involved in a system seldom is clear. However, even if the process is clear, there are still a couple of obstacles, for example; components in a system might work in different environments and they might be utilized differently. The result may appear as a virtually constant failure rate. A related problem is to keep track of the age for all components. Besides data assessment issues, ease of calculation is another motive for the assumptions, exponentially distributed failure and repair times result in constant failure and repair rates,

which is a property that makes the modeling easier. Easier modeling of individual components allows for analysis of bigger systems, with many components.

One effect of the assumption of exponential time to failure is that the failure rate becomes constant; leading many to assume that preventive maintenance becomes unnecessary. This is however not necessarily true. There is nothing that conditions that a maintenance action will leave the maintained component at the same level of constant failure rate as before the maintenance. That is, with a piecewise constant approach to failure and repair rates much of the reliability characteristics of the modeled entity can be captured. Furthermore a perceived constant level may only indicate that the preventive maintenance is performed in such an extent that any aging effects are drowned out by random failures.

It is furthermore interesting to note the occurrence of the exponential distribution in [4], for the Kristinehamn case study.

2.6.3 Two state model

The assumption of a two state model, usually that a component/system functions or not, is very common, and many reliability calculation methods are based on this assumption. A two state network is modeled as a system, components with serial and/or parallel couplings between two nodes, e.g. supply and load. These systems either functions or not, hence the name "two state model". The assumption has a significant impact on the reliability model; this might be especially true for systems that consist of components that are directly connected to each other such as electric power networks are. For example if a circuit breaker is short unable to open it surely does not function, but still has an impact on the system, i.e. by not being able to break the flow of energy. On component level the assumption of one failure mode can be defended by an additional assumption stating that there exists a fully functional automatic protection system (consisting of fuses, relay activated circuit breakers, etc…). However this assumption involves a quite significant number of components that almost certainly have their own failures and failure effects.

On a system level the assumption of a two state model becomes somewhat difficult to interpret for electric power networks with several supply and/or load points. The extreme situations are easily identified; the system is completely failed when no load points receives energy and fully functional when all load points are served from all supply points. However, the middle ground with a number of "broken" lines is not covered by the assumption of two states. The conclusion is that the two state model is quite limiting for power systems, but it can be used when studying smaller parts of the network, i.e. dividing the network into parts with one source and one sink (one supply point and one load point). The results from the smaller parts can then be combined into the whole network again for analysis of the whole structure. How to combine the smaller parts is not obvious and is addressed in Chapter 3, paper III and VI.

2.6.4 Failure effects and consequences

The simplification of failure effects is partly related to the previously discussed assumption of two state models. The failure effect is usually simplified to one average consequence per

component/load point failure. This despite that most equipment has several ways in which they can fail and that some equipment is prone to fail at heavy loads. For example in the calculation of not delivered energy an assumption of average energy consumption is frequently used, this might be somewhat erroneous when there is a relationship between failure rate and energy consumption, see paper IV.

3   Component reliability importance indices

Power distribution systems does in general have several states of functionality (e.g. several load points that can function separately), which makes it reasonable to model them as multi-state systems [38], i.e. systems that allow for several levels of function of for example availability. The component reliability importance indices presented in subchapter 3.1 are based on systems that are binary, i.e. either functioning or not (two states). This is an approach which proves ambiguous for networks with for example more than one load point, as for example shown in paper III, Table 3. One component might be crucial from the perspective of one load point while virtually unnecessary from another load point's perspective. This calls for an approach that takes the whole network's reliability performance into account in one measure and relates this measure to the individual component. The concept of the developed indices is to utilize customer interruption costs as a measure of system reliability performance.

Component reliability importance indices for power systems is identified as a topic of increasing interest to the research community. This can be seen in that most of the publications in the topic are relatively new (see references for this chapter). The increased interest is probably explained by the reregulation of the electricity market, resulting in a higher interest in good payoff of maintenance actions, and in increased possibilities to perform advanced reliability calculations.

This chapter starts with a brief introduction to general component reliability importance indices, followed by a survey on what has been done in this specific topic for power systems. The chapter continues with a more detailed presentation of the indices developed within the PhD project. The chapter ends by outlining an approach to component reliability importance indices for transmission systems.

3.1 Traditional component reliability importance indices

This subchapter contains a short description of some of the most referred component reliability importance indices, followed by a brief discussion on their potential use in transmission and distribution systems.

3.1.1 Birnbaum's reliability importance

Birnbaum's measure of component importance is a partial derivative of system reliability with respect to individual component failure rate [47]. It can also be argued that this is a sensitivity analysis of system reliability with respect to component reliability. This index gives an indication of how system reliability will change with changes in component reliability.

$$I_i^B(t) = \frac{\partial h(\mathbf{p})}{\partial p_i} \tag{3.1}$$

where h is the system reliability depending on all component reliabilities $\mathbf{p}$ (and system structure) and p_i component i's reliability. A drawback with this method is that the studied component's reliability does not affect the importance index (for the specific component). Another issue regarding this index is that it cannot be used in order to predict the effect of several changes at the same time, i.e. reliability changes in several components at a time [56]. This is, however, a drawback shared with most component reliability importance indices.

3.1.2 Birnbaum's structural importance

Birnbaum's structural importance does not take any reliability into account, and hence it can be stated that this method is truly deterministic. The method defines component importance as the component's number of occurrences in critical paths, normalized by the total number of system states.

Definition of structural importance in accordance with [47] and [57]:

$$I_\Phi(i) = \eta_\Phi(i) / 2^{n-1} \tag{3.2}$$

where $\eta_\Phi(i)$ is the number of critical path vectors for component i and 2^{n-1} is the total of possible state vectors. In other words; the number of critical paths a component is involved in is proportional to its importance. The structural importance can be calculated from Birnbaum's reliability importance by setting all component reliabilities to ½ [47].

One characteristic of this method is that it does not take probabilities into account, however it can be argued that this is the whole idea with such an index. Such a method is interesting in the case of sparse reliability data and could moreover be used for identifying critical component-positions in new designs. However it might be up to debate if some other value than ½ should be used in (3.1) in order to establish the structural importance.

Note that the definition of Structural importance as defined here, in line with the definitions in [36] and [44] distinguish from the definition in [51]. In [51] the definition of Structural

importance is defined as a partial derivative of the system probability of failure with respect to a components failure probability (this definition is very close to Birnbaum's measure of importance).

3.1.3 Fussell-Vesely's measure of importance

Given system failure, Fussell-Vesely's measure of component importance is the probability that at least one failed minimal cut set contains the studied component (in failed state) [47].

$$I_i^{VF} = \frac{P(D)}{P(J)} \tag{3.3}$$

where $P(D)$ is the probability that at least one minimal cut set containing component i is failed and $P(J)$ is the probability that the system is failed. An interpretation of this index is the answer to the question: If the system fails, what is the probability that the studied component will be involved in the failure? A drawback with Fussell-Vesely's index is that it does not take into account the component's contribution to system success [58].

3.1.4 Failure criticality importance index

The failure criticality index (I^{FC}) is developed in order to obtain a reliability index from reliability calculations based on simulations. The basic idea is to divide the number of system failures caused by component i in (0, t) with the number of system failures in (0, t) [59], see (3.4). One of the major advantages with this method is that it calculates a component reliability importance at a small cost in computation time from an already existing reliability simulation, no extra simulation rounds are needed.

$$I_i^{FC}(t) = \frac{n_i}{N} \tag{3.4}$$

where n_i is the number of system failures caused by component i and N is the total number of system failures. "Caused" should here be interpreted as if the component had not failed that particular system failure would not have happened. That is, the finally causing component that lead to the system failure gets its failure count (n_i) increased with one (see paper III for an example). The authors of I^{FC} also propose another related measure where the denominator is replaced with the number of the studied component's total failures. This alternative gives an indication of the percentage of failures that are critical for the system.

3.1.5 More component reliability importance measures

Except those component reliability importance measures presented previously there are numerous of other measures developed. Some of those are briefly presented here, with references for further reading.

3.1.5.1 Risk Reduction Worth (RRW)

RRW is current system unreliability divided with system unreliability with the studied component in a perfect condition (i.e. component reliability $p_i(t) = 1$) [47], [56].

3.1.5.2 *Risk Achievement Worth (RAW)*

RAW is closely related to RRW, and defined as the unreliability achieved with the studied component in a constant failed state (pi(t) = 0) divided with the actual unavailability [47], [56].

3.1.5.3 *Sensitivity analysis*

There are many forms of sensitivity analysis that can be performed and interpreted as component importance indices. As long as the sensitivity analysis is performed on component level it can be classified as an importance index. Many of the importance indices discussed in this thesis more or less fall within this wide classification. For a thorough assessment of sensitivity analyses see [60].

3.1.5.4 *Time independent component reliability importance measures*

All indices, with the exception of I^{FC} and Birnbaum's structural importance, presented previously are via component reliabilities time dependant. The time dependency of these indices are often criticized, since they only give a momentarily measure of importance [61]. The criticism might not be that critical in a context of power transmission and distribution because of two reasons. Firstly, long life times makes it reasonable to believe that, for example, failure rates are changing slowly in time and can be modeled as close to constant over relatively short time periods. Secondly, usually data is sparse and seldom possible to use for more than constant failure rates. Nevertheless seasonal variations and a long time perspective in the assessment of component importance might still lead to problems.

One solution to the problems with time dependence might be time independent measures. One example of such a time independent measure is presented in (3.5) [57].

$$I_i^{BP} = \int_0^\infty I^B(t)dF_i(t) \tag{3.5}$$

where F is the distribution function for component i. I^{BP} is the probability that the system life coincides with the life of the studied component. One general problem with importance indices is that they are expensive in terms of computation time, this characteristic is even more pronounced for time independent indices. For further reading regarding time independent measures see [61].

3.1.6 Reliability importance indices applicability onto electric power systems

One approach to the problem of calculating component importance for networks with multiple supply and load points is to study small parts of the network at a time, typically by studying a customer load point at a time. By dividing the network into these smaller groups it becomes possible to calculate traditional component importance indices. However, one central problem with this approach is to determine the importance relationship between components in different branches as well as for shared components. Furthermore, the approach becomes problematic with several feeding points, which point should the calculations "originate" from. These problems are addressed with the development of the proposed indices in 3.3.

3.2 Importance index methods for electric power systems

This subchapter discusses reliability importance indices used or developed for transmission and distribution systems. Since very few publications have been found within this topic a wider interpretation of component importance is utilized, for example, in the end of this subchapter, project prioritization is briefly discussed. Project prioritization is discussed since such methodologies share some common characteristics and aims with component prioritization methods (essentially what to do, and when).

3.2.1 Traditional component importance indices

In [51] and [62] some of the previously presented traditional component reliability importance indices are evaluated. In the applied numerical examples, in [62], the shortcomings of the used indices are illustrated in the failure criterions that are used. For example "system failure occurs when the supply to all four load points is interrupted". Without elaborating the example more it can directly be discussed whether this is an appropriate criteria or not. Certainly the system is failed when no load point is supplied with power, but how should the case with for example two out of four load points failed be treated, the system is not fully operational (nor totally failed). Nevertheless, the general indices are useful for smaller networks and other areas with *one* well defined objective (e.g. power delivery from point A to point B).

3.2.2 Project prioritization

In the electric power transmission and distribution literature there are methods for project prioritization presented. The prioritization process in these methods often involves a direct or indirect component importance measure. Examples of these measures are found in [36] and [63].

In [36] a method is presented for prioritization of maintenance activities, component contribution to SAIFI, SAIDI and MAIFI$_E$ is calculated (a weighted combination of a number of indices presented in 2.5.1 is used), this in order to be able to estimate effects on the system reliability indices of maintenance activities on component level.

In [63] whole projects are evaluated, this might seem a bit out of topic for this thesis, but the methodology is closely related to the method of component prioritization and hence component importance. The focus of this method is to minimize total cost, i.e. outage cost, investment cost, maintenance cost and operation cost. These costs are used for prioritization of available projects.

3.2.3 Component importance

Energy not delivered is the focus in [64], which presents a method for identifying components based on their expected contribution to energy not delivered (or energy not delivered on time). The importance is used for prioritization of components. In [65] a system is analyzed by a sensitivity analysis. One components failure rate is reduced to zero (perfect component) at a time and changes in system indices are recorded.

These two approaches are both related to the maintenance potential presented in paper I. However they distinguish from the maintenance potential in that they use traditional system reliability measures (presented in subchapter 2.5.1) for the assessment of component importance and not interruption cost.

In [66] a method utilizing reliability worth (customer interruption costs) for identification of segments in the system is presented. Segments, that are expected to cause much interruption costs for the customers are identified. The approach is applied on a high level, i.e. the segments correspond to three groups, a generating source, a substation group and the distribution system. If this approach is performed on the component level, instead of segments, it would be very close to the methods presented in 3.3.2 and 3.3.3.

3.2.4 Component criticality importance measures

Recently a number of methods for component importance for transmission systems were presented in [67]. These measures are constructed in order to avoid the problem around time dependant importance indices. As measure of reliability the system unavailability is used both at load point level and system level (with the failure criteria that there is no power delivery at all).

3.3 Developed component reliability importance indices for power systems

This subchapter presents a number of component reliability importance indices developed by the author, see paper I, III and VI. In order to perform an analysis of component reliability importance indices a single measure of power system reliability performance is needed. The decision is to use customer interruption costs (also known as reliability worth) as this measure. The methods are, however, not limited to the selected performance measure, as seen later in this chapter.

Since the power supply is more or less considered as always available some sort of unavailability measure becomes useful. It is not possible to point out a specific point in development when unavailability (interruption costs) becomes more suitable than availability measures, but in general it can be stated that when most electric power users count on the power supply as always available then interruption costs becomes interesting to use. (Note the word "interruption", which indicates loss of supply from something that is generally thought of as available.) Then there is the problem of identifying the interruption costs. One related issue, not addressed in this thesis, is if it is "fair" to diversify customers that pay the same fee for power delivery? As it can be seen above, the question about customer interruption comes down to discussions. But there exist a number surveys that indicates approximately the same values throughout different countries see [68] and [69]. For a discussion on the specific situation for Sweden see [70], which also discuss the costs used in regulation.

An extended discussion on customer interruption costs as a measure of power system performance can be found in [4]. The conclusion drawn is that in areas with highly developed power supply systems, a measure of interruption cost becomes significant. In this thesis the

values for customer interruption costs are those established by Swedenergy [68]. One of the fundamental strengths with the use of customer interruption cost as a measure is that values are comparable between different power systems, which cannot be said for general reliability measures. One simplification that is made, in the case studies, is that the costs are linear, that is one initial cost of the interruption followed by a cost that linearly depends on the duration of the interruption. It is important to note the distinction between concept and implementation; future models should not necessarily be limited to this linear approach.

3.3.1   Interruption cost index I^H, hazard rate index

The concept of I^H, the hazard rate index, is to study the interruption cost with respect to component reliability, see paper I. The method is based on the concept of I^B, see subchapter 3.1.1, which is extended for assessment of multistate networks (for example; networks that serve several load points). I^H use total interruption costs instead of probabilities as a measure of system reliability (the interruption costs do however depend on probabilities). Note that the analysis is performed on component failure rate instead of component reliability. The interruption cost based index is defined as follows

$$I_i^H = \frac{\partial C_s}{\partial \lambda_i} \qquad [\text{€/f}] \tag{3.6}$$

where C_s [€/yr] is total yearly interruption cost and λ_i [f/yr] component i's failure rate (the component index i will not be written in the following text). The importance index identifies components that are critical for the system with respect to their individual impact on total interruption cost with changes in component failure rate, see paper I. In application studies within the project it has been noted that I^H corresponds to the total expected interruption cost (for all load points) that would occur if component i failed. Hence, if there is one maintenance action available that would result in the same absolute change in failure rate for any component in the network, I^H would then be the natural index to use for a prioritization of what component that the action should be performed on.

The index is focused on failure rate. Reliability importance measures are generally focused on component availability, that is both failure rate and repair rate. To apply the concept of I^H onto repair times might prove to be more straightforward than failure rates and would complement I^H. This is due to one interesting aspect; in general it is easier to estimate how repair time changes with different actions than how maintenance actions affect the failure rate, and hence predicted system effects of these repair rate related actions might be more precise.

3.3.2   Maintenance potential I^{MP}

Analogous with Birnbaum's importance index I^H is not affected by the actual studied components failure rate but "only" by component repair time and the position of the component and all other components in the system. Hence the concept of maintenance potential (paper I) is introduced. Maintenance potential corresponds to the total expected yearly cost reduction that would occur in the case of a perfect component, i.e. no failures for the studied component (hence maintenance potential). Another way to express this measure is

the expected total interruption cost that the studied component is expected to cause (alone or together with other components) during one year.

Maintenance potential is defined as:

$$I_i^{MP} = C_S(\lambda) - C_S(0_i, \bar{\lambda}) \quad [€/yr] \tag{3.7}$$

Where C_S is the customer interruption cost and λ_i [f/yr] component i's failure rate.

In the studies that this thesis is built on the following relation between the hazard rate index and the maintenance potential has been seen:

$$I_i^{MP} \approx I_i^H \lambda_i \quad [€/yr] \tag{3.8}$$

where I^H [€/f] is defined in (3.6). This relationship is not likely to hold if the interruption cost is non-linear.

3.3.3   Simulation based index I^M

The simulation based index is built on the concept of I^H and I^{MP}, combined with the failure criticality index [59], see paper III. It is an index that is derived from simulations that calculate customer interruption costs. If there already exist simulations of the reliability and/or customer interruption costs the index is possible to compute at low additional calculation cost, by keeping track of a relatively low number of events (component failures and related system costs).

The simulation based index, I^M, is calculated by designating the total interruption cost caused by an interruption to the finally causing component, i.e. if the component is the final cause of failed delivery to one or more load point(s), the studied component is held responsible for the whole interruption cost. The accumulated cost over time for the component is then divided with the total simulation time in order to get an expected interruption cost per time unit (year). The index is defined as follows

$$I_i^M = \frac{K_i}{T} \quad [€/yr] \tag{3.9}$$

where K_i is the total accumulated interruption cost over the total simulation time T for component i.

The interruption cost perspective of the index allows us to identify the components that are likely to cause the most costs in terms of interruption. Hence, the index gives us an indication on what components that should be prioritized for maintenance actions (or in some cases re-design of the structure that results in the high value of I^M). Correspondingly, I^M indicates what components for which it might be beneficial to reduce preventive maintenance. It is however important to note that a relatively low value of I^M might be due to an individual low component failure rate and that the power system (i.e. the total interruption cost) is sensitive

for changes in those components' failure rates. This is analogous with the maintenance potential, neither the maintenance potential nor the simulation based index identifies the components that the system is most sensitive to regarding changes in failure and repair rates. But the components that cause the current interruption costs. Hence precaution should be taken regarding what components that get reduced attention.

It might seem somewhat unreasonable to formulate an index as previously defined i.e. by holding the component that trip the (sub)system responsible for the whole event, as similarly defined in section 5.1 in paper III (I^{FC}, the criticality index). Unreasonable since there might be several components involved in the failure. Nevertheless, since simulations generally include many events, this should not be an issue, in the long run all components will get their share of caused failures. However, the major reason for just "blaming" one component is that the measure becomes unambiguous. Consequently minimal cut sets are not needed in order to calculate I^M. In a complex network with advanced mechanisms it might not be possible to deduce minimal cut sets. Hence, for a more complex system the proposed index, I^M, might be a suitable measure.

One alternative approach to the suggested method is to assign the interruption cost to all components in the failed minimal cut set, not just to the single component that caused the failure. The drawback with such an approach is, as previously mentioned, that it becomes necessary to calculate all minimal cut sets and to keep track of which is failed.

3.4 Comparison of proposed indices I^H, I^{MP} and I^M

The interruption cost approach in I^H, I^{MP} and I^M distinguish from the more classical indices in more than the multiobjective approach. One additional major difference is that the initiation of an interruption can be penalized and that the length of an interruption does not necessarily have to have linear consequences with respect to time. However, based on the same concept these indices differ from each others. Table 3.1 demonstrates a number of basic differences between the proposed indices.

The relation between I^H and I^{MP} is by the components failure rate. That is the estimate of the maintenance potential (I^{MP}) equal the expected cost in case of failure (I^H) multiplied with the studied components failure rate, as presented in equation (3.8). Since I^M is calculated by simulations there is no direct relation between the other two indices and the simulation based index. However, the observant reader notes that I^M and I^{MP} have the same unit, that is [€/yr].

TABLE 3.1. DEVELOPED INDICES

Name	Unit	Description	Calculation
I^H	[€/f]	The expected cost *if* the studied component fails.	Analytical
I^{MP}	[€/yr]	Total expected yearly cost reduction that would occur in the case of a *perfect component*.	Analytical
I^M	[€/yr]	Total expected yearly interruption cost *caused* by the component (finally causing).	Simulation

Hence it is important to note the distinction in their definitions, for they do not only differ in their calculation. The maintenance potential is the potential savings in the case of a perfect component. This results, for example, in that two redundant components in parallel gets the same level of importance (I^{MP}). That result is explained by the fact that if one component becomes perfect, there is no more to be saved on the other component. The simulation based index, I^{M}, on the other hand represent the expected interruption cost caused by the specific component. Having said this it is noteworthy that I^{MP} and I^{M} often becomes almost equal, especially if there are no component-level-redundancy, as seen in paper III.

The sum of all I^{M} for all components corresponds to the total expected yearly interruption cost. This is not true for I^{MP}, however for most systems the sum of I^{MP} comes very close to the total expected interruption cost, as shown in paper I and II. Because of the differences between I^{MP} and I^{M} it is not straightforward to calculate a corresponding value to I^{H} for simulation based reliability calculations. This is, however, done in paper V in order to get an estimate of I^{H}.

3.5   Case study, Birka

Application studies have been performed for the proposed indices, see paper I, II, III, V, and VI. In these studies two different meshed power distribution networks have been investigated, Kristinehamn and Birka. This subchapter presents a brief overview of the results for one of these networks, the Birka system.

3.5.1   The network

The Birka system is located in the southern parts of Stockholm. The system, see Fig 3.1, which is thoroughly presented in [3] and [4], includes a 220/110kV station (Bredäng) and one 110/33kV, 33/11kV station (Liljeholmen). These two stations are connected with two parallel 110kV cables. From the Liljeholmen station there are two outgoing 33 kV feeders, Högalid (HD) and Stockholm subway (SJ), there are also 32 outgoing 11kV feeders (LH11), here represented by one average set of components (28-35). The model includes 178 components, numbered 1-58, with 16 copies of component 28-35. The components are divided up into four types, these are; circuit breakers, cables, transformers and bus bars. In the network, every component has a specific failure rate and repair rate. In total, this network serve approximately 38 000 customers where the load point SJ consist of one customer, that is the subway. The load point LH11 represent one average load point of 32 actual outgoing feeders, which in total serve 14 300 customers. The load point HD feeds approximately 23 400 customers [3]. The model has exponentially distributed repair times and time to failures and independent components.
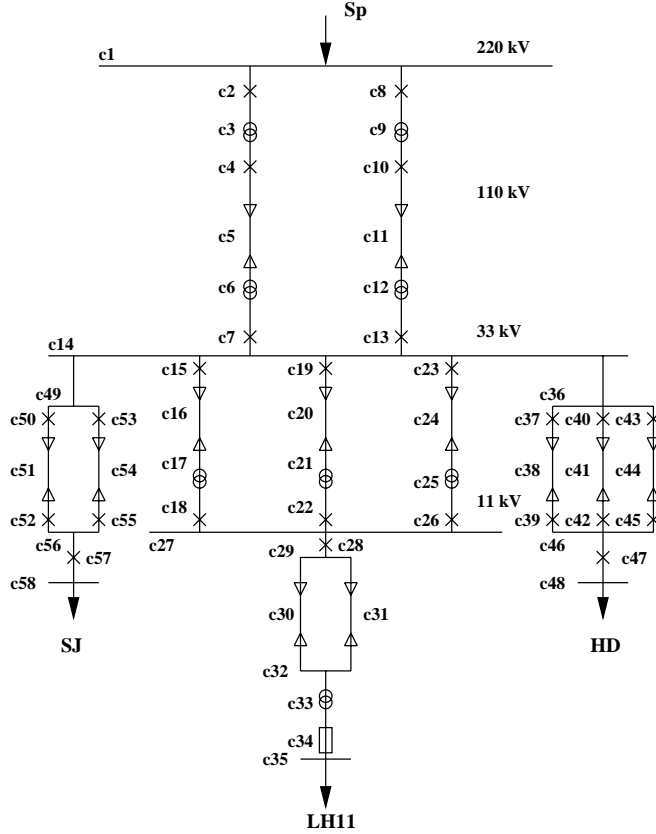
Figure 3.1. The studied Birka system [3], note that components 28-35
are "average components" representing in total 32 outgoing feeders.

3.5.2 Customer interruption costs

Costs for interruptions on an aggregated system level are one of the major factors for the
indices proposed in this thesis. For electric power systems these costs are usually referred to as
interruption costs and represent the cost at different load points in the system. The resulting
system interruption cost for the whole network is used as a measure of total system reliability
performance and in the calculation of the importance indices. The expected yearly load point
interruption costs are in this thesis based on the number of interruptions and the total
interruption duration and on node specific interruption cost parameters (k_L and c_L), as follows:

$$C_s = \sum_L \lambda_L (k_L P_L + c_L P_L r_L) \qquad [\text{€/yr}] \tag{3.10}$$

where C_s is the total interruption cost for the system, P_L [kW] average power, λ_L [f/yr] and r_L
[h/f] are reliability indices for the load point L, and k_L [€/f, kW] and c_L [€/kWh] are cost

constants representing the customer types and composition at load point L. Note that λ_L and r_L are functions of input data, i.e. results from reliability calculations based on failure rate, repair rate and network structure. This model implies that the cost of a specific interruption is defined as an initial cost plus a cost that depends linearly on the duration of the interruption. This model of interruption costs is based on the cost modeling in [68] and [69], i.e. a customer specific cost per lost kW and per kWh. Specific data for the studied case is presented in Table 3.2.

TABLE 3.2 INTERRUPTION COSTS PER LOAD POINT

Customer LP	€/f, kW	€/kWh	kW	# Customers
LH11	0.73	3.07	24 600	14 300
HD	0.42	1.64	23 000	23 400
SJ	1.44	7.11	800	1

The first column of numbers is the fixed cost for interruption per kW, the second column is the cost for energy not delivered, the third is average power consumption and the last the number of customers (note that the number of customers for load point LH11 is the number of customers connected to c27). Based on [3] and [68], converted to euro.

3.5.3 Results

The system has been investigated in two different studies with respect to reliability importance indices, see paper I and III. The first study is performed with the analytically based tool RADPOW [3] while the second study is based on Monte Carlo simulation techniques.

Results from the application studies are presented in Fig 3.2, Fig 3.3 and Fig 3.4. Fig 3.2 displays the reliability indices I^H for the studied network. I^H stretch from 0 to 0.87 million €/f. It can be seen in Fig 3.2 that the reliability of component 47 is the most important one from an I^H perspective, which implies that the system is most sensitive to absolute changes to component 47's failure rate. This is an interesting result since it place focus on a component that does not affect the whole system, but only the supply to the customers at load point HD. However, since HD is an important part of the system and the repair time of component 47 is relatively long, this result is sensible. After component 47 the importance for the components level out, the reason for this is that there are a number of components that affect the whole system but are modeled with a relatively short restoration time. To the right in the plot there are a number of components with zero or close to zero importance. These components' reliabilities can be concluded to have a small or none affect on the system cost, given the utilized model assumptions.

One approach to the data presented in Fig 3.2 (I^H) is to compare components of the same type with each other (for example 33kV breakers), in order to determine the most important positions in the network. Such a comparison could be used as decision support in a renewal strategy and/or for repositioning of components (components with different reliability).
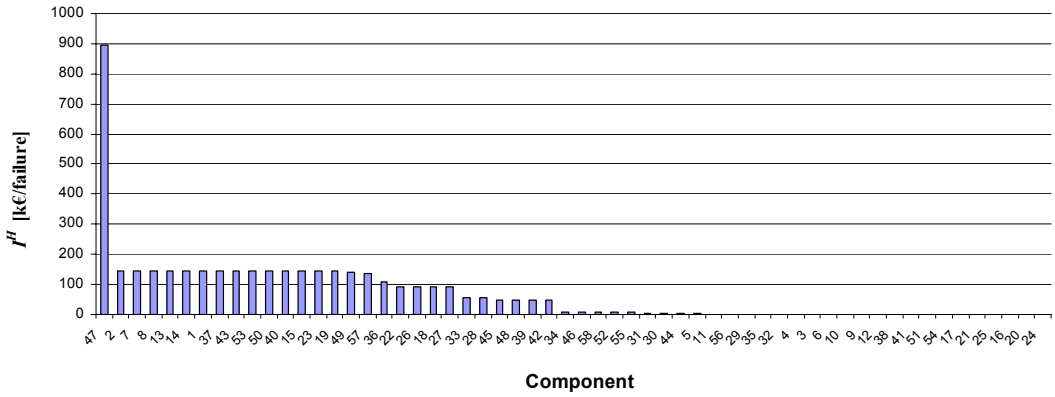
Figure 3.2. Components sorted on I^H [€/f], component 47 is identified as the component whose failure rate has the biggest impact on total customer interruption cost, figure from paper VI.
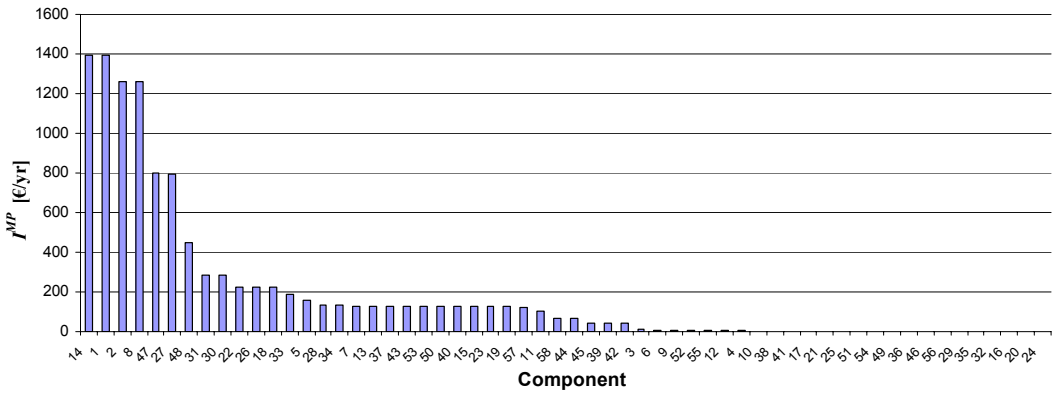
Figure 3.3. Maintenance potential, I^{MP} [€/yr]. Components 1 and 14 are identified as the most important components, figure from paper VI.
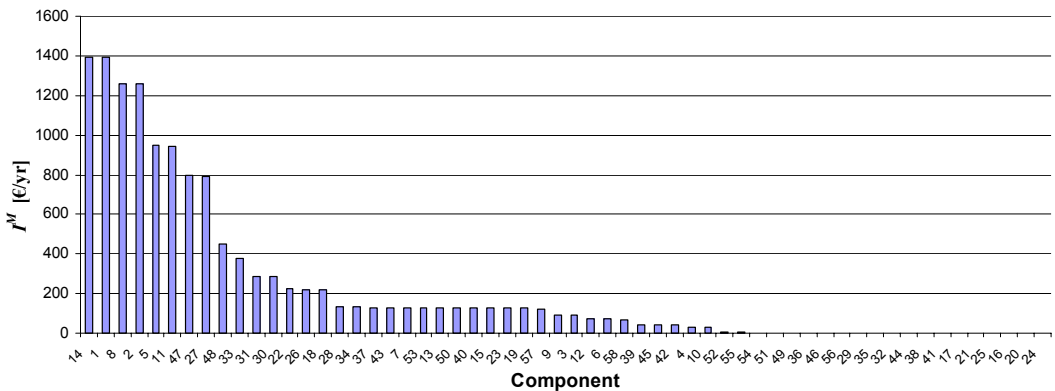
Figure 3.4. Caused interruption cost component reliability importance, I^M [€/yr], where component 1 and 14 are identified as most important. Calculations based on simulations, figure from paper VI.

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The importance index I^H combined with the maintenance potential, presented in Fig 3.3, enables the construction of a figure like Fig 3.5. From this figure it is possible to identify what components that are important for the system, both in terms of maintenance potential and reliability importance. One approach is to maintain components in the upper right corner more than components in the lower left. Components in the upper left are reliable but crucial for the system, these components might benefit from for example inspections. The components located in the lower right are cost drivers that are not so sensitive to smaller changes in failure rate, these components might need to be replaced and/or the network in that area needs to be redesigned.

Figure 3.4 presents the importance of the components involved in terms of average caused interruption cost per year. Note that some of the components have an importance of 0 €/yr, this is due to the fact that events that require three independent components to be failed at the same time has an extremely low probability. For the studied system these events generally do not happen, even with simulation times in the magnitude of billions of years. In Fig 3.4 it can be seen that the most important components (from an I^M perspective) are 14 and 1, followed by 8 and 2. It is interesting to note that there are a number of components that cause a large part of the interruptions. The six most critical components (10% of the population) cause 48% of the interruption cost. And the 12 most critical components (20% of the population) cause 76% of the interruption cost. This is close to the so called Pareto 20/80-rule, in this case 20% of the population cause 80% of the trouble.
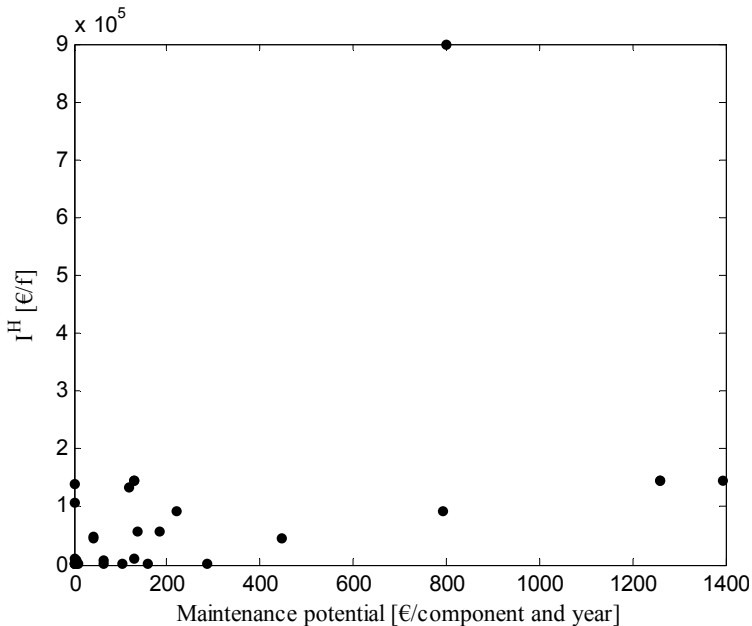

Figure 3.5. Visualization of I^H and I^{MP}. Note that the number of points is less than the number of components; this is due to similar data input for several components. The component at the top of the figure is component 47. The point furthest to the right represent component 1 and 14 and the next point contains data for component 2 and 8. Figure from paper I.

3.5.4   Conclusion

Here we have seen results from the three proposed component reliability importance indices, specifically developed for power distribution systems. The major advantage of the indices is that they provide one picture of the component importance with respect to the whole network reliability performance instead of one separate view for every load point. To achieve this, the author has chosen to use customer interruption cost as a measure of network performance. The case studies show that it is possible to calculate the proposed indices for relatively complicated networks with interesting results as outcome there of. Hence, the conclusion is that the indices are useful, whenever we look for efficient reliability actions.

3.6   Additional indices and tool for analysis

In this chapter we have presented three indices for component reliability importance adapted to electric power systems. These indices have been identified as useful in the maintenance optimization routines described later in this thesis. It is however clear from the presented traditional indices, presented in 3.1, that more indices can be developed. For example an index corresponding to Fussell-Vesely's index but adopted to power system reliability measures. Furthermore, indices based on other measures of system performance than reliability worth, e.g. measures on SAIFI, SAIDI, etc, are interesting to study. System reliability performance with respect to other data than the failure rate is, in addition, relevant to study, especially the repair time, other interesting aspects are switching times (manual switching) and replacement times. Below are some of these measures briefly presented followed by a discussion of applicability of the presented methods into other areas.

3.6.1   Component reliability importance indices implemented into a power system reliability tool

In the reliability tool RADPOW a number of additional indices have been implemented within the PhD project. The indices are numerically calculated by alteration of the input data. The indices, outlined below, utilize the concept of customer interruption cost (reliability worth) and traditional power system reliability measures (e.g. SAIDI and SAIFI) as measure of system reliability in order to establish the importance of the components.

Three major groups of indices are calculated in the tool:
1. Importance of the individual component's failure rate.
2. Importance of the individual component's repair time.
3. Component maintenance potential, i.e. how the system measures would be affected by an always available component (failure free).

For all of these three groups component importance is established with respect to SAIDI, SAIFI, CAIDI, ASAI, AENS and customer interruption cost. In total this results in 18 importance measures for every component. Which of the indices to use, in an optimization and/or identification process of important components, depends on the objective. E.g. a company whose performance is measured in SAIFI and SAIDI will naturally study component reliability importance indices based on these.

One simplified interpretation of the indices of group 1 is that the values correspond to the expected "system reliability loss" in case of a failure of the studied component. The interpretation of group 2 is that the value corresponds to the expected value per year for a reduction of the repair time with one hour. These values can for example be compared with the cost of placing repair equipment closer to the studied component. The interpretation of group 3 is the value (SAIDI, SAIFI, etc…) that is possible to save on making the studied component perfect in reliability terms (i.e. failure free). Note that this is the potential savings from making one component perfect. Two components in parallel gets the same potential If one of the components is made perfect there is no potential "left" for the other component. This gives an indication on how much system performance it is potentially possible to gain by making a component failure free.

The calculations are performed according to the following process:
1.   Basic run of RADPOW, with calculation of minimal paths, etc. Store system outputs (interruption costs, SAIDI, SAIFI, etc).
2.   For component i increase the failure rate (or the repair time depending on which set of indices that are to be calculated) with a small value ε.
3.   Call for a new reliability calculation (RADPOW without deducing minimal paths, etc, since this is already calculated).
4.   The indices are now formed by subtracting the original values, step 1, from the new values, step 3. The differences are then divided by ε and stored. This results in a number of numerical partial derivatives of the systems reliability measures with respect to component failure rate/repair time (these measures are called component reliability importance indices).
5   Restore original values for component i (passive and active failure rate).
6   Perform 2-5 for all components (increment i).

The approach for calculating the maintenance potential for the components is similar to the above. The difference is that instead of a small modification, ε, the failure rate is set to zero at step 2, and in step 4 only the differences are calculated (no division).

3.6.2   Transmission components and component reliability importance – more indices outlined

The work presented within this thesis is focused towards distribution systems and this is reflected in the developed component reliability indices. Since most of the interruptions that the average customer is exposed to originate from the distribution systems it becomes straightforward to connect values of interrupted supply (power, energy, and interruption costs) to the components reliability. However, for the power transmission components a failure should rarely cause an interruption, i.e. according to the n-1 criteria. This calls for measures that capture the problem of failed high voltage equipment, examples are:
 - If the component fails the n-1 criteria is not fulfilled. (1/0 for every point in time)
 - Transmission capacity reduction in a number of important cuts if the component fails.
 - Expected electric power market price increase if the component fails.

These measures could either be average expected values over a time period (month or year) or instant pictures of the system at time t.

Component reliability importance indices have yet to be developed and tested based on these types of measures. Furthermore, it might be interesting to apply the previously presented indices, in Chapter 3.3, to transmission system components in order to compare them with distribution system components.

3.6.3   Other areas of applicability

Beside the previous discussed applicability of the proposed indices for power transmission systems it is observable that similar indices might be useful in other areas, not restricted to the power industry. Typically areas with multistate networks (especially several start and end nodes), a continuous demand and a relatively expensive infrastructure. Examples of other areas that fit the description are water and gas supply, district heating and communication networks. All of these areas show some important similarities in their distribution of requested services and hence similar component reliability importance indices might be interesting to develop. Another area not so closely related but where the methods still might be applicable is transportation, e.g. addressing road and railway quality. Additional areas are various supply and command structures that might be possible to analyze with similar approaches. It is noted that if similar component reliability importance indices are developed for other areas this does in addition, enable the optimization framework, presented in next chapter, to be applied.

4 Maintenance optimization

One of the major aims of this thesis is to present a method that support asset management decisions by finding a solution to the problem of optimal balance between corrective and preventive maintenance (the maintenance problem). In the literature, a number of methods exist, e.g. see [36], [64] and [71], that focus on capturing the optimal level of maintenance with respect to a specific objective, such as minimizing a specific interruption index while meeting a budget constraint. This thesis takes the concept of these methods further by applying the methods of multiobjective optimization to the maintenance optimization with respect to the reliability performance of the whole network. This is done using a similar approach to that in the distribution system development planning described in [8]. The difference is that the proposed method focuses on maintenance instead of planning. Furthermore, the method has been developed, but not limited, to deliver optimal solutions for computational-intense reliability calculations that are based on simulations. This is an attribute that allows for detailed modeling of the studied network. The multiobjective approach puts the customer interruptions on one side and the maintenance budget of the distribution system operator (DSO) on the other. Thus, the proposed method provides a span of optimal solutions that the decision maker can choose among, each with different expected outcomes for maintenance budget and customers. One inherited strength of the method, from the developed component reliability importance indices, is that it considers several load and supply points simultaneously (multiple states). The approach of multiobjective multistate reliability methods, as presented in this chapter, is new and a survey of related methods can be found in [72], which also contains a method related to the method presented within this chapter.

In this chapter an optimization framework is presented, primarily based on paper V. In paper VII a simplified approach is presented, together with an application study.

4.1 Multiobjective approach to the optimization problem

The task of finding the optimal balance of preventive and corrective maintenance is approached as a multicriteria/multiobjective optimization problem. On one hand, we have the customers' demands for power delivery and on the other hand we have the maintenance cost for the DSO. In the optimization total customer interruption cost is used as the measure of system reliability performance from the customer perspective. The maintenance costs are closely related to the analyzed network, its components, structure and available resources.

It is possible to extend the multiobjective approach by studying every load point's availability as an individual objective instead of the total interruption cost. Some cases might, for example, call for pure Pareto improvements [73], where all customers are viewed separately, i.e. improvements that reduce costs or at least keep costs at current levels for all parties involved. To study all customers independently while requiring Pareto improvements narrows down the feasible solution space. Furthermore, with more objectives, the solution space fast becomes difficult to grasp with the increasing number of load points.

It is interesting to note that the two objectives (customer interruption cost and cost of maintenance) do not entirely point the solution in two different directions, since the cost of corrective maintenance to a certain degree correlates with the customers' inconvenience. More preventive maintenance is expected to result in both reductions in customer interruption costs and cost of corrective maintenance.

4.2 Maintenance optimization framework

4.2.1 Objective function

As objectives customer interruption cost is used for the customers and maintenance cost (preventive and corrective) of the network for the DSO. A scaling, s, is introduced between the customer performance measure and the DSO measure. This scaling is varied in order to obtain a number of non-dominated solutions with specific tradeoff between customers and DSO. The objective function of the optimization is presented in (4.1).

$$min \ s*C^{IC} + C^{CM} + C^{PM} \quad [€/yr] \tag{4.1}$$

where C^{IC} [€/yr] is the expected yearly system customer interruption cost, C^{CM} [€/yr] the cost of corrective maintenance, C^{PM} [€/yr] the cost of preventive maintenance and s is the scale factor (tradeoff). The unit of the scale factor, s, becomes DSO money per unit of customer money. The scale factor constitutes a translation of the expected customer interruption costs into terms of DSO costs. C^{IC} and C^{CM} are obtained from reliability calculations and depends on the maintenance strategy; they are functions of the chosen maintenance strategy, i.e. the preventive maintenance performed. C^{PM} is based on the maintenance strategy and is indirectly the parameter that the other costs depend on. The cost of preventive maintenance depends on the state of the components, and the selectable preventive maintenance actions constitute the actual optimization parameters.

According to the asset management discussion, in Chapter 2, the measure for the DSO ought to be revenue, instead of maintenance costs ($C^{CM} + C^{PM}$). However, in the suggested objective function it is assumed that the income does not vary significantly with the reliability of the network. Especially the profit margin of "unsold" energy is generally very small, compared to the costs of maintenance and customer inconvenience. Hence the maintenance costs are used. However, if there exist regulation of the price of network tariffs based on reliability parameters, or other penalties connected to the reliability performance, these could be included. But then the customer interruption cost should probably be excluded from the objective function, or at least reduced and some type of indices as suggested in 3.6.1 be applied. The regulation is a third part of the contract between customer and DSO and is currently excluded from the present calculations. This, since, the regulation in general can be said to try to align DSO objectives to customer node reliability, which in this context is considered to be covered by the customer interruption cost. Furthermore, it can be argued that the cost connected to the customer interruptions in the end will affect the DSO in terms of loss of goodwill, increased regulation and customer support.

4.2.2 Work flow

The optimization is based on calculations of customer interruption costs and component importance derived from reliability calculations that are inherently costly in terms of computation time. This push the optimization approach toward a method that requires few calls on calculation of objective function and other outputs. Another aspect of the optimization is that the reliability calculation constitute a "black box" that an optimization routine cannot see through. However, the concept of component reliability importance indices allows for a certain degree of visibility into this "black box".

It is assumed that the caused interruption cost is linearly dependant on the failure rate of the component, when no other data are changed, that is, assuming that a relative change in failure rate results in the same relative change in customer interruption cost caused by the specific component. Given maintenance actions and estimates of failure rate changes and maintenance cost/savings caused by these, a cost-benefit ratio can be developed. This is the ratio between the change in interruption cost and the cost/savings of the investigated action. By doing this for all available actions for all components, the available actions can be ranked. The cost change of a preventive maintenance action depends on the specific maintenance activity considered, and the activity is assumed to give an estimate of the change in the failure rate for the actual component. It is assumed that the cost of corrective maintenance is linearly dependant on the failure rate, e.g. if the failure rate is reduced with 50% the expected cost of corrective maintenance is reduced with 50% for the specific component. For estimates on how much the customer interruption cost will "profit", P, the following equations are proposed:

$$P_{i,j}^{C^{IC}} \approx \Delta\lambda_{i,j} I_i^H \qquad [\text{€/yr}] \qquad\qquad\qquad (4.2)$$

$$P_{i,j}^{C^{IC}} \approx \Delta\lambda_{i,j} \frac{I_i^M}{\lambda_i} \qquad [\text{€/yr}] \qquad\qquad\qquad (4.3)$$

where i is the component and j is the considered maintenance action. (4.3) is based on the similarity between I^{MP} and I^M, as seen in Chapter 3, and the relationship between I^{MP} and I^H and hence gives an estimate on (4.2), which in itself is an approximation, at least when customer interruption costs not are linear dependant on duration and number of interruptions. (4.3) is used in paper V. It is important to note that not only added maintenance can (should) be considered. Reduced maintenance and increases in failure rates are as well within the modeling scope and enables solutions that move maintenance resources from less critical to more critical components.

The value of every possible maintenance action, $P_{i,j}$, is evaluated according to (4.4), here with (4.2) used for estimates on customer interruption cost changes.

$$P_{i,j} \approx \Delta\lambda_{i,j} C_i^{CM} + \Delta C_{i,j}^{PM} + s\Delta\lambda_{i,j} I_i^H \qquad [\text{€/yr, action}] \qquad (4.4)$$

The optimization, which can be described as a steepest descent method, commences with a *leap*. The leap introduces the best cost-benefit ratio actions for every component into the solution. This is done despite violating the assumption that predictable results can only be obtained by the change of maintenance (failure rate) for just one component at a time. The leap is followed by a stepwise approach that does not violate the above assumption. In other words, all available maintenance actions are evaluated, but only the most profitable one is selected, given that it is expected to result in a better objective function. The optimization work flow is illustrated in Fig 4.1.

The start condition for the optimization is that all components are at their initial (current) state. Then a reliability calculation is performed with component reliability importance indices as output, as well other reliability measures. One of (4.2) and (4.3) is used to estimate the impact on customer interruption cost of all maintenance actions available together with estimates on how the maintenance budget will change; see (4.4). The estimates are then used to select *all* seemingly beneficial maintenance actions (this is the leap). This is done despite the fact that every maintenance action is evaluated individually, neglecting the consequences of all the other actions. This approach does not warrant a local optimum being reached and therefore we proceed with more cautious "steps", i.e. continue with a new reliability calculation based on the maintenance actions chosen from the previous step/leap. As before, we evaluate all available maintenance actions, but here only select the most beneficial maintenance action (hence this is called a step). The steps, with reliability calculations, are then performed until no more improvements can be found. The achieved optimal point (potentially local) is stored. One optimization cycle is then accomplished and the scale, *s,* is incremented. The calculation continues with a leap starting from the previous optimum. This is continued until there are no more scales to optimize for.
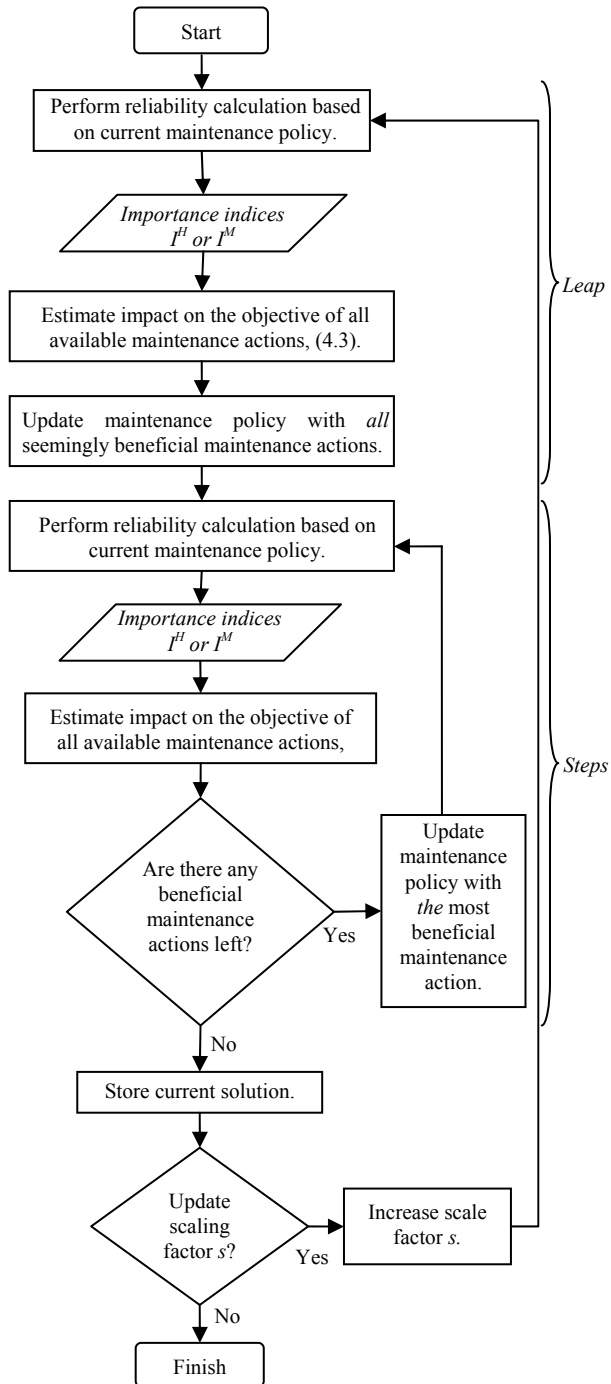
Figure 4.1. Optimization workflow.

4.2.3 Selection of optimum

Given that the method has not found local optima, the suggested approach will deliver a number of optimal points, exemplified in the case study below. These points will be located on the Pareto border and are all optimal from a specific point of view. The solution that is selected by the decision maker depends on many factors such as the current status and behavior of the network and customer relations. The different solutions provide the decision maker with important information on the expected consequences of the different maintenance policies. Two extreme types of selection process can be identified:

1. Keep current maintenance budget and reduce customer interruption costs.
2. Keep current level of expected customer interruption costs while reducing maintenance budget.

In general it is possible chose an optimum between these extremes that can be viewed as soft constraints, the solutions between 1 and 2 constitute Pareto improvements from current maintenance policy. However, some cases might call for increased maintenance budget or increased customer interruption cost, such changes are no Pareto improvements and will probably cause some concern from involved parties if introduced.

4.3 Case study, Birka continued

The case study is continued for the network presented in 3.5. The reliability calculations are based on simulations and hence (4.3) is used and consequently (4.5) instead of (4.4) for evaluation of maintenance actions.

$$P_{i,j} \approx \Delta\lambda_{i,j} C_i^{CM} + \Delta C_{i,j}^{PM} + s\Delta\lambda_{i,j} \frac{I_i^M}{\lambda_i} \quad \text{[€/yr, action]} \tag{4.5}$$

The maintenance actions are modeled on an aggregated level, i.e. if the components should be maintained as of today or if the preventive maintenance should be increased or decreased. This is modeled as if there were three different preventive maintenance alternatives for each component in the network:

1. Keep current preventive maintenance level; average failure rate is assumed to remain unchanged; no change in cost for preventive and corrective maintenance.
2. Improve the preventive maintenance; the average failure rate is assumed to be *halved* for the studied component; the additional cost of this is one cost unit.
3. Decrease the preventive maintenance; the average failure rate is assumed to be *doubled* for the studied component; cost savings: one cost unit.

Furthermore, it is assumed that the cost of one corrective maintenance action is β cost units [u]. In this case, β is set at 10 cost units. The cost of corrective maintenance is chosen in relation to the maintenance effects in order to introduce incentives into the operator's maintenance budget to perform preventive maintenance. The relationship between changes in failure rate and cost of corrective maintenance is expressed as

$$\Delta C^{CM} = \beta \sum_i (\lambda_i^{new} - \lambda_i) \quad \text{[u]} \tag{4.6}$$

where *i* denotes component number. The change in preventive maintenance is calculated according to the formula:

$$\Delta C^{PM} = sum(incr\ maint) - sum(decr\ maint) \quad [\mathrm{u}] \tag{4.7}$$

where *sum(incr maint)* is the number of components with increased preventive maintenance actions, while *sum(decr maint)* is the number of components with decreased maintenance.

Note that the assumed maintenance alternatives in general "punish" relocation of maintenance resources in terms of total number of component failures. Consider the example of two components, both with the same initial failure rate, *λ,* and both being at alternative 1. By moving maintenance resources, i.e. moving one component to alternative 2 and the other to alternative 3, this results in the sum 2 1/2 *λ* (compared to 2 *λ*, before maintenance reallocation). The values presented in this subchapter might be considered somewhat extreme, and they are chosen deliberately to show on effects of differences between diversified maintenance policies for components. Studies have been performed for other values of *β* and lessened effectiveness of preventive maintenance, presented in the sensitivity analysis of paper V and [74].

4.3.1   Results

The result of the optimization routine is a number of optimal points (solutions) which are all optimal from a specific point of scale. In Fig 4.2 a number of optimal points for the case are displayed, as well as the starting point (present situation). Note that since every optimization is built on results from a separate simulation, some of the optimal points are dominated by other optimal points. A point is dominated when another point exists that is better in respect of at least one criterion without being worse in any other criteria. The existence of these points is explained by the fact that every optimization is based on one or more (individual) simulations. In the work preceding this thesis, it has been seen that with more iterations in each simulation the number of dominated points decreases. In Table 4.1, more details are found for the solutions presented. Solutions 7-13 all dominate the "initial point". Even when considering SAIDI and SAIFI, solutions 8-13 dominate the initial point, despite SAIDI and SAIFI not being directly included in the optimizations. Solutions 7-13 are probably more interesting than the others, since they do not aggravate the situation for any of the two parties involved. This is, however, only true if we look at the total customer interruption cost. If we study every load point separately, it can be seen in Table 4.1 that the interruption cost for node SJ is higher for solution 1-13 than for the starting point. One approach to this somewhat problematic situation might be to state that solutions 7-13 constitute Pareto improvements from a system perspective, which implies that we utilize our resources for the common good of the customers. Another approach might be to put constraints on the optimization, ensuring that the reliability offered to customers does not fall below current levels, or to penalize customer node interruption costs that are above today's level. If we want to investigate this issue further, we need to split up the utilized customer objective into three new objectives, i.e. one measure for every load point. It is noteworthy that such an approach will most likely be less efficient from a global perspective. Having noted this possibility of approaches that consider individual constraints on customer nodes, the study is continued with the focus on the common good, i.e. lowest total cost.
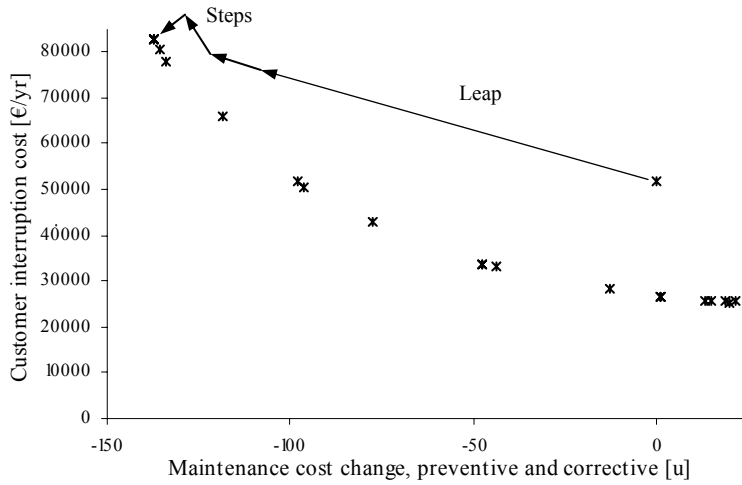
Figure 4.2. The optimal solutions calculated. The x-axis corresponds to changes in maintenance budget in comparison to today's budget. Note the starting point for the optimization (not an optimum), located at (0, 51 912). The arrows illustrate the optimization process to one optimum. Figure from paper V.

TABLE 4.1 OPTIMIZATION RESULTS

Meas. Solution	C_{LH11}^{IC} [€/yr]	C_{HD}^{IC} [€/yr]	C_{SJ}^{IC} [€/yr]	$\sum C^{IC}$ [€/yr]	C^{PM} [units]	$\sum comp.$ failures [f/yr]	SAIFI [int/yr]	SAIDI [h/yr]
Org.	47009	4283	620	**51912**	**n/a**	**4.01**	0.144	0.271
1, 2, 3	73734	8049	1160	**82943**	**-144**	**4.66**	0.211	0.451
4	72103	7204	1046	**80353**	**-142**	**4.64**	0.192	0.434
5	70612	6302	909	**77823**	**-140**	**4.63**	0.175	0.416
6	58492	6361	917	**65770**	**-124**	**4.57**	0.174	0.356
7	46181	4726	788	**51695**	**-87**	**2.91**	0.121	0.280
8	45589	4225	725	**50539**	**-85**	**2.90**	0.113	0.271
9	39038	3398	727	**43163**	**-66**	**2.86**	0.104	0.227
10, 11	29930	3147	694	**33771**	**-33**	**2.57**	0.098	0.178
12	29449	2934	698	**33081**	**-29**	**2.56**	0.092	0.174
13	24767	2929	701	**28397**	**3**	**2.43**	0.089	0.151
14, 15	23763	2495	515	**26773**	**17**	**2.42**	0.079	0.141
16	23242	2232	409	**25883**	**30**	**2.35**	0.074	0.135
17	23052	2213	344	**25609**	**32**	**2.33**	0.074	0.134
18	23116	2091	347	**25554**	**36**	**2.31**	0.073	0.133
19	23042	2095	307	**25444**	**37**	**2.30**	0.073	0.133
20	23170	2068	306	**25544**	**39**	**2.28**	0.073	0.133

"Org." represents the non-optimized original solution, i.e. maintenance policy as of today. Data used in the optimization process are marked in bold. A number of solutions are identical; these are presented in the same row. C^{PM} corresponds to the net change of preventive maintenance units. Note that C^{CM} is calculated from the column with number of component failures and (4.6). Table from paper V.

4.3.2   General discussion of results

If the optimization problem is studied from the perspective of the DSO, one approach is to see how much we can decrease the maintenance budget, without decreasing the service to the customers. This is achieved by identifying the solution with the nearest lower customer interruption cost compared to the solution of today (0, 51 912). The maintenance cost difference between the starting point and the optimal point now reached gives us an estimate of today's maintenance policy inefficiency, that is, how much it is possible to save on today's maintenance policy without reducing average customer service. This approach suggests solution number 7 for the case study, which would significantly reduce the cost of preventive maintenance. Likewise, we can perform this operation in reverse by going down from today's (0, 51 192) solution to the Pareto border in order to localize the point that, given today's budget, will give us the lowest customer interruption cost. This approach suggests solution 13. According to Table 4.1, this solution, with the utilized assumptions, would result in an almost halved customer interruption cost. While the preventive maintenance is increased for this solution, the cost of corrective maintenance is lowered, resulting in a slightly lower maintenance cost than that of today.

4.3.3   Selection of optimum, decision aid

In Table 4.2 a visualization of the solutions is displayed, the visualization is interesting since it helps the operator to get another view of the solutions. A number of important components can for example be identified (e.g. component 5, 11, 30 and 31) these components should never, according to the optimization intervals, be maintained less than of today. It is also possible to identify less significant components (e.g. component 4 and 10). Between these two extremes there are components that with increasing maintenance budget will get more and more maintenance.

TABLE 4.2 VISUALIZATION OF SOLUTIONS

Comp. \ Solution	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	3	3	3	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
2	3	3	3	3	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2
3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1	1	2
4	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
5	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2
6	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1
7	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	2	2	2	2	2
8	3	3	3	3	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2
9	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1	1	2
10	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
11	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
12	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1	1
13	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	2	2	2	2	2
14	3	3	3	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
15	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	2	2	2	2	2
16	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
17	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
18	3	3	3	3	3	3	3	3	3	3	3	1	1	2	2	2	2	2	2	2
19	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	2	2	2	2	2
20	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
21	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
22	3	3	3	3	3	3	3	3	3	3	3	1	1	2	2	2	2	2	2	2
23	3	3	3	3	3	3	3	3	3	3	3	3	3	1	1	2	2	2	2	2
24	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
25	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
26	3	3	3	3	3	3	3	3	3	3	3	1	1	2	2	2	2	2	2	2
27	3	3	3	3	3	3	1	1	2	2	2	2	2	2	2	2	2	2	2	2
28	3	3	3	3	3	3	3	3	3	1	1	1	2	2	2	2	2	2	2	2
29	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
30	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
31	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2
32	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
33	3	3	3	3	3	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2
34	3	3	3	3	3	3	3	3	3	1	1	1	2	2	2	2	2	2	2	2
35	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3

Visualization of twenty solutions. The maintenance budget is increasing from left to right. Red (3) indicates less maintenance, yellow (1) that the maintenance should be performed as of today and green (2) that the maintenance should be increased. Note that the table is truncated after component 35. [74].

4.3.4 Results continued for one optimum (no. 10)

In this section optimum number 10 is studied in more detail, to exemplify a specific solution. Normally, the DSO should choose a suitable solution. In this case, we continue and assume that the DSO chooses solution number 10. This might be motivated with that this point has a suitable combination of lowered customer interruption costs and lowered maintenance cost. One additional advantage of this point is that the interruption cost for node SJ is relatively close to the starting value (the other two are significantly below).

The resulting maintenance plan stipulates that the preventive maintenance level should be increased for 56 components while being decreased for 89 components and kept the same for 33 components. Figure 4.3 presents an illustration of the suggested actions for optimum number 10 applied to the system.
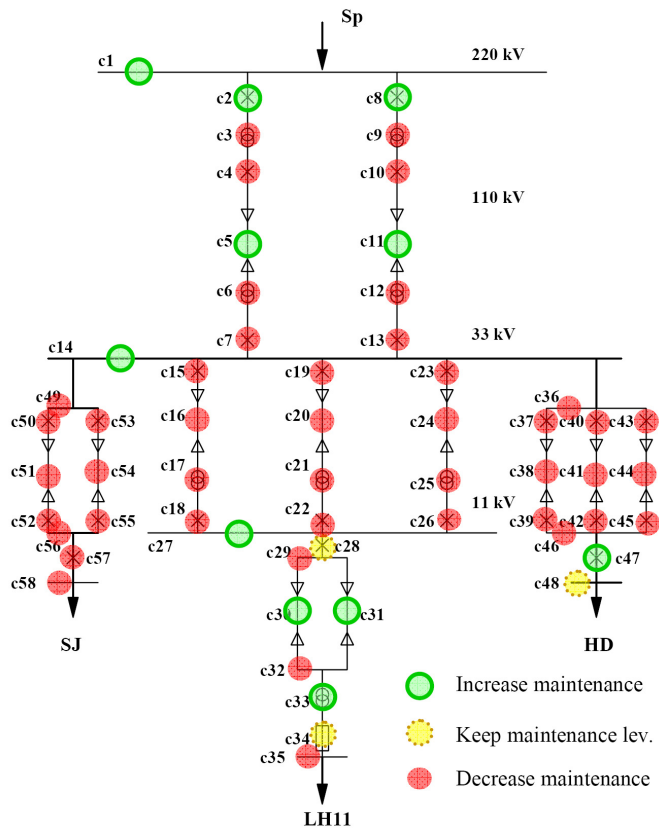
Figure 4.3. Illustration of optimum number 10 for the Birka system. Figure from paper V.

5 Closure

This chapter contains a brief summary of the methods and results presented in this thesis and a discussion on a number of identified interesting future research topics. The chapter ends with an outline of the applicability of the presented methods for the industry.

5.1 Conclusions

This thesis proposes a maintenance optimization framework with a multiobjective approach for power systems. The framework can be used for development of a maintenance policy that improves the utilization of maintenance resources. It has been shown that with a diversification of the maintenance between components, it is possible to decrease total cost of maintenance while increasing average reliability for the customers. The two main characteristics of the approach are multiobjective optimization and the multistate-reliability modeling, accounting for systems with several supply and load points simultaneously. The multiobjective optimization put customer interruption costs on one hand and total maintenance cost on the other. Beside allowing studies of multistate systems this approach enables the user to compare and optimize for components from different networks. The optimization is built on developed component reliability importance indices, which in themselves constitute a tool for maintenance prioritization that can be useful. For large systems the optimization and calculation of indices are demanding on both the data and the calculation side. However, if these data intense reliability calculations are performed, a good foundation for asset management decisions is laid. The applicability of the optimization and component reliability importance indices have been shown in case studies, based on genuine data, showing that the methods can be implemented in practice.

A consequence of the developed methods is that components of the same type should sometimes be maintained differently due to their location (importance) in the network, and on how they are operated. This is a result from a maintenance policy that moves resources to the most important components. In this context it is important to point out that the maintenance actions considered can be of both increased and decreased maintenance, enabling the

optimization solver to diversify the maintenance. One additional important factor is the correlation between failures and power consumption. The main effect of this correlation is that with average values for power consumptions and failure rates, the energy not delivered and customer interruption cost are underestimated.

5.2 Future work

A number of identified possible improvements and applications of the presented methods are here outlined.

5.2.1 Research

The presented studies address maintenance actions that change the failure rate of the components. Continued research and application studies may include analysis on changes to repair times, spare parts and switching times. This is supported by new functionality in the reliability tool RADPOW [54]. However, currently RADPOW does not respond to external calls, which could be a next step, i.e. adapt RADPOW to support requests from an optimization routine. This would enable fast implementations of various maintenance optimization methods.

The optimization method can be further improved, as for example outlined in paper V. However, given the available data, as of today, it might prove more beneficial to focus on acquiring data and to consider more entities to put into the model, such as the repair and replacement times. Given better data, component reliability models with time- and utilization-dependant failure rates could be used in the optimization, which would require a more sophisticated solver algorithm, adding time and component condition into the optimization. One related topic is the value of knowledge of component condition. Addressing this knowledge value may give answers to questions like; "Is it cost beneficial to mount diagnostic equipment permanently on a specific component?" and/or "How often shall we inspect the component?".

When maintenance is performed, the maintained component is generally disconnected from the network, resulting in a temporary reduction of the system reliability. Furthermore, the disconnection and reconnection in themselves can result in failures, there is for example a small probability that the switching equipment will fail. The temporary reduction may be called "reliability cost of maintenance" and is a topic that has to be further investigated. The main question is if the reliability cost (reliability reduction) is significantly smaller than the system reliability improvement due to the improved (maintained) component?

In subchapter 3.6.2, three reliability importance indices adapted for transmission systems are briefly discussed. These could be further developed and tested, adopting the methods, presented in this thesis, to transmission systems.

5.2.2 Industry application

The optimization framework is ready to be applied to power distribution systems. Beside a reliability model of the studied network, estimates on effects of maintenance actions (changes in failure rate) and their related costs are required. One additional use of the optimization framework is for development of guidelines for replacement and maintenance routines for common system topologies.

A first step toward optimizing the maintenance is to apply the developed component reliability importance indices. These indices can guide a reallocation of maintenance resources or identify where more reliable equipment should be installed in a network. Here the tool RADPOW can be applied in order to identify the most important components in the network.

The developed approach for the importance indices and the optimization method can be utilized in multi-state networks that utilize a measure of total performance, as discussed in 3.6.3. Examples of such areas, beside electric power systems, are other types of infrastructure; water supply, gas supply, railway and road quality. Additional areas that might be considered, are other networks with some type of flow, e.g. command and/or supply structures. Hence, the methods presented in this thesis opens up a number of fields for maintenance optimization.

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