Reliability Centred Maintenance for Electric Power Distribution Systems

Lina Bertling

Stockholm 2002

Doctoral Dissertation
Royal Institute of Technology (KTH)
Department of Electrical Engineering

BBN 93-7223-365-9
TFR1-1-15-2003-01
KBN 1053-738X
BBN KTH-ETS, R-02/01-5

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Thesis submitted in accordance with academic requirements for the Degree of Doctor of Philosophy at the Royal Institute of Technology (KTH) Department of Electrical Engineering Division of Electric Power Systems
Akademisk avhandling som med tillstånd av Kungl Tekniska Högskolan framlägges till offentlig granskning för avläggande av teknisk doktorsexamen fredagen den 13 september 2002 kl 10.00 i Kollegiesalen, Administrationsbyggnaden, Kungl Tekniska Högskolan, Valhallavägen 79, Stockholm. Opponent: Dr John Endrenyi Kinectrics Inc (tidigare Ontario Hydro Research Division), Toronto, Canada.

ISBN 91-7283-345-9
TRITA-ETS-2002-01
ISSN 1650-674X
ISRN KTH/ETS/R--02/01--S

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Cover illustration: Vera Porad Falk (graphic design), Lina Bertling (photos and figures), and Björn Holmgren (the water-tree picture).

Norstedts Tryckeri AB, Stockholm 2002


Abstract

Today's electric power distribution systems operate in a liberalized market. These systems should therefore be able to provide electricity to customers with a high degree of reliability and be cost-effective for suppliers. The cost of maintaining system assets, especially through preventive maintenance (PM), is both a major and a relatively easy cost to see. This situation calls for improved PM strategies that can demonstrate both the benefits they provide in reliability and the total cost of their implementation. Reliability-centred maintenance (RCM) is a systematic method for achieving a cost-effective PM strategy.

This thesis presents an enhanced RCM methodology that: (1) is based on a quantitative relationship between PM performed at the system component level and overall system reliability, and (2) can be applied generally to the analysis of electric power distribution systems, and (3) includes cost considerations. The approach used for achieving this generic RCM methodology included the activities listed below.

- Development of a computer program for reliability evaluation called RADPOW (reliability assessment of distribution power systems).
- Formulation of an RCM framework identifying procedures and input data required for performing RCM analysis.
- RCM application studies on one rural overhead line system and one urban underground system. This included a comprehensive study of disturbance statistics focusing on causes of failures, undertaken in close cooperation with one electricity utility.
- Detailed analysis of the cable component resulting in the definition of a functional relationship between failure rate and PM. The failure rate model was then implemented to evaluate the effect and the total cost of different PM methods and strategies on system reliability.

Conclusions from this study shows that it is beneficial to apply PM strategies based on the results of quantitative systematic techniques such as the RCM methodology developed in this thesis.

Keywords: electrical distribution system, reliability, preventive maintenance, reliability centred maintenance, RCM, RADPOW.

ISBN 91-7283-345-9 • TRITA-ETS-2002-01 • ISSN 1650-674X • ISSN KTH/ETS/R-02/01--S
Sammanfattning

Eldistributionssystem drives idag på en avreglerad elmarknad. De skall därför hålla en hög till försörjligit för eleverans men även hanteras kostnadseffektivt. Kostnaden för att underhålla komponenter i systemet är en dominerande och en separerbar kostnad framför allt den för förebyggande underhåll (FUH). Denna situation skapar ett behov av förbättrade strategier för FUH vilka kan visa hur en underhållsättgård påverkar till försörjligitten och den totala kostnaden. Funktionssäkerhetsinriktat underhåll (RCM) är en systematisk metod för att uppnå kostnadseffektiva strategier för FUH.

Denna avhandling presenterar en förbättrad RCM-metod vilken: (1) inkluderar ett kvantitativt samband mellan till försörjligitten (funktionssäkerhet) för systemet och FUH för komponenter, (2) kan användas för analys av ett generellt eldistributionssystem, och (3) inkluderar metoder för kostnadsanalys. För att uppnå detta resultat har aktiviteter enligt följande lista utförts.

- Utveckling av ett datorprogram RADPOW för till försörjligitetsanalys, (reliability assessment of distribution power systems).
- Formulering av ett ramverk för en RCM analys vilken identifierar ingående procedurer och indata.
- RCM tillämpningsstudier av ett landsortnät med luftledningar samt ett tätortsnät med markkabelledningar. Dessa studier inkluderar en omfattande analys av driftstörningsstatistik fokuserad på felorsaker, vilken utförts i nära samarbete med ett eldistributionssiret.
- Kabelkomponenten har analyserats i detalj. En modell med ett funktionellt samband mellan felintensitet och FUH har definierats. Denna modell har implementerats och effekten på systemets till försörjligitten och total kostnad för olika FUH metoder och strategier har analyserats.

Slutsatsen är att det är kostnadseffektivt att tillämpa FUH strategier vilka baseras på resultat från kvantitativa systematisk metoder, liksom den utvecklade RCM-metoden i denna avhandling.

Nyckelord: Eldistributionssystem, Till försörjligitten, Förebyggande underhåll, Funktionssäkerhetsinriktat underhåll, RCM,RADPOW.

ISBN 91-7283-345-9 • TRITA-ETS-2002-01 • ISSN 1650-674X • ISRN KTH/ETS/R--02/01--S
Preface

This thesis represents the final result of my work as a PhD student at the Department of Electrical Engineering, the Division of Electric Power Systems, and the Royal Institute of Technology (KTH), since 1997. It also concludes ten years as a student at KTH.

It was the word of reliability that one day brought me into this department for the first time. I was just finishing my MSc thesis at the Department of Mathematics (KTH), in association with the Defence Material Administration (FMV), entitled Reliability analysis of verification processes for Leopard 2s. I found this project to give the opportunity to explore further the application of the theories that had caught my interest.

During this time I have learned that research is like life: it is complex, but as soon as you realize this, you have taken a good step forward along the right path. However, the road to the end of the path is unknown. It is only through setbacks that we can learn and find clarity, happiness, and achieve the understanding required to provide solutions. I have also realized that even though mathematical theories provide fantastic language and tools, the application of the same presents the greatest challenge. I believe that the real beauty of mathematics lies in its ability to provide a solution to a problem, which will always be the only justifying reason for any mathematical model made. I have learned that it is both a contribution and a challenge to present a complicated problem in a simple way, which requires both a deep understanding as well as a humble attitude. The opportunity to meet and work with those who do this successfully has been an invaluable source of inspiration.

This thesis mainly contributes to knowledge not by introducing sophisticated mathematical models and theories, but by proposing methods that based on both practice and theory provide support for solving the issues of today and tomorrow’s electric power distribution system. That are the electrical distribution systems that are planned, operated and maintained in a liberalized market, which brings the economic aspects into the focus alongside the technical, and more specifically to provide solutions for an effective strategy for maintenance. This work brings together probability theory through reliability analysis as well as the practical maintenance of
the technical system and the objective is to better meet the future requirements for an effective management of electric power systems.

I hand over this work with a wish that my words will both answer and put questions. I hope that it could provide an insight from the both sides of practice and theory, and to be a source of inspiration for further analysis in the field.

This work could however not have been accomplished without the the invaluable guidance by the supervisors as following: Professor Roland Eriksson (from April 2000), head of the Department of Electrical Engineering (KTH) and Division of Electrotechnical Design, Professor Göran Andersson (until April 2000), former head of the Division of Electric Power Systems and currently professor at the Swiss Federal Institute of Technology Zurich (ETH), and Professor Ron N. Allan, international advisor and associate with the Manchester Centre for Electrical Energy (UMIST).

This framework encapsulates the results of a long time of solid work. However on a more personal note, memories of long evenings following long days spent hard at work soon fade, and it is those little things that brought joy into the daily routine that remain. I remember walking up to the campus passing remarkable beautiful flower arrangements and hearing the birds sing, or remember when I flew over the campus on our own machine, during one of my flight lessons as a new student at the Vehicle programme at KTH. I remember the ice-creams and coffee breaks, seeing my former MSc colleagues and friends, enjoying the beautiful courtyard in the campus grounds. I remember the lunch breaks with my colleagues taking a short walk in the park of Liljanaskagen, passing all the contented dogs out having a run, or the lunchtime concept in the chapel at the Röda Korsets Sjukhus, next door. I remember taking a break from work to join an inspiring art experience, on one of those numerous visits, arranged by the art association at KTH. I remember discussing research education at numerous of mettings and visiting PhD students at other universities sharing different experiences. I remember encouraging the visiting researchers and students to speak Swedish. I remember all those trips around the world, and opportunities to immerse myself in other cultures and environments. I wish to thank all of you that contributed to these valuable moments in life. The meeting with all has enlightened my life, and therefore the work being summarized within the two parts of this overall framework.
Acknowledgements

I would first of all like to express my deep gratitude to my supervisors. To Professor Roland Eriksson for your great enthusiasm from the very first day until the end of this path of work. Thank you for always supporting and listening to my ideas and arguments and for providing me with the trust to realize my own path of work. To Professor Göran Andersson for initiating and appointing a reference group for the project and for introducing me to the world of research. To Professor Ron N. Allan for providing me with excellent supervision and advice during this time. I have felt very privileged having the opportunity of being your student. Your guidance through research work has been most valuable and enjoyable.

Financial support for this research project was provided by the Competence Centre in Electric Power Engineering at KTH which is gratefully acknowledged. I wish to express my particularly gratitude to the following persons related to the reference group: Dan Andersson at the Sydkraft power utility (for providing material for the Flymen network), Dr Stefan Arnborg at the Swedish National Grid (Svk) (for introducing me to reliability evaluations at Svk and as a former colleague introducing me as a newcomer into the routines at the Division), Bengt Näslund at the Swedish National Energy Administration (for inviting me to present and publish results at the national conference Energetinget on energy systems), Sven Jansson at the Swedish Power Utilities Research and Development Organization ELFORSK (previously at Swedenergy AB that includes an association for the Swedish power utilities) (for providing disturbance statistics from the Swedish Service Interruption reporting system, and for invitation to join a working group at Swedenergy AB on reliability centred maintenance (RCM) for power utilities which was active in 2000-2001), Dan Karlsson and Jan Lundqvist at STRI AB (an independent company developing and testing electrical power transmission and distribution systems), Per Överbeck at the Vattenfall power utility.

I wish to thank the other members of the working group on RCM at Swedenergy AB for many stimulating discussions and for sharing their expertise and their shown interest in my work.

As part of this research project, I spent approximately four months at the University of Saskatchewan (USASK), Canada, involved with the Power
Acknowledgements

Systems Research Group lead by Professor Roy Billinton. I wish to acknowledge my admirations and appreciation to Professor Roy Billinton, it was a privilege and pleasure to study and work in co-operation with you and your group. I also wish to give special thanks to my colleagues there and students: Professor Sherif Faried, Dr Mahmud Fotuhi-Firuzabad, Bagen, Cui Lan and Susan Tang. I also wish to thank the following for becoming my “family” and dearest friends: Marjie Baltazar, Ross Clements, Daniella Roschinski and Anna-Lena Sommerfelt.

Close co-operation has been established with Birka Nät AB, which provided significant input through making available the knowledge required for accomplishing this work. I wish to thank Lars-Ake Gustafsson and Mats Åhlén for sharing your expertise, time and enthusiasm. Thanks for all the valuable and enjoyable discussions and technical visits. Many thanks also to Daniel Terranova (for initiating the co-operation) and Kjell Gustafsson (for providing system data). I wish also to thank the personnel at Birka Service for contributing in the discussions about cable faults and maintenance.

I have had the opportunity to participate as Course Coordinator and Lecturer in an external course run by STF AB (a company for engineering education). I wish to thank Klas-Göran Sundvall and Kerstin Pelz at STF for your trust. Teaching is the best way to learn and therefore this experience has contributed to this work. I also wish to thank Dr Lawrence Jones (now at Alstom US) and Dr Olof Nilsson (now at Vattenfall) for suggesting me as a lecturer for this course and for the time we spent as colleagues (especially for the gospel songs [Jones] and the lunch schedule [Nilsson]).

A special thanks to Tech Lic Björn Holmgren (now at ABB) and Dr Peter Werelius (now at Programma Electric AB) former a part of the Research Group on Cable Insulation at the Department, for for letting me use their results as input for my studies.

To my family of colleagues, current and past, national and international, I could not name you all, but I wish to tell that the meeting with you all will continue to hold a special place in my memory. You have contributed to the greatest learning of all, coming from the meeting and interaction with people.

I wish to thank you all at the Department, for the friendly and open-minded working environment with a great mix of people and cultures in time and room. Special thanks to: Professor Lennart Söder (for being my
primary teacher in electric power systems, thanks for your inspiration), Lille-
mor Hyllengren (for your skilled administrative support and for the care and
thoughtfulness that provide a great environment for accomplishing things),
Dr Erik Thunberg, now at the Swedish National Grid, (for support in solving
Unix computer problems and for the shared joy in exploring the features of
\LaTeX{}), Jan Timmerman (for encouragement and shared dreams about the
open sea, and once a year about a “Semla”), Tech Lic Jonas Persson (for
encouragement and all the shared entertaining moments), Tech Lic Ying He,
now at Vattenfall, (for the many laughs, varities of Chinese tea kinds and
sweets, and enjoyable trips round the world), Margaretha Surjadi (for your
concern and spreading of light), Tech Lic Mikael Amelin (for your sense of
humour), Dr Peter Bennich (for good friendship), Dr Viktoria Neimane,
now at Vattenfall, (for your concern and friendship), Fredrik Carlsson (for
friendship and shared interest in research education questions), Göte Berg
(for help with practical issues and many common interests in art and mu-
sic), the EMD personnell (for contributing to an atmosphere of fun in the
Department and always inviting me to your events) and Peter Lönn (for
support with computer issues).

I also wish to give a special thanks to: the PhD students at KTH that
entrusted me representing them trough the PhD student union in various
ways, the personnell at KTH that in several ways contributed to a sound
working environment, and a special thanks to my colleague at KTH Tech
Lic Nulifer Ipek (for being there), Dr Per-Anders Löf, now at ABB, (for
following the progress in the project). I wish to thank Associated Professor
Math Bollen for the critique of my work, being opponent for the licentiate
thesis, and for the following many good times and discussions) and also to the
other colleagues at Chalmers University of Technology for good friendship.

Finally, I wish to thank, you that hold my heart, my family and close
personal friends, without whom this would not have been possible. Thanks
for all the love and support over the years. I hope to be able to return it in
the years to come.

Lina Bertling
Stockholm,
August,2002.
Abbreviations

AC  Alternating current
AENS  Average energy not supplied per customer served
ASAI  Average service availability index
CAIDI  Customer average interruption duration index
CAIFI  Customer average interruption frequency index
Cigré  International council on large electric systems
CM  Corrective maintenance
CTAIDI  Customer total average interruption duration index
DC  Direct current
ELFORSK  Swedish Power Utilities Research and Development Organization
EPR  Ethylene propylene rubber
EPRI  Electric power research institute
HD  Högalid power station
HV  High voltage
int.  Interruption of voltage
LH  Liljeholmen power station
LV  Low voltage
MATLAB  Matrix laboratory
mth  Months
MV  Medium voltage
NKR  Norwegian crowns (SEK 1.5 ≈ NKR1)
no.  number
PD  Partial discharging
PE  Polyethylene
PM  Preventive maintenance
PP  Polypropylene
PVC  Polyvinyl chloride
RCM  Reliability-centred maintenance
RADPOW  Reliability assessment program of power distribution systems
RMS  Root mean square value
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
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<tr>
<td>SAIDI</td>
<td>System average interruption duration index</td>
</tr>
<tr>
<td>SAIFI</td>
<td>System average interruption frequency index</td>
</tr>
<tr>
<td>SEK</td>
<td>Swedish crowns (SEK 10 ≈ Euro 1 ≈ USD 1)</td>
</tr>
<tr>
<td>SINTEF</td>
<td>Foundation for scientific and industrial research at the Norwegian Institute of Technology</td>
</tr>
<tr>
<td>SJ</td>
<td>Statens järnväg</td>
</tr>
<tr>
<td>Svel</td>
<td>Association of Swedish electrical power utilities (included in Swedenergy AB)</td>
</tr>
<tr>
<td>Svk</td>
<td>Svenska Kraftnät (the Swedish National Grid)</td>
</tr>
<tr>
<td>UMIST</td>
<td>The Manchester Centre for Electrical Energy</td>
</tr>
<tr>
<td>USASK</td>
<td>The University of Saskatchewan</td>
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<tr>
<td>XLPE</td>
<td>Cross-linked polyethylene</td>
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To my parents
Jan and Margareta
who
introduced me into the world of art and engineering,
tought me enjoying hard work and the beauty of life.
Showed the joy in travelling and exploring other cultures,
gave me my first camera to catch a glimpse of life,
gave me the opportunity to live my life in a place,
which beauty warms my heart every morning.
Chapter 1

Introduction

1.1 Problem Formulation

1.1.1 Background

Electricity distribution systems themselves constitute the
greatest risk to the interruption of power supply.

Using electrical energy on demand is one of the fundamental presumptions
of a modern society, and the advent of digitalized techniques has increased
the need for high reliability of supply. Moreover, failure statistics [1],[2],
[3],[4], [5], reveal that the electrical distribution systems themselves constitute
the greatest risk to the uninterrupted supply of power. Traditionally
however, distribution systems have received less attention than the generation
and transmission parts of the overall electrical power system. This
is emphasized by the clear difference in the number of publications within
the various relevant fields (see the bibliographies [6], [7],[8],[9],[10], [11],[12]).
The main reasons why distribution systems have not traditionally been the
centre of focus are that they are less capital-intensive and that their failures
cause more localized effects compared with transmission systems. However
the focus on the transmission system is moving toward distribution as the
business focus changes from consumers to customers.
1.1. Problem Formulation

Introduction of liberalized market has led to a shift from technical to economical driving factors.

Electric power systems have undergone major changes during the last few years due to the introduction of the so called deregulated or liberalized market. (Sweden for example was one of the first countries to deregulate its power-supply market, doing so in January 1996 [13].) This has implied that the driving factors have moved from technical to economical and whole new players have made their appearance on the field. This fundamental and global-level change in the running of power systems has brought about a diversity of effects, including new opportunities and new complications. Of course the change in itself is under great scrutiny. A recent and comprehensive publications dealing with this topic can be found in [14], see also [15].

Cost-effective expenditure requires undertaking preventive maintenance (PM) if the benefits in reliability are to balance the cost of implementing the measures.

Electrical power distribution systems are owned and operated by the power utilities. These utilities are themselves active in the deregulated market and face various market requirements. On the one hand for example, there are the customers paying for a service (delivered energy) and the authorities imposing regulation, supervision, and compensation depending on the degree of fulfillment of contractual and other obligations see for example Norway [16] and Sweden [17]). On the other hand, the owners place cost-effective expenditure requirements on the utilities. This means that electricity utilities must satisfy quantitative reliability requirements while at the same time trying to minimize their costs. One clear and predominant expense for a utility is the cost of maintaining system assets, for example through adopting preventative measures, collectively called preventive maintenance (PM). PM measures can impact on reliability by either, (a) improving the condition of an asset, or (b) prolonging the lifetime of an asset. Reliability on the other hand, can be improved by either lowering the frequency or the duration of power supply interruptions. PM activities could impact on the frequency by preventing the actual cause of the failure. Consequently in cost-effective
expenditure, PM should be applied where the reliability benefit outweighs the cost of implementing the PM measure.

**Increased complexity and the demands for handling the PM require new systematic and quantitative approaches.**

Electrical utilities are changing the way they run maintenance to meet the increased requirements for efficiency and effectiveness [5], [18]. The pressure to reduce operational and maintenance costs is already being felt [19], and the conducting of PM is undergoing change [15],[20]. The cost of PM is expected to increase in the future due to a growth in PM demand. This in turn is an effect of trying to keep expenses low by using the available assets for a longer period of time utilizing maximum lifetimes [21]. Another change in the conducting of maintenance, having the same cost-effectiveness objective, is the use of subcontractors where specific PM measures are bought on contract. Moreover, manufacture is becoming increasingly incorporated into maintenance systems [19]. Another observable effect is the trend of merging many smaller utilities into fewer and larger ones, with the accompanying large-scale advantages. This results in larger systems where personnel no longer possess detailed knowledge or experience. Therefore new systematic methods for conducting maintenance routines are required that are not reliant on the knowledge of specific individuals. In summary, the situation for conducting PM shows an increase in complexity and demand, that in turn requires adopting new systematic and quantitative approaches.

**Reliability-centred maintenance is a systematic method wherein the maintenance of system components is related to improvement in system reliability.**

It can be acknowledged that a more complex maintenance situation needs to be adopted featuring more systematic methods that can in turn be demonstrated using a quantitative relationship between reliability, PM measures, and expenses. An effective maintenance strategy should provide the best solution for obtaining a required system function (availability of supply in this case) constrained by cost. Reliability-centred maintenance (RCM) is just such a method wherein system-component maintenance is related to the improvement in system reliability [22],[23],[24]. The main feature of RCM is
its focus on preserving system function where critical components for system reliability are prioritized for PM measures. However the method is based more on qualitative than quantitative measurements.

**RCM is not new, however detailed quantitative application to power systems has still not been fully developed.**

RCM methodology developed in the 1960s to handle the PM of increasingly larger and more complex Boeing aircraft. The aim of RCM was to attain a certain level of reliability and reduction in the expenses associated with maintenance. The results were successful and the methodology developed further. In 1975 the US Department of Commerce defined the concept RCM and declared that it should be used in all major military systems [22]. In the 1980s, the Electric Power Research Institute (EPRI) introduced RCM to the nuclear power industry. Interests in the power distribution sector turned to RCM with the introduction of the "market", which as previously discussed introduced economic driving forces as well as a more complicated level of handling maintenance. Power utilities are currently undergoing major changes within their maintenance planning, and adopting RCM could be one way of achieving an effective strategy. This has been evaluated by for example Swedenergy AB [25].

What differentiates the application of RCM in electrical power distribution from other previously named systems is that reliability is not as critical in power distribution as it is in for example aircraft or nuclear power plants. Additionally, there is not as much revenue to be gained by implementing sophisticated reliability methods in for example simple radial power distribution systems. However this situation is changing with deregulation and the introduction of new players and ways of operating and handling maintenance. New driving factors can provide the incentive to try out new methods, and perhaps a simple RCM approach providing quantitative indices could be a solution. Another interesting observation of the differences between the levels of criticality in these different systems, is that a power distribution system is repairable. Failures have a certain level of acceptability in both number and duration, which is not the case for example in nuclear power plants. This leads to a situation where there are more solution options for maintenance issues.
1.1. **Problem Formulation**

Techniques and theories for reliability evaluation and maintenance planning in power systems have been well developed separately (for example [6]-[12],[26],[27], [28],[29], [30],[31],[32]). The earliest publication appearing in the bibliographies [6]-[12] relating to this field comes from Calabrese in 1933, and the first major group of papers from Lyman in 1947. However there is a lack of techniques in use that relate to both of these two issues. This may indicate that the techniques currently available are not good enough.

One probable reason for this is the gap between theory and practice, where sophisticated theoretical methods are too complicated to be used effectively. Advanced theoretical optimization theories do not automatically solve the practical problems of planning maintenance. Another reason could be that the data input required for the models are not available, and that there has been a lack of incentive to solve this. However there is a belief that this will change.

**In this thesis, an enhanced RCM methodology including a quantitative relation between PM and reliability has been developed.**

The need for improved PM strategies capable of showing the benefits of PM on system reliability and costs in electrical power distribution systems has been identified. Furthermore, it has also been shown that one possible solution for this would be the development of an improved RCM methodology that includes a quantitative relationship between reliability and maintenance. Furthermore, it has been identified that the main difficulties that need to be overcome are: (i) the gap between theory and practice, and (ii) the lack of input data to support the methodology. Solving these issues therefore provides the starting point for this thesis.

1.1.2 **Objective**

The objective of this work has been to develop appropriate techniques and methods to support strategies for PM in electrical power distribution systems. Moreover, the strategies developed should be cost effective, which implies that they should balance the benefits in system reliability against the costs of maintenance methods, and the frequency and selection of components to be measured. This has led to the utilization of the RCM method.
1.1. **Problem Formulation**

However, this method needs to be enhanced for specific application to electrical power distribution systems, and for including a quantitative measure of reliability.

The objective is therefore to develop an RCM methodology that:

- includes a quantitative relationship between the PM of system components and system reliability,
- can be applied generally to the analysis of electrical power distribution systems, and
- includes cost considerations in the formation of cost-effective PM plans.

1.1.3 **Approach**

**Overall project overview**

This is one of two research projects undertaken within a broader area entitled "Reliability Aspects for Electric Distribution Systems", and performed at the Competence Centre in Electric Power Engineering at KTH. A list of publications from this centre and the department of Electrical Engineering can be found in the annual reports (for example [33]).

Figure 1.1 below provides an overall picture of the research project. The starting point is the issue of *quantitative impacts on the unavailability of power*, which is one of the measures of reliability performance. Unavailability of power can in principle be reduced in either of two ways: (i) by lowering the *frequency of interruption*, that is the number of failures, or (ii) by reducing the *outage time*, that is the duration of failure. In the overall research project "Reliability Aspects for New Electricity Distribution Systems" both these aspects for improving reliability have and are being analysed. The focus for addressing the first aspect above involves the application of RCM methodology (providing the focus of this thesis), and the focus of addressing the second aspect is by increasing the level of *automation* (performed by Ying He [34]). In order to address both research aspects, the overall project was divided into two stages.

The first stage focused on the development of a tool called the reliability assessment of distribution power systems (RADPOW). The second stage focused on the application and further development of RADPOW with the
1.1. Problem Formulation

The aim of investigating the impact on reliability by applying RCM (increased automation).

![Diagram](image_url)

**Figure 1.1.** Overall project overview

Development of the reliability evaluation program RADPOW

The previous section suggested that there is a need for the systematic and quantitative reliability analysis of electrical power distribution systems. Reliability evaluation is not a new topic, therefore it is reasonable to presume that tools for such purposes are already available. However, even though there are tools available for evaluating reliability, they have all got their specific limitations and no widely acceptable tool was found in the marketplace [35]. Therefore, a decision was made to develop a new computer program for reliability analysis within the overall research project. Apart from providing support for the reliability analysis, the development of this tool is also beneficial because it: (i) creates new expertise in the field, (ii) provides overall insight into the resulting programme which is necessary for research, and possible further developments by for example incorporating new components and techniques.
1.2 Overview of the Thesis

The properties required of this new computer program are summarized as follows it must be able to:

- compute basic reliability indices,
- decide the impact of new technologies,
- analyse electrical systems with new network topologies,
- decide the impact of protection and control in the system, and
- be flexible and easy to develop further.

The first activities in developing such a reliability assessment program were to implement basic evaluation methods and techniques. These provide the basis for application-oriented activities and more detailed reliability measures in the future and serve as the base upon which new developments of methods and modules can be founded.

Approach used in the development of RCM methodology

The following approach has been used to achieve an RCM methodology that fulfills the objectives of this work. The first step was to gain an understanding of the concepts involved in RCM and to formulate a framework. The second step was to apply this framework to real systems and real input data. The final step, based on the understanding achieved during the application studies, was to formulate a generic methodology. Figure 1.2 illustrates the RCM methodology development approach. Consequently, the task of achieving a cost-effective maintenance plan, can be solved using the approach shown on the right hand side of Figure 1.3, where the problem has been identified as a learning process. Moreover, by adopting this approach, real problems can be identified and real solutions found to overcome them, and the theory can be put into practice.

1.2 Overview of the Thesis

The structure of the thesis follows the same order as the approach used to develop the generic RCM methodology. This means that the first part of the
1.2. Overview of the Thesis

**Figure 1.2.** Approach to developing the RCM Methodology.

**Figure 1.3.** Task solution methods: (a) conventional, and (b) the method used here.
thesis involves the evaluation of general reliability techniques and maintenance strategies. This is then followed by applying these to real distribution systems, which includes a comprehensive section relating to input data, and another on the modelling and analysis of the cable component behaviour. This is followed finally by formulation of the resulting generic methodology. The overall thesis structure can be broken down into individual chapters as follows:

- **Introduction**
  
  *Chapter 1,* provides an introduction, background and rationale for the work, the approach adopted, and the main results obtained in this doctoral project.

- **Reliability Techniques and Maintenance Strategies**
  
  - *Chapter 2* introduces and defines fundamental concepts for the analysis that follows.
  - *Chapter 3* introduces basic evaluation methods and techniques for reliability modelling and analysis.
  - *Chapter 4* presents the computer program developed for reliability analysis of distribution power systems (RADPOW). Firstly it provides a description of the main features and the structure of the RADPOW program, secondly an overall and detailed presentation of its functions.
  - *Chapter 5* introduce various maintenance procedures.
  - *Chapter 6* provides an introduction to the reliability-centred maintenance method (RCM) and experiences using it. It also summarizes the formulated RCM framework and introduces the study applications that led to development of the generic RCM methodology.

- **RCM Application Studies**
  
  - *Chapter 7* introduces the various components of the distribution system, and identifies available sources of statistics that include the causes of component failure. The underground cable component has been analysed specifically.
1.2. Overview of the Thesis

- Chapter 8 presents results from a comprehensive study of the causes of failures in an underground cable system. This study was undertaken at the Swedish power utility, Birka Nät AB, and is based on knowledge from disturbance statistics and the experiences of maintenance personnel.

- Chapter 9 provides deeper knowledge about the behaviour of the cable component. This includes a description of the specific phenomenon of water treeing, which leads to degradation in the condition of the cable, and methods for measuring and preventing the same.

- Chapter 10 presents two RCM application studies; the first being a rural overhead power line system (Flymen System), and the second, an urban underground power cable system (Birka System). The approach used for relating reliability and PM Approach I implies the assumption that maintenance has a measurable percentage impact on reducing the causes of component failure.

- Chapter 11 defines a model for the quantitative relationship between reliability and PM for an underground cable component that is at risk of faulting due to water treeing. This is based on the results of experience, experiments and physical expressions. The resulting model includes the time parameter and is referred to as Approach II. The modelling of the cable component has the express purpose of demonstrating how to develop theory with the intention of generating generic principles.

- Chapter 12 puts the model developed for the relationship between reliability and PM of a cable component into a system perspective. System, and cost and benefit analyses are done to compare different maintenance methods and strategies used in PM, and completes the RCM method for the Cable Application Study.

- Formulation of a Generic Approach

Chapter 13 summarizes the Cable Application Study and presents the subsequent formulation of a generic RCM methodology for electrical power distribution systems.
1.3. Main Contributions

The main contributions of this thesis are summarized in the following.

1. The thesis develops a computer tool called RADPOW (Reliability Assessment of Distribution Power Systems) for making reliability evaluations, which has been developed in cooperation with Ying He [34]. The RADPOW tool is based on analytical techniques for the evaluation of reliability indices in a general power distribution system. The main features of the program are that it:

   - computes basic reliability indices load point indices and system indices,
   - analyses general distribution systems,
   - maintains the network structure for the analysis,
   - is implemented in the object-oriented language C++, and
   - is written as separate modules for the different functions.

2. The thesis presents a formulation of an RCM framework that encapsulates the logical order of the various procedures required, the need for interaction between system and component levels, and an indication of the various sorts of input data needed. Furthermore, these procedures are formulated into three different stages for the RCM analysis, being:
   (i) system reliability analysis, (ii) evaluation of PM and component behaviour, and (iii) system reliability and cost-benefit analysis.
3. In relation to RCM Application Studies, the thesis presents...

(a) A general overview of the literature containing statistics on electrical power distribution system components, focusing on the causes of failures.

(b) A comprehensive survey on the causes of failures; done in cooperation with the Swedish power utility (Birka Nät AB), including knowledge from both disturbance statistics and the experiences of maintenance personnel. In addition to providing input data for the RCM application studies, this survey also contributes an analysis of today's maintenance situation from a utility perspective, and recommendations for improvements to the disturbance reporting system.

(c) A definition and implementation of a model for defining a quantitative relationship between reliability (failure rate) and PM for an underground cable component. In addition, the effect of the condition of degradation of the cable due so called water treeing has been analysed along with prevention of the same. This model provides input data for the RCM analysis using Approach II.

(d) A defined failure rate model that not only provides results for increasing the understanding of the cable component, but also contributes by identifying the difficulties, as well as the possibilities for achieving this with the use of available data and knowledge about component behaviour.

(e) RCM application studies of real distribution systems with real data including:
   
   - analysis of a rural overhead line system and an urban underground cable system. Both these systems have been run through the RCM procedures (except the cost analysis), and the modelling of the relationship between reliability and PM has been done using Approach I, based on average values.
   - A more detailed study of the urban underground cable system focusing on the causes of failures of the 11 kV underground cable. The complete RCM process has been run through, and the modelling of the relationship between reliability and PM includes the time parameter, Approach II.
4. Formulation of the Generic RCM Methodology demonstrated by the application studies undertaken previously. The resulting methodology, formulated into the above defined three stages of RCM analysis, exhibits the following main characteristics. It is:

- easily adapted to the system, and supports both simple (Approach I) and thorough (Approach II) RCM analysis,
- includes an entire system perspective that is, it analyses the components that are applied to measure PM, as parts of the entire system operating for securing system function,
- clearly shows the quantitative impact of PM on system reliability and cost, and
- shows on the input data required to support the RCM analysis, and on the usefulness of the same consequently.

1.4 List of Publications

Results from this work have been published in research papers, a licentiate thesis, and a number of internal university reports. These have been listed and described below. In addition, there has also been involvement in other studies and publications related to this work (see [25] and [36]).

Thesis

Results from the first part of the research project have been presented in the following licentiate thesis.


Papers

Papers published within the framework of this work are listed below:

1.4. List of Publications


2. Bertling L., ”Underhållsstrategi för rätt tillförlitlighet”, Energitinget, Eskilstuna, Sweden, April, 2002 (Swedish); English title: ”Maintenance Strategy for Correct Reliability” (Swedish National Energy Administration).


1.4. List of Publications


Reports

Internal reports at the department presenting the results of this work are listed below. These reports are either related to the RCM methodology development and listed under RCM, or relate to the reliability tool development and are listed as RADPOW. All of the reports have been published at the Department of Electrical Engineering and division of Electric Power systems (EES) at KTH.

- **RCM**


- **RADPOW**


Chapter 2

Definitions and Terminology

2.1 Electrical Power Distribution Systems

2.1.1 Historical Background

Until the 1870s electricity was a matter of interest only to engineers and researchers [37]. Experiments were conducted to learn more about electrical phenomena, and batteries were the main source of power. Then the Belgian researcher Zenobe Gramme invented the generator, which could provide greater electrical currents than the battery. This saw the beginning of the breakthrough for electricity. Electrical feeders were then built from small and large power plants to provide light and run electrical machines for primary and secondary industries. The first incandescent lamp came into being around 1880, invented simultaneously by the American Thomas Alva Edison and the Englishman Joseph Swan. It was then that the benefits of electricity for daily (especially nightly) life became clear, and with it came the birth of institutions such as public libraries. Electricity had finally reached its customers providing the demand and rational for electrical power delivery systems.

2.1.2 Power Distribution Systems

Power delivery systems consist of transmission and distribution systems (T&D systems) for the transport of electrical power from producers to cus-
2.1. Electrical Power Distribution Systems

Customers. These consist of thousands of overhead lines, substations, transformers and other equipment spread over large geographical areas, and interconnected to deliver power on demand to customers. The major design of a T&D system is based on two physical and economic constraints.

The first constraint being that it is more economical to transport power at high voltages because of the reduction in losses, but higher voltage transmission requires equipment with greater capacity which is in turn itself more expensive. However, the voltage level that European customers utilize is 250 V/416 V (three-phase). This is not an economical level for transmission, therefore costly voltage transformers are required.

The second constraint is that power is more economical to produce in large amounts, but it must be delivered in small quantities at low voltage levels (£20 \( - \) 250 V). Although it should be acknowledged that with the reconstruction of electric power systems due to the introduction of deregulation this is now only partially true. A new phenomenon called distributed generation has recently been introduced, and with this it could become cost effective to produce smaller or larger quantities of power based on economical rather than technical factors. Some examples of studies in this field have been provided in [38].

Basically then, the T&D system is designed to transport power from a few large generating plants to many smaller sites (the customers). Furthermore, this has to be done using hierarchical voltage levels, from high to low.

As a consequence of this hierarchical structure, the T&D system can be thought of as being composed of several distinct levels of equipment, denoted by the following: transmission, switching, sub-transmission, substations, feeders, service/secondary and customer equipment) [39].

However the fundamental question is, which part of the whole system is the distribution system? In [39] three types of distinctions between distribution and transmission systems have been presented.

1. *Voltage levels*: transmission \( \geq 34.5 \) kV and distribution \( \leq 34.5 \) kV.

2. *Function*: distribution includes all utilization voltage equipment and all overhead lines that feed service transformers.

3. *Configuration*: transmission includes a network, and distribution includes only the radial equipment in the system.
According to [40] and [41], in the Swedish distribution system the distinction between distribution and transmission is based on the hierarchical voltage levels and agrees with the first item above. Specific limits are defined, and the distribution system refers to voltages from $0.4 - 22$ kV.

According to [42], in the UK, the distribution system is defined for the voltage levels $415$ V - $33$ kV, and so follows the first distinction. However, more recently this has been redefined to include $132$ kV [43]. Furthermore, a distinction by function is made in [1], where three different hierarchical levels have been used in the analysis of the power system, namely generation, transmission and distribution.

Item 3 is not applicable to all these references because the distribution systems described are not only radial.

In this thesis, an electric power distribution system is a system that is not limited by voltage levels or network configurations (implication not a limitation two for example distributed systems with radial feeding). The characteristics of the system are instead based on the two roles customer and utility who receive or provide electrical power respectively. Furthermore, the technical system has been greatly simplified in regard to the voltage and current phenomena, and all the dynamic characteristics have been disregarded. This simplification is more suited to lower voltage levels, which therefore justifies its use in evaluating distribution systems.

2.1.3 Terms

The following basic definitions come from the European standard EN 50160 [44].

- The **customer** is the purchaser of electricity from a supplier.

- The **supplier** is the party who provides electricity via a public distribution system, (referred to here as an **electricity utility**).

- The **supply-terminals** are the points of connection to the public system used by the customer, for example the electricity metering point, or the point of common coupling (referred to here as **load points**).
• The **supply voltage** is the root mean square value (RMS) value of the voltage at a given time at the supply-terminals, measured over a given interval.

• The **nominal voltage** \( (U_n) \) is the voltage by which a system is designated or identified and to which certain operational characteristics are referred.

• The **declared supply voltage** \( (U_c) \) is the voltage applied to the supply-terminal, which is normally the nominal voltage \( (U_n) \) of the system, but by agreement between the supplier and the customer, a different voltage \( (U_c) \) can be applied.

• The **supply interruption** is a condition where the voltage at the supply-terminals is lower than 1% of the declared voltage. A supply interruption can be classified as:
  - prearranged (or planned) when consumers are informed in advance, or
  - accidental, when caused by failures. Failure can for example be related to external events or to equipment.

Accidental interruptions are classified as:
  - long interruptions (interruptions \( \geq 3 \) min), or
  - short interruptions (interruptions \( \leq 3 \) min).

However different definitions are used for interruptions; for example in the UK the limit is 1 min.

In Sweden, information is recorded for each accidental and planned supply interruption. This information consists of the number of interruptions, their length of duration, and the number of customers affected [45].

Some fundamental concepts that together form the basis of the Swedish disturbance reporting system DAR, presented in [46] and the accompanying glossary [47] are defined and presented below.

• A **disturbance** in a power system (or component) implies an event which results in an involuntary decrease of the system’s ability to deliver electrical power.
• If a system that is normally under voltage becomes dead or disconnected, it suffers an **interruption of voltage**.

• Interruption of voltage can be involuntary (for example a disturbance), or voluntary (for example planned). If an interruption of voltage causes customers to lose supply, they are exposed to an **interruption of supply**.

The supply interruptions in this thesis are generally referred to as **outages** or **failures**. These denote the state of a component when it is not available to perform its intended function due to some event directly associated with the component. An outage may cause an interruption of service (power supply) to customers, which is in accordance with [1].

### 2.1.4 Failures

![Failure Diagram]

**Figure 2.1.** Definitions of failure.

The general definitions of **failure** that is used in this thesis can be structured according to Figure 2.1. Failures can be divided primarily into damaging faults and non-damaging faults. Outages caused by damaging faults
are usually called permanent forced outages, while outages caused by non-damaging faults are categorized again after the action of restoration into: (i) transient forced outages when the system is restored by automatic switching and the outage time is negligible, and (ii) temporary forced outages when the system is restored by manual switching or fuse replacement. Long interruptions are often caused by damaging faults (permanent faults) and short interruptions are often caused by transient faults.

A structure for the different types of outages, capturing the models of restoration, are defined in [48] (and by Figure 191-24) with a corresponding presentation in [49] (and by Figure III-3).

Furthermore, damaging faults can be separated into two models of failure passive failure and active failure defined as follows in [48].

**Definition 2.1.** An active failure is a failure of an item which causes the operation of the protection devices around it and results in the opening of one or more fuses.

**Definition 2.2.** A passive failure is a failure that is not an active failure.

The failed item (component) by an active failure is consequently isolated and the protection breakers are re-closed. This leads to service restoration to some or all of the load points. However, for the passive failure service is restored by repairing or replacing the failed component (or by re-closing a disconnector and using another feeder for supply).

The outage time of a failure is made up of various items depending on the cause. Figure 2.2 shows two different time sequences following active and passive failure. As can be seen in the figure, the active failures can be restored by either repair or replacement, or by switching. The dotted line in Figures 2.1 and 2.2 indicates active failures that are restored by switching and not caused by a damaging fault. These are referred to as additional active failures.

**Definition 2.3.** An additional active failure is a failure mode that occurs when a component fails actively and causes interruption through its impact on other components.
Figure 2.2. Outage time sequences
2.2 Used Reliability Indices

This section presents some basic reliability indices that have been used in this thesis as general terms for quantitative measure of reliability. These indices are also those indices that can be evaluated by the reliability evaluation computer program RADPOW, discussed further in Chapter 4. These indices corresponds to general used indices as defined in literature for example by [1], [50], [51], [52].

It is however important to recognize that there are alternative formulations of the terms for reliability. For example the standard [53] formulates a three level stages with dependability, availability and reliability. For a comprehensive evaluation of reliability indices see for example [49] and also [54], and also the standard [48].

2.2.1 Load Point Indices

The program developed evaluates the following basic reliability indices for each specified load point in a distribution system network:

- expected failure rate $\lambda$ [f/yr],
- average outage duration $r$ [h/f],
- annual expected outage time $U$ [h/yr], and
- average loss of energy $LOE$ [kWh/yr].

Equations for evaluating these load point indices can be found in Chapter 4.

2.2.2 System Performance Indices

The basic problem with trying to measure reliability is how to relate the two quantities, frequency and duration [39]. One way of solving this is to use the following system performance indices classified according to [51] and [1].
2.2. Used Reliability Indices

- System average interruption frequency index (SAIFI) [int/yr,cust],

\[
\frac{\text{total number of customer interruptions}}{\text{total number of customers served}} = \frac{\sum \lambda_i N_i}{\sum N_i} \tag{2.1}
\]

where \( \lambda_i \) = the expected failure rate of the load point \( i \), and \( N_i \) = the number of customers for load point \( i \).

- System average interruption duration index (SAIDI) [h/yr,cust]

\[
\frac{\text{sum of customer interruption durations}}{\text{total number of customers served}} = \frac{\sum U_i N_i}{\sum N_i} \tag{2.2}
\]

where \( U_i \) = the annual expected outage time of load point \( i \).

- Customer average interruption frequency index (CAIFI) [int/yr,cust]

\[
\frac{\text{total number of customer interruptions}}{\text{total number of customers interrupted}} = \frac{\sum \lambda_i N_i}{\sum N_{ai}} \tag{2.3}
\]

where \( N_{ai} \) = the number of customers affected at load point \( i \).

- Customer average interruption duration index (CAIDI) [h/int]

\[
\frac{\text{sum of customer interruption durations}}{\text{total number of customer interruptions}} = \frac{\sum U_i N_i}{\sum \lambda_i N_i} \tag{2.4}
\]

- Customer total average interruption duration index (CTAIDI) [h/yr,cust]

\[
\frac{\text{sum of customer interruption durations}}{\text{total number of customers interrupted}} = \frac{\sum U_i N_i}{\sum N_{ai}} \tag{2.5}
\]

- Average energy not supplied per customer served (AENS) [kWh/yr,cust]

\[
\frac{\text{total energy not supplied}}{\text{total number of customers served}} = \frac{\sum LOE_i}{\sum N_i} \tag{2.6}
\]

where \( LOE_i \) = average loss of energy of load point \( i \).
2.3. **Maintenance Strategies**

- Average service availability index (ASAI)
  \[
  \frac{\text{customer hours of available service}}{\text{customers hours of service demand}} = \frac{\sum N_i \cdot 8760 - U_i N_i}{\sum N_i \cdot 8760}
  \]

Note that CTADI and CAIFI include the total customers that are interrupted, which implies that each individual customer is only counted once regardless of the number of times their supply is interrupted. This however does not apply to CAIDI where all interruptions for each customer are counted. Moreover the indices are related according to the following:

\[
\text{CAIDI} = \frac{\text{SAIDI}}{\text{SAIFI}} \quad \text{and} \quad \text{CAIDI} = \frac{\text{CTAIDI}}{\text{CAIFI}}
\]

If \(N_{ai}\) equals \(N_i\), then SAIFI equals CAIFI. This assumption was made for implementation in RADPOW, therefore the index CAIFI has not been used further in the application studies.

2.3 **Maintenance Strategies**

Maintenance is an activity undertaken with the purpose of enabling the fulfillment of a desired performance in a component by maintaining its ability to correctly function or return to a previous level of function. In this thesis the maintenance activities have been divided into two different groups according to their aim.

- **Preventive maintenance (PM)** aims to reduce the probability of the component failing, for example via lubrication, the replacement of components or inspection.

- **Corrective maintenance (CM)** aims to restore performance after failure via repair.

It is however important to recognize that there are different definitions and terminology for maintenance concepts. For example the expressions of PM and CM are used in [55], but not in [15]. Moreover, in the evaluation of maintenance strategies as presented in [26] and [27] other terminology has been used for the maintenance. These are based on available approaches for maintenance for example predictive maintenance.
Chapter 3

Reliability Evaluation

This chapter introduces basic evaluation methods and techniques for reliability modelling and analysis.

3.1 Introduction

This thesis analyses one fundamental problem area, that being failure events in electric distribution systems. In order to make analysis of this fundamental issue possible, abstract models have been created using a mathematical language rather than presenting the problem analogously (for example as network maps do). An abstract model can be either deterministic or probabilistic. In a deterministic model, reality can be approximated with a mathematical function, for example distributed voltage can be described using a sinusoidal function. In a stochastic or random model, the unknown behaviour is included in the model, for example the voltage discrepancy from a sinusoidal function. Probability theory is used to analyze this random behaviour. The techniques used in this work are based on stochastic models.

Reliability theory is well documented and this section presents some fundamental aspects directly related to the analysis performed and summarized in the thesis. The main sources of the material contained in this section include [56], [57],[58],[59],[60], [61] and [62].
3.2 Comparison of Evaluation Techniques

Like all mathematical analyses, reliability analysis concentrates firstly on modelling the mathematical problem, and secondly on finding solutions to the problem using the model. Furthermore, the model can be used to solve the problem directly and mathematically (analytical method), or indirectly by numerical experiments (simulation method). A comparative study of these two fundamental methods for assessing reliability is discussed later on in this section and summarized in Table 3.1. A conclusion is presented at the end of the section, constituting the selection of the method for RADPOW.

Table 3.1. Comparable features of computational methods.

<table>
<thead>
<tr>
<th>Analytical method</th>
<th>Simulation method</th>
</tr>
</thead>
<tbody>
<tr>
<td>The model often needs to be simplified.</td>
<td>Every phenomena which can be modelled can be simulated.</td>
</tr>
<tr>
<td>Relatively short solution time needed.</td>
<td>A large amount of computing time is needed for finding solutions.</td>
</tr>
<tr>
<td>Always the same results for a given model and input data.</td>
<td>Results dependent on the actual random numbers and the number of repeated simulations.</td>
</tr>
<tr>
<td>Output limited to average values.</td>
<td>Probability distributions associated with the reliability indices as output.</td>
</tr>
</tbody>
</table>

3.2.1 Analytical Method

In the analytical method, reliability evaluation techniques are used directly on the model by solving the mathematical equations. Moreover, there are two fundamental techniques used for reliability evaluation, namely network modelling and Markovian modelling. The most commonly used out of these two is the network modelling technique. Amongst other methods, the RELNET program from UMIST in the UK [63], and RELRAD from EFI in Norway [64] are based on this technique. The Markovian modelling technique has been used for the R-RADS program at the University of Washington [65]. One reason for the popularity of network modelling techniques may
stem from the simplicity of the method and the natural similarities between the network model and the distribution system topology.

**Network Modelling**

A technical system can always be thought of as being composed of components. In the network modelling technique, the structural relationships between a system and its components are considered. The physical system is transferred into a reliability network using the system operational logic and knowledge about the physical behaviour and requirements of the system. Details of these techniques have been presented in [50], [66].

One of the central problems in reliability analysis is modelling the failure behaviour of the system. This can be done by deducing possible failure modes as the *minimal cut set* does.

**Definition 3.1.** A **cut set** is a set of components which upon failure, cause a failure of the system. A cut set is minimal when it cannot be reduced any further and still remain a cut set.

There are a number of different approaches to obtaining minimal cut sets. A distribution system can be treated as a system composed of load points the subsystems. One approach, referred to as the *load-point driven* technique, deduces minimal cut sets for each load point by identifying each event that leads to a failure of that load point. Furthermore, reliability indices are deduced for each load point and these indices are then combined to provide the system indices. An algorithm for the deduction of minimal cut sets by using the *minimal paths* technique has been specified in [67].

**Definition 3.2.** A **path** is a set of components that when operating guarantees the operation of the system. A path is minimal when it cannot be reduced any further and still remain a path.

Another approach to obtaining cut sets not based on reliability networks is the MOCUS algorithm [66]. This algorithm uses *fault trees* for evaluating the failure probability of a subsystem. A fault tree is a logical diagram that displays the relationship between an undesired event in the system and the cause of that event. The aim is to identify events via logical conditions that lead to the event that is under investigation the top event.
3.2. Comparison of Evaluation Techniques

In a comparative study [68], a load-point-driven approach has been compared with an event-driven approach. The principle of the event-driven approach is to treat each failure event separately, and see the effect of the failure on the whole system by identifying the affected load points. Consequently, the major difference between the two approaches is that in the load-point-driven approach all failure events for each load point are considered in turn, but in the event-driven approach, all load points affected by one failure event are considered in turn.

Markovian Modelling

In the Markovian model, it is assumed that in an interval of given length, the probabilities of a working component failing (or a failing component being repaired) are only dependent on the state of the system at the beginning of this small interval, and the length of the interval [69]. This property of lack of memory means that information on how the system entered the current state or when it entered the state is not needed. For a detailed description see [69], [66].

The major drawback with this technique is the large number of states needed to model a system. This is due to the fact that the number of states increases exponentially with the number of factors studied. Therefore many simplifying assumptions have to be made to limit the Markov model to a manageable size.

3.2.2 Simulation Method

In the simulation method, an actualization of the process is simulated and after having observed the simulation process for a given period, estimates are made of the unknown parameters. The simulation is consequently treated as a series of real experiments.

There are several types of simulation processes. In reliability analysis, simulation often concerns stochastic processes, that is the simulation of random events. These simulation methods are commonly referred to as Monte Carlo simulations. Stochastic simulation can be used in a random or a sequential way. In the random approach, the simulation creates randomly chosen intervals, and in the sequential approach the intervals are chosen in chronological order. This implies that if a system model is simulated, where
3.3. Modelling of Life Distribution Functions

3.2.3 The Method used in RADPOW

The decision about which method to use in RADPOW was based on the result from the comparative study of computational techniques for evaluation of reliability [68]. These are summarized as follows:

- the analytical method has been used as the basic approach for the reliability assessment,
- the network modelling technique and the minimal cut set (load-point-driven) approach have been used for the deduction of failure modes, and
- the Monte Carlo simulation technique has been incorporated with the basic approach, to provide the probability distributions associated with the reliability indices of interest.

3.3 Modelling of Life Distribution Functions

A common application of probability theory, as well as the fundamental issue for this thesis, is to predict the lifetime of a unit using probability theory. The lifetime of a unit can be described by a random variable $X$. The distribution function describes the probability that the lifetime is less or equal to $t$. 
3.3. Modelling of Life Distribution Functions

The fundamental functions for a one-dimensional, continuous, stochastic variable is defined as follows.

One way to describe the characteristics of a one-dimensional continuous random variable \( X \) is to use its distribution function. For a given outcome of \( X \), \( (x) \) is the probability \( P(X \leq x) \) that \( X \) is smaller or equal to \( x \). If this is made for all of \( x \), a function \( F_X(x) = P(X \leq x) \) is obtained, which is defined for all values in the interval \(-\infty < x < \infty\).

**Definition 3.3.** The **distribution function** for the continuous one-dimensional random variable \( X \) is defined by:

\[
F_X(x) = P(X \leq x), \quad -\infty < x < \infty
\]  

(3.1)

The distribution function is evaluated as follows:

\[
F_X(x) = \int_{-\infty}^{x} f_X(t) dt
\]  

(3.2)

If a function \( f_X(x) \) exists so that Equation 3.2 applies, then \( X \) is said to be a continuous random variable. The function \( f_X(x) \) is called the density function for \( X \).

**Definition 3.4.** The **density function** for the continuous one-dimensional random variable \( X \) is defined by:

\[
f_X(x) = F_X'(x)
\]  

(3.3)

in every point \( x \) where \( f_X(x) \) is continuous.

The density function describes how the total probability (1) is distributed over the infinite number of possible \( x \) values.

Based on the two functions above introduced \( (F_X(x) = F(t) \) and \( f_X(x) \)), the lifetime evaluation uses the two functions defined below.

**Definition 3.5.** The **reliability function** (or the survival probability function) \( R_X(t) \), defined by:

\[
R_X(t) = 1 - F_X(t)
\]  

(3.4)
3.3. Modelling of Life Distribution Functions

Definition 3.6. The failure rate function (or hazard function) \( \lambda(t) \) is defined by:

\[
\lambda(t) = \frac{f_X(t)}{R_X(t)}
\]

(3.5)

An unavailability function that is the inverse of availability is consequently \( 1 - R_X(t) = F_X(t) \). In addition there are two measurements that are of specific interest here, being the expected lifetime and the variance \( V(X) \). The variance is commonly denoted by \( \sigma^2 \). The variance measures the distribution of different outcomes for the random variable, and the standard deviation is defined by \( D(X) = \sqrt{V(X)} \). The result is a measure of the distribution that has the same units as the random variable. The standard deviation is commonly denoted by \( \sigma \).

Let \( X \) be the random variable for the length of life of a component or system of components. Table 3.2 summarizes the different functions and measurements for this, as well as presents their relationships defined by the distribution of the variable \( X \).

These characteristics are general and could be used to define any continuous random variable \( X \). However there are several distribution functions that are widely used for modelling, for example uniform distribution, normal distribution, log normal, exponential distribution, Weibull distribution and more. One way of modelling the lifetime of a component is consequently to assume that it can be described by the characteristics of a known distribution, and then select parameter values that fit the specific purpose.

3.3.1 Exponentially-distributed Random Variable

The assumption that the lifetime follows an exponential function is widely adopted. The reason for this is that the resulting failure rate functions imply a constant failure rate. The characteristic functions are presented below.

Definition 3.7. An exponentially-distributed random variable \( X \in Exp(m) \) has the following characteristics for the density and distribution functions respectively:

\[
f_X(x) = \begin{cases} 
1/m \cdot e^{-x/m} & \text{if } x \geq 0 \\
0 & \text{if } x < 0
\end{cases}
\]

(3.6)
### 3.3. Modelling of Life Distribution Functions

<table>
<thead>
<tr>
<th>Notation</th>
<th>Name</th>
<th>Definitions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_X(x)$</td>
<td>Distribution function</td>
<td>$F_X(x) = P(X \leq x)$</td>
</tr>
<tr>
<td>$R_X(x)$</td>
<td>Reliability function (or survival</td>
<td>$P(X &gt; x) = 1 - F(x)$</td>
</tr>
<tr>
<td>$f_X(x)$</td>
<td>Probability density function</td>
<td>$F_X(t(x)) = -R_X(t(x)$</td>
</tr>
<tr>
<td>$\lambda(x)$</td>
<td>Failure rate (hazard) function</td>
<td>$\lambda(x) = \frac{f_X(x)}{R_X(x)} = \frac{F_X(t(x))}{(1 - F_X(x))}$</td>
</tr>
<tr>
<td>$m$</td>
<td>Expected lifetime</td>
<td>$m = \int_0^\infty x f_X(x)dx = \int_0^\infty R_X(x)dx = \int_0^\infty \mu^2 f_X(x)dx$</td>
</tr>
<tr>
<td>$\sigma^2$</td>
<td>Variance</td>
<td>$\sigma^2 = \int_0^\infty (x - \mu)^2 f_X(x)dx$</td>
</tr>
</tbody>
</table>
where $m > 0$

$$F_X(x) = \begin{cases} 0 & \text{if } x < 0 \\ 1 - e^{-x/m} & \text{if } x \geq 0 \end{cases}$$  \hfill (3.7)

It can be easily deduced that the resulting failure rate function (defined in Table 3.2) is constant, meaning that another notation for $m$ is therefore $\lambda$.

Figure 3.1 shows the characteristic functions for the exponentially-distributed lifetime with $m = 2$. The first graph shows the density function. The larger the value of $m$, the more widespread the probability mass over the interval $(0, \infty)$ becomes.

**Figure 3.1.** Functions for an exponentially-distributed random variable $X(m = 2)$.  

3.3.2 Weibull-distributed Random Variable

Accurate modelling of the system components requires distribution functions that allow different characteristics of the failure rate functions. One of the widely known distribution functions that includes several characteristics for the failure rate function is the Weibull function.

**Definition 3.8.** A Weibull-distributed random variable $X \in Weibull(a, b)$ has the following characteristics for the density and distribution functions respectively:

$$f_X(x) = \begin{cases} \frac{c}{a} (x/a)^{c-1} e^{-(x/a)^2} & \text{if } x \geq 0 \\ 0 & \text{if } x < 0 \end{cases}$$

(3.8)

where $a$ and $c$ are positive numbers, and

$$F_X(x) = \begin{cases} 0 & \text{if } x < 0 \\ 1 - e^{-(x/m)^c} & \text{if } x \geq 0 \end{cases}$$

(3.9)

This function has been shown to be useful for example with breakdown strength data. Different values of the parameters $a$ and $c$ provide a band of distributions, and some special cases are: $c = 1$ which gives the exponential distribution, and $c = 2$ which gives the Rayleigh distribution.

Figure 3.2 presents results for the Weibull distribution.

The Weibull distribution of the lifetime variable, as presented in Figure 3.2, is shown for a collection of functions with multiple characteristics. Moreover, it can be seen that the failure rate function (the bottom right graph) is shown for the following three characteristics: (i) increasing failure rate ($b \geq 1$), (ii) decreasing failure rate, when $b \leq 1$, and (iii) constant failure rate, when $b = 1$.

The last of these characteristics is the special case when the Weibull-distribution equals the exponential distribution $Exp(m)$.

3.3.3 Failure Rate Modelling for the RCM studies

The methods for the modelling of failure rate that are used in this study is to either: (i) assume that the lifetime distribution equals a known distribution with an estimated parameter (which is done in Approach I of the application
Figure 3.2. Functions for the Weibull-distributed random variable $X$ for three cases.
study presented in Chapter 10 where the exponential distribution is assumed and on which the methods implemented in RADPOW are based), or (ii) use data for an actual component and approximate functions for the same component, which is done in Approach II. There are different techniques for approximating data to known functions, two of which are: (i) linear equation fit to data the least square method where the data is fitted to a function, then the function is transformed into a linear function, and the resulting equation system is solved, or (ii) polynomial fit to data where the data is fitted in a least square sense to a polynomial of a defined degree.

At least theoretically, a failure rate function could consequently be shaped into an infinite set of functions. The previous section presented an analysis of how the failure rate function would behave if the lifetime distribution followed the known Weibull distribution.
Chapter 4

The Reliability Computer program RADPOW

This chapter presents RADPOW, the computer program developed for reliability analysis of systems distributing electrical power. The chapter begins with a description of the main features and the structure of the program. Then comes an overall and detailed presentation of the functions of RADPOW. A detailed description is then provided of those modules and the functions developed by the author. To assist in the understanding of the features of these functions, the principles have been demonstrated using a small test system. In addition, the assumptions and the weaknesses identified in the validation of RADPOW have been presented.

4.1 Introduction

The introductory chapter of this thesis presents the rationale behind the development of RADPOW (see Section 1.1.3), as well as the properties required of the system). The evaluation methods and reliability techniques used in the development are introduced in Section 3.2.3. This chapter provides an overall presentation of the computer program, as well as a detailed presentation of the functions implemented for the deduction of the reliability indices.
4.2 Specifications for the RADPOW Program

4.2.1 Development Strategy

Development of a complete reliability assessment program requires the joint efforts of many students and researchers over several years. It is therefore appropriate to divide the development period into several stages. The first stage in this work was to implement the basic evaluation methods and techniques as per Section 3.2.3. The work done in the first stage serves as the basis on which the new developments of methods and modules can be incorporated. The first stage of development (as presented in [70] and [34]), resulted in the version referred to as RADPOW 1999 (see presentations of additional versions in Section 4.3.3). The second stage of development was oriented more towards program application and detailed reliability measures for different purposes. Within this work, RADPOW has been applied in the development and application of RCM methodology that is for maintenance planning. Finally, the last stage of the work has been devoted to making the program more user-friendly, so that it can be easily transported to different power utilities.

4.2.2 Programming Language and Methodology

RADPOW is used to evaluate the reliability of general power distribution systems. The intended users of the program are students, researchers and
power utilities. However at this stage of program development, the program is only being used by researchers. In addition, the program is designed to run on computers with C++ compilers.

The program is intended to provide a software platform on which new modules can be built flexibly. The continued structure of the program should be strictly modular, with well defined interfaces between the modules, so that new developers can join the project, and find it easy to read and understand the code that others have written before them. Furthermore, the code should be created in a truly modular way so that the new modules share the general structure of the program and can be added without changing existing modules.

To fulfill these requirements the program has been developed based on an object-oriented software development methodology referred to as the object oriented modelling technique (OMT), for further reading see [71].

The computer language used was C++, which is effective and object-oriented. C++ was chosen after discussions with the Department of Numerical Analysis and Computing Science (NADA) at the Royal Institute of Technology (KTH), Stockholm. Rules and recommendations relating to enhancing the readability and enforcing a disciplined uniformity of style in the writing of the C++ programming code have been specified in [72], which serves as the basis for continuing developmental work on RADPOW.

### 4.2.3 Reliability Indices as RADPOW output

RADPOW output indices are measures of reliability at each load point (load-point indices), and of the average behaviour of the overall system (system indices). These are evaluated as average expected values as either of load point or system indices are presented in Section 2.2. The equations implemented for the evaluation of load-point indices are presented in detail in Section 4.5.

Figure 4.1 displays the overall algorithm for the evaluation of the reliability indices in RADPOW.
Figure 4.1. Algorithm for the evaluation of the reliability indices in RADPOW
4.3. Overview of the RADPOW Computer Program

**Figure 4.2.** The main function modules in RADPOW. The author has developed the Mincut, Assbreak, Aafail and Lpind modules, and an application for maintenance.
4.3 Overview of the RADPOW Computer Program

4.3.1 Main Function Modules

Figure 4.2 illustrates the basic modular architecture of RADPOW. This figure also identifies which of the modules the author has developed that deduce and evaluate the load-point indices. These functions are presented in more detail in Sections 4.4 and 4.5, which provide a presentation of the evaluation formula for load-point indices.

This same figure also presents current development status at the time of writing this thesis. The different versions of RADPOW are discussed further in the next section. The development of an application for maintenance, which is the main focus of this thesis is discussed further in Chapter 6.

The various different RADPOW modules are introduced below.

- The modules denoted by Netw (Network), Branch, and Comp (Component) are all designed so that they can store and manipulate the primary system and component data during the running of the program. The types of data manipulated include:
  - network topology data,
  - component reliability data,
  - customer and power data, and
  - load flow data (after the addition of the Load flow module).

Appendix A contains a detailed presentation of the RADPOW input data.

- The module Minpath (Minimal path) is used to obtain all the minimal paths from supply points to load points.

- The Mincut (Minimal cut) module’s main function is the deduction of minimal cut sets for each load point to be analyzed. Minimal cut sets are deduced for the first and second order that is the failure modes when one or two components to fail (see the description in Section 4.4.2).
4.3. Overview of the RADPOW Computer Program

- The Assbreak (Associated breakers) and Aafail (Additional active failures) modules have been designed to deduce associated breakers or fuses for components, and to deduce additional active failure modes (see the description in Sections 4.4.1 and 4.4.3).

- The Lpind (Load point indices) and Sind (System indices) modules are used to evaluate load-point and overall system indices respectively. Reliability indices are calculated for each failure mode and summarized for each load point and for the system (see the description in Section 4.4.4).

- The Databank (data bank) module will be designed to provide for the storage and retrieval of data, and preserve data integrity. This will serve as an information centre for the entire program.

- The Ocost (outage cost) module is designed to evaluate customer outage costs (see the comments in Section 4.9).

- The Simulation model will be designed to evaluate the probability distributions for outage duration ($t$ [h/f]) for each specified load point, and for the customer interruption duration index (CAIDI [h/int]).

- The Loadflow (load flow) module has been implemented to perform load flow analyses when partial loss of continuity criteria are used for a load-point failure.

- The module blocks, including RADPOW MAINTENANCE and RADPOW AUTOMATION, have been created to place special modules in different application directions. In the future these modules will include special functions for further application purpose as well as more detailed reliability measures. Application for maintenance is discussed further in Chapter 6.

- Considering that various special functions may also be used by other application user(s), the Library module should be created to house these special functions.
4.3. Overview of the RADPOW Computer Program

**Figure 4.3.** Data flow between the main function modules in RADPOW.
4.3.2 Data Flow and the overall Algorithm

Figure 4.3 shows data flow between the main function modules for the evaluation of reliability indices. The overall algorithm for the evaluation of reliability indices is presented below.

1. The primary system transfers data from input data files into a network model with associated component and reliability data. It also provides these data for the analysis.

2. Minimal paths are deduced for all load points.

3. Associated breakers and fuses for all load points are deduced for the components that are included in at least one normally closed minimal path.

4. Additional active failure modes are deduced for all load points.

5. Minimal cut sets are deduced for each load point.

6. Reliability indices are evaluated for each load point and failure mode.

7. Steps 4 - 6 are repeated for each load point defined to be analyzed, and the load-point indices for the system are summarized.

8. Specific system indices are evaluated based on the load-point indices, customer input data and power data.

4.3.3 The various Versions of RADPOW

The first stage of development of RADOW resulted in the version referred to as RADPOW_1999. This version includes the basic evaluation methods and techniques for reliability assessment. This version of the program was presented and used for application studies in [70] and [34].

The most significant restriction in RADPOW_1999 is that the criterion for failure is based on the total loss of continuity (TLOC). TLOC implies that a load point is interrupted and load disconnected only when all paths between the load point and the sources are disconnected [1]. This criterion is valid given the assumption that each available path may support required
load levels to satisfy system requirements. This restriction has been overcome by the development of a routine for power flow assessment, where information about maximum values of voltage levels and power flows have been given. Consequently TLOC can be extended to include partial loss of continuity (PLOC). This implies that the failure criterion include events that do not fully interrupt the connections between source and load point, but are sufficiently serious to require disconnection of some load [1]. The development of this module for load flow analysis was done within a masters project undertaken in 2000 [73]. The development work was undertaken as an extension of RADPOW_1999, adding a new module called Loadflow. The resulting version of RADPOW is referred to as RADPOW_1999_PF [74].

By introducing a simple change in the main file for RADPOW_1999_PF, RADPOW can be run without including the power flow analysis [74], which has been done to produce the results presented in this thesis. Consequently, the versions RADPOW_1999_PF and RADPOW_1999 can produce equivalent output.

The second stage of development, which is application oriented within the field of maintenance and automation, is currently in progress.

4.3.4 Application

To compile RADPOW, the different modules need to be compiled along with the main program, as the main program calls the different functions contained in the modules. In addition, in order to run RADPOW on a particular electrical distribution system, the different input data files (10) also need to be defined. These commands are entered via a terminal window (see Figure 4.4 below), for compiling and then running RADPOW. Note that the inclusion of the module for power flow evaluations (from version RADPOW_1999 to RADPOW_1999_PF), resulted in the inclusion of two changes in the commands: (i) an additional file for compiling the program loadflow.cm and (ii) two more input data files, namely pilo and pfrx.

4.4 Description of the Functions Developed

This section provides a detailed description of the following modules that the author has developed: Assbreak, Mincut, Aafail and Lpind. The input
data, output data and the algorithm have been described for each module. A specification of the input data for RADPOW is provided in Appendix A.

For a detailed description of the other modules that have been implemented, please see [34], or the RADPOW documentation in [75] and [76]. In short, it can be summarized that the Minpath module uses an algorithm for the deduction of minimal paths according to the algorithm specified in [67]. Furthermore, the system indices are evaluated based on the formula defined in Section 2.2.2.

4.4.1 The Assbreak Module

The Assbreak (Associated breakers) module deduces the breakers or fuses associated with components in the system. The breakers or fuses associated with a component are the breakers or fuses that will trip when the component fails. The components that are being analyzed are included in at least one normally closed minimal path to a load point, since these components are noted by the algorithm. The breakers or fuses associated with one component could be included in several minimal paths. Therefore, this module is run once per system that is for all the load points at the one time.

Input data:

The input data for this module include:

- minimal paths to all load points to be analyzed,
- branch data, and
4.4. Description of the Functions Developed

- component data.

**Output data**
The output data from this module include:

- a list of components with their associated breakers and fuses.

**Algorithm**
The algorithm for the Assbreak module involves several searching procedures for breakers and fuses in the minimal paths. These paths are modelled by branches that in turn consist of components. Each branch starts and ends with a bus, and it is from these end-points that the different branches are connected to establish a path. Figures 4.5 and 4.6 illustrate the algorithms for the deduction of associated breakers and fuses. For a more detailed description of the algorithms see [75].

### 4.4.2 Module Mincut

The Mincut (minimal cut sets) module deduces minimal cut sets of the first and second order for each load point. Furthermore, this module provides the normally open paths for each load point as output.

**Input data**
The input data for this module include:

- the load points to analyze,
- all minimal paths in terms of branches,
- branches included in minimal paths identified as normally open (n/o) or normally closed (n/c), and
- branch data.
4.4. Description of the Functions Developed

![Flowchart](image)

**Figure 4.5.** Algorithms 1(4) and 2(4) used in the deduction in the Assbreak module.

**Output data**

The output data from this module include:

- minimal cut sets restricted to the first and second order in terms of components, and
- minimal paths normally open in terms of components.

**Algorithm**

The overall procedure defined to deduce the minimal cut sets for each load point proceeds according to the following steps.
1. Create a new minimal path vector that does not include paths with normally open points.

2. Transform the new minimal path vector into terms of component numbers.

3. Deduce component numbers that are included in all paths; these are minimal cut sets of the first order.

4. Create temporary paths to be used in the following analysis by erasing each element that appears in a minimal cut set of the first order.
5. Deduce two positive elements (component numbers), one or both of which appear in all paths; these are the minimal cut sets of the second order.

6. Summarize the minimal cut sets into a vector.

For a detailed description of individual functions, see [76] and [75].

4.4.3 The Aafail Module

The Aafail (additional active failures) module deduces additional active failure modes for each load point. Additional active failures are active failures that are not included in permanent failures. Two different additional active failure modes are considered: (i) failure modes caused by a failed component and the trip of its associated breakers; these are referred to as failure modes of the first order, and (ii) failure modes caused by a failed component and one of its associated breakers or fuses that are stuck, and the trip of their associated breakers or fuses; these are referred to as failure modes with the probability of switching devices being stuck.

Input data

The input data for this module include:

- a list of the components in the system with associated breakers and fuses,
- minimal paths in terms of branches,
- minimal cut sets in terms of components, and
- branch, component and reliability input data.

Output data

The output data from this module include:

- additional active failure modes of the first order and failure modes with the probability of the breakers and fuses getting stuck.
Algorithm

The overall algorithm defined to deduce additional active failure contains the following steps.

1. Create a new minimal path vector that does not include paths with normally open points.

2. Transform the minimal path vector in terms of component numbers. This includes repeated numbers for the components of type bus bars. The new minimal path vector in terms of components is used in Step 5.

3. Sort out minimal cut sets of the first order from the minimal cut set vector.

4. Study each component in the system that is:
   (a) included in normally closed minimal paths, and
   (b) not a first order minimal cut set.

5. Deduce failure modes through the following steps.
   (a) Deduce whether there is a minimal path that does not include the component and its associated breakers or fuses.
   (b) If a path does exist, continue on to Step 5(d).
   (c) If a path does not exist, then a failure of the component is a first order additional active failure. Continue to investigate the next component from Step 3.
   (d) Study the associated breakers and fuses of the component.
   (e) Repeat Steps 4 and 5(a) for an associated breaker or fuse of the component.
   (f) If a minimal path exists that includes neither the associated breakers or fuses of a component (this refers to assb), nor the associated breakers or fuses of each of the assb, then a further type of additional active failure is found, which is referred to as the failure mode with the probability of sticking ("stuck probability") which implies failure of the component and unsuccessful switching of its associated breaker or fuse.
(g) Repeat Steps 5(b)-5(d) for each breaker or fuse associated with the component.

6. Repeat Step 4 onwards for all components.

4.4.4 The Lpind Module

The Lpind (Load-point indices) module evaluates indices for all load points that are defined to be analyzed for the system. The indices are first evaluated for each load point and then summarized to provide basic system indices by running the Lpind module several times from the main program. The load-point indices are in turn evaluated as the sum of indices for the different failure modes. Two types of failure modes are included: (i) failure modes deduced by the minimal cut set approach, and (ii) failure modes deduced by the associated breakers and fuses. The latter are caused by the trip of breakers or fuses that is the primary protection for the system.

Input data

The input data for this module include:

- minimal cut sets of the first and second order in terms of components,
- minimal paths n/o in terms of components,
- additional active failure modes of the first order, and failure modes with "stuck probability" for breakers and fuses,
- branches included in minimal paths identified as normally open (n/o) or normally closed (n/c); component data for n/o point,
- power input data (average load not supplied per bus bar), and
- reliability input data.

Output data

The output data from the module include:

- load-point indices for individual load-points and the summarized load-point indices for the system that is the basic system indices.
Algorithm

Figure 4.1 displays the overall algorithm for the evaluation of basic reliability indices. For detailed evaluation formula, see Section 4.5.

4.5 Reliability Evaluation Formulae for Load-point Indices

This section presents the formula that have been used in RADPOW for the evaluation of load-point indices.

As discussed in Section 3.2.1, network modelling and the Markovian technique are different approaches used in the modelling and evaluating of reliability. However for a detailed study of larger and more complicated systems, the network modelling provides an over-simplified model, and the Markovian model gets too complicated. Therefore, an alternative method based on the Markovian approach but with a set of approximative equations has been implemented in the Lpind module (see the description of the approximative method in [50],[1]). The corresponding approximated equations are provided below.

First-order events, representing a serial reliability system, together with \( i \) represent the different components of the system:

\[
\lambda_s = \sum \lambda_i, \tag{4.1}
\]

\[
U_s = \sum \lambda_i r_i, \tag{4.2}
\]

\[
r_s = \frac{\sum \lambda_i r_i}{\lambda_s} = \frac{U_s}{\lambda_s}, \text{ and} \tag{4.3}
\]

\[
LOE_s = U_s \cdot p\text{notsup}, \tag{4.4}
\]

where \( p\text{notsup} \) is the product of the total number of customers and the total active power per customer (kW/cust). These values provide the customer and power input data.
Second-order events (overlapping events) representing a parallel reliability system, where 1 and 2 represent the two components that fail:

\[\lambda_{12} = \frac{\lambda_1 \lambda_2 (r_1 + r_2)}{1 + \lambda_1 r_1 + \lambda_2 r_2} \approx \lambda_1 \lambda_2 (r_1 + r_2) \Leftrightarrow \lambda_1 (\lambda_2 r_1) + \lambda_2 (\lambda_1 r_2), \quad (4.5)\]

\[r_{12} = \frac{r_1 r_2}{r_1 + r_2} \quad (4.6)\]

and

\[U_{12} = \lambda_{12} r_{12} \approx \lambda_1 \lambda_2 r_1 r_2. \quad (4.7)\]

Note that there is a difference in the units used for the parameters where average outage duration is given in hours but failure rate is evaluated in failures per year. The following conversion factor for hours/year is therefore required in all formulae including a mix of \(r\) and \(\lambda\): 8760 [hours/year].

Figure 4.7 shows an overlapping failure. The system is in operation in State 1 and has failed in State 0. Moreover, Equation 4.5 can be expressed in words as follows: [50]:

*the failure of the system occurs if Component 1 fails followed by failure of Component 2 during the restoration time for Component 1; or if Component 2 fails followed by the failure of Component 1 during the restoration time for Component 2.*

However in the analysis using RADPOW, several different failure types are studied. Therefore, the equations should also include overlapping events for different types of failures. The above equations refer to overlapping events of the same failure type.

Consider the overlapping outages caused by two different failure types \((x\text{ and } y)\) in a similar manner. There would be four different combinations of
overlapping events that would occur, and Equation 4.5 would be extended accordingly to:

$$
\lambda_{12}^{xy} = \lambda_1^x (\lambda_2^y r_1^x) + \lambda_2^x (\lambda_1^y r_2^x) + \lambda_1^y (\lambda_2^x r_1^y) + \lambda_2^y (\lambda_1^x r_2^y).
$$

(4.8)

The resulting restoration times would however be more complicated when several failure types are included. For one of the four overlapping failure events, the resulting average time would be:

$$
r_s^{1xy} = \frac{r_1^x r_2^y}{r_1^x + r_2^y}.
$$

(4.9)

Furthermore, if Equation 4.9 for each of the overlapping failure events, and Equation 4.8 are used as input in Equation 4.3, then the following equation for the restoration time is obtained (only three of the four terms are shown):

$$
r_s^{xy} = \frac{\lambda_1^x (\lambda_2^y r_1^x)}{\lambda_1^{xy}} \cdot \frac{r_2^y}{r_1^x + r_2^y} + \frac{\lambda_2^x (\lambda_1^y r_2^x)}{\lambda_2^{xy}} \cdot \frac{r_1^y}{r_2^x + r_1^y} + \frac{\lambda_1^y (\lambda_2^x r_1^y)}{\lambda_1^{xy}} \cdot \frac{r_2^x}{r_1^y + r_2^y} + \ldots.
$$

(4.10)

However the following constraint applies for scheduled maintenance:

a component should not be taken out for maintenance if this would cause system failure.
The above constraint leads to the following two exceptions from the earlier equations: (i) no first-order maintenance outages would occur; this is logical since scheduled maintenance would not be performed on a component if the effect would be the occurrence of a failure event, and (ii) no overlapping failures would occur if the second event is caused by maintenance. This behaviour can be modelled using the following approach.

Let Equation 4.5 refer to the following scenario:

*failure of the system occurs if Component 1 is maintained followed by the failure of Component 2 during the maintenance time of Component 1, or if Component 2 is maintained followed by the failure of Component 1 during the maintenance time for Component 2.*

The corresponding failure rate for the two overlapping failure events, where one is caused by scheduled maintenance \((x\) and \(m\)) would then appear as:

\[
\lambda_{12}^{xm} = \lambda_1^m (\lambda_2^{x_m}) + \lambda_2^m (\lambda_1^{x_m}).
\]

(4.11)

Furthermore, the outage time can be evaluated using Equation 4.10, but with two terms, and the following equation for the restoration time is then obtained:

\[
r_{rs}^{mx} = \frac{\lambda_1^x (\lambda_2^m r_1^m)}{\lambda_{12}^{xm}} \cdot \frac{r_1^m r_2^m}{r_1^x + r_2^m} + \frac{\lambda_2^x (\lambda_1^m r_2^m)}{\lambda_{12}^{xm}} \cdot \frac{r_2^m r_1^m}{r_2^x + r_1^m}.
\]

(4.12)

Reliability indices are evaluated for the following different failure modes.

1. Minimal cut set failures:
   (a) minimal cut sets of the first order \((c1)\), and
   (b) minimal cut sets of the second order \((c2)\).

2. Primary protection failures:
   (a) additional active failures of the first order \((a1)\), and
   (b) additional active failures including a probability of switching devices being stuck \((as)\).
Furthermore, the indices for the load points are the sum of the indices for these failure modes expressed as follows:

\[ \lambda_{ip} = \lambda_{ip}^{c1} + \lambda_{ip}^{c2} + \lambda_{ip}^{a1} + \lambda_{ip}^{as}, \]  

(4.13)

\[ U_{ip} = U_{ip}^{c1} + U_{ip}^{c2} + U_{ip}^{a1} + U_{ip}^{as}, \text{ and} \]  

(4.14)

\[ r_{ip} = U_{ip}/\lambda_{ip}. \]  

(4.15)

In Sections 4.5.1 - 4.5.4, the logic used for the calculation of these load-point indices has been presented. Note that the units of time are both years (yr) and hours (h). Therefore conversion between the units is needed in some evaluations.

4.5.1 Minimal Cut Sets of the First Order

The average failure rate for minimal cut sets of the first order is evaluated using Equation 4.1 as follows:

\[ \lambda_{ip}^{c1} = \sum_{i=1}^{n} \lambda_{p,i} + \lambda_{te,i} + \lambda_{tr,i}, \]  

(4.16)

where \( i \) is the component number for the actual failure event and \( n \) is the number of failure events.

For restoration of power after a permanent failure, a normally open path is used where possible, with the probability that the normally open path can be used provided that it does not include the failed component. The restoration time where a normally open path is re-closed will be the same as the switching time \((r_s)\). \( P \) is the probability that the normally open path cannot be used. If the normally open path is not used, restoration is effected by repair \((r_r)\) or replacement \((r_p)\). Replacement is undertaken if the failed component has a replacement time greater than zero. By letting \( r_{r/p} \)
symbolize the possibilities of restoration by repair \((r_r)\) or replacement \((r_p)\),
then the actual restoration time is given by:
\[
r = (1 - P) \cdot r_s + P \cdot r_{r/p}.
\] (4.17)

The unavailability is evaluated by:
\[
U_{ip}^{(1)} = \sum_{i=1}^{n} \lambda_{p,i} \cdot r + \lambda_{te,i} \cdot r_{c,i},
\] (4.18)
if a normally open path is used, and
\[
U_{ip}^{(1)} = \sum_{i=1}^{n} \lambda_{p,i} \cdot r_{r/p,i} + \lambda_{te,i} \cdot r_{c,i},
\] (4.19)
if a normally open path is not used.

The restoration time is evaluated by:
\[
r_{ip}^{(1)} = U_{ip}^{(1)}/\lambda_{ip}.
\] (4.20)

4.5.2 Minimal Cut Sets of the Second Order

The average failure rate for minimal cut sets of the second order consists of
the following terms:
\[
\lambda_{ip}^{(2)} = \lambda_{pp} + \lambda_{pm} + \lambda_{pte} + \lambda_{tet} + \lambda_{tem}.
\] (4.21)

The equations discussed earlier in this section are used to evaluate these
terms.

The following expressions are obtained for \(\lambda_{pp}\), in same way as for \(\lambda_{tet}\),
using Equations 4.5 and 4.6:
\[ \lambda_{pp} = \lambda_1^P (\lambda_2^P r_1^P) + \lambda_2^P (\lambda_1^P r_2^P), \quad (4.22) \]

\[ r_{pp} = \frac{r_1^p r_2^p}{r_1^p + r_2^p}, \quad (4.23) \]

and

\[ U_{pp} = \lambda_{pp} r_{pp}. \quad (4.24) \]

The following expressions are obtained for \( \lambda_{pte} \) using Equations 4.8 and 4.10:

\[ \lambda_{pte} = \lambda_1^P (\lambda_2^{te} r_1^P) + \lambda_2^P (\lambda_1^{te} r_2^P) + \lambda_1^{te} (\lambda_2^P r_1^e) + \lambda_2^{te} (\lambda_1^P r_2^e), \quad (4.25) \]

\[ r_{pte} = \frac{\lambda_1^P (\lambda_2^{te} r_1^P)}{\lambda_{pte}^{te} \lambda_1^{te}} \cdot \frac{r_1^{pte}}{r_1^p + r_2^{pte}} + \frac{\lambda_2^P (\lambda_1^{te} r_2^P)}{\lambda_{pte}^{te} \lambda_2^{te}} \cdot \frac{r_2^{pte}}{r_2^p + r_1^{pte}} + \ldots, \quad (4.26) \]

and

\[ U_{pte} = \lambda_{pte} r_{pte}. \quad (4.27) \]

Finally, the following expressions are obtained for \( \lambda_{pm} \), in same way as for \( \lambda_{tem} \) using Equations 4.11 and 4.12:

\[ \lambda_{pm} = \lambda_1^m (\lambda_2^m r_1^m) + \lambda_2^m (\lambda_1^m r_2^m), \quad (4.28) \]

\[ r_{mp} = \frac{\lambda_1^P (\lambda_2^m r_1^m)}{\lambda_{pm}^{m} \lambda_1^{m}} \cdot \frac{r_1^{p}}{r_1^{m} + r_2^{m}} + \frac{\lambda_2^P (\lambda_1^m r_2^m)}{\lambda_{pm}^{m} \lambda_2^{m}} \cdot \frac{r_2^{p}}{r_2^{m} + r_1^{m}}, \quad (4.29) \]

and
4.5. Reliability Evaluation Formulae for Load-point Indices

\[ U_{pte} = \lambda_{pm} r_{pm}. \quad (4.30) \]

Where possible, a normally open path is used, where restoration time is the same as the switching time, being:

\[ r'_{xy} = ((1 - P) \cdot r_s + P \cdot r_{xy}), \quad (4.31) \]

where \(x\) and \(y\) denote the different combinations of the overlapping failure events as discussed above.

The unavailability can then be evaluated by:

\[ U_{ip}^{c2} = \sum \lambda_{pp} \cdot r'_{pp} + \lambda_{tete} \cdot r'_{tete} + \lambda_{pte} \cdot r'_{pte} + \lambda_{pm} \cdot r'_{pm} + \lambda_{tem} \cdot r'_{tem}, \quad (4.32) \]

if a normally open path is used, and

\[ U_{ip}^{c2} = \sum \lambda_{pp} \cdot r'_{pp} + \lambda_{pte} \cdot r_{pte} + \lambda_{tete} \cdot r_{tete} + \lambda_{pm} \cdot r_{pm} + \lambda_{tem} \cdot r_{tem}, \quad (4.33) \]

if no normally open path is used.

However, the restoration time for temporary events that is the re-closure time for a breaker is very short compared with the other restoration times discussed, therefore the resulting outage time for overlapping temporary failure events approximately equals the re-closure time, thus \( r'_{tete} \approx r_c \). Consequently for both Equations 4.32 and 4.33, the re-closure time is used for evaluating the restoration time for overlapping temporary failures in RAD-POW.

The restoration time can then be evaluated by:

\[ r_{ip}^{c2} = U_{ip}^{c2} / \lambda_{ip}. \quad (4.34) \]
4.5.3 Additional Active Failures of the First Order

The average failure rate for additional active failures of the first order is evaluated using Equation 4.1 as follows:

\[ \lambda_{ip}^{a1} = \sum_{i=1}^{n} \lambda_{a,i} + \lambda_{te,i} + \lambda_{tr,i}, \]  

(4.35)

where \( i \) is the component number for the actual failure event, and \( n \) is the number of failure events. This leads to the following equations for evaluating the unavailability and outage time:

\[ U_{ip}^{a1} = \sum_{i=1}^{n} \lambda_{a,i} \cdot \tau_{s,i} + \lambda_{te,i} \cdot \tau_{c,i}, \]  

(4.36)

and

\[ t_{ip}^{a1} = U_{ip}^{a1} / \lambda_{ip}. \]  

(4.37)

4.5.4 Additional Active Failures with the Probability of Switching Devices being Stuck

The following is the expression for additional active failures with the probability of switching devices being stuck:

\[ \lambda_{ip}^{aS} = \sum_{i=1}^{n} \lambda_{a,i} \cdot P_{s,i}, \]  

(4.38)

where \( P_{s,i} \) is the probability that the associated breaker or fuse for the failed component \( i \) is stuck, and \( n \) is the number of failure events. This leads to the following:

\[ U_{ip}^{aS} = \sum_{j=1}^{n} \lambda_{a,j} \cdot \tau_{s,j}, \]  

(4.39)

and

\[ t_{ip}^{aS} = U_{ip}^{aS} / \lambda_{ip}. \]  

(4.40)
4.6 Application for a Test System

To present the various features of the approach used to deduce failure modes, the principles have been demonstrated on a small system shown in Figure 4.8. This system has been studied for two different cases: (i) when component 18 is a normally open point, referred to as Test System 1a, and (ii) when component 18 is a normally closed point, referred to as Test System 1b.

![Diagram](image)

**Figure 4.8.** Test System 1, showing Components c and Branches B.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>☺</td>
<td>transformer</td>
</tr>
<tr>
<td>✗</td>
<td>breaker</td>
</tr>
<tr>
<td>☺</td>
<td>disconnector</td>
</tr>
<tr>
<td></td>
<td>bus</td>
</tr>
</tbody>
</table>

**Figure 4.9.** Components used in Test System 1.

4.6.1 Main Features of the Test System

The test system consists of the following main features.
4.6. Application for a Test System

- It is made up of both basic parallel and radially meshed subsystems.
- It contains the main components found in a distribution system.
- Load can be transferred by closing the disconnectors that are normally open (c18).
- It has more than one supply point (Supply Points 1 and 2).
- It has more than one load point (Load Points 5 and 6).

4.6.2 Deduction of Failure Modes for the Test System

Deduction of associated breakers

The breakers associated with the components in the system can be obtained by inspection. Table 4.1 presents the results from RADPOW for Test System 1 and Cases a and b. As evident from the results, the difference between these cases is that more associated breakers were found in Test System 1b. This occurs for the following components: 5, 6, 10, 12, 14 and 18. More associated breakers are found in this case because the normally open point is closed and the three paths are connected.

Deduction of minimal cut sets

Minimal cut sets and normally open paths can be obtained by inspection for each load point. Table 4.2 presents the results from RADPOW for Test System 1a, and Table 4.3 for Test System 1b.

Deduction of additional active failure modes

Additional active failure modes for each load point can be obtained by inspection. Table 4.4 presents the results from RADPOW for Test Systems 1a and 1b. Note that the first order minimal cut sets can not cause an additional active failure mode since all components associated with a load point form a minimal cut set. A breaker or fuse that fails to switch or operate is in a stuck state and is marked with an S.
4.6. Application for a Test System

Table 4.1. Results from the Assbreak module for Test Systems 1a and 1b.

<table>
<thead>
<tr>
<th>Component number</th>
<th>Associated breakers for Test System 1a</th>
<th>Associated breakers for Test System 1b</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>[7]</td>
<td>[7]</td>
</tr>
<tr>
<td>2</td>
<td>[8]</td>
<td>[8]</td>
</tr>
<tr>
<td>3</td>
<td>[7, 9, 11]</td>
<td>[7, 9, 11]</td>
</tr>
<tr>
<td>4</td>
<td>[8, 13]</td>
<td>[8, 13]</td>
</tr>
<tr>
<td>5</td>
<td>[10, 12]</td>
<td>[10, 12, 14]</td>
</tr>
<tr>
<td>6</td>
<td>[14]</td>
<td>[10, 12, 14]</td>
</tr>
<tr>
<td>7</td>
<td>[9, 11]</td>
<td>[9, 11]</td>
</tr>
<tr>
<td>8</td>
<td>[13]</td>
<td>[13]</td>
</tr>
<tr>
<td>9</td>
<td>[7, 10, 11]</td>
<td>[7, 10, 11]</td>
</tr>
<tr>
<td>10</td>
<td>[9, 12]</td>
<td>[9, 12, 14]</td>
</tr>
<tr>
<td>11</td>
<td>[7, 9, 12]</td>
<td>[7, 9, 12]</td>
</tr>
<tr>
<td>12</td>
<td>[10, 11]</td>
<td>[10, 11, 14]</td>
</tr>
<tr>
<td>13</td>
<td>[8, 14]</td>
<td>[8, 14]</td>
</tr>
<tr>
<td>14</td>
<td>[13]</td>
<td>[10, 12, 13]</td>
</tr>
<tr>
<td>15</td>
<td>[9, 10]</td>
<td>[9, 10]</td>
</tr>
<tr>
<td>16</td>
<td>[11, 12]</td>
<td>[11, 12]</td>
</tr>
<tr>
<td>17</td>
<td>[13, 14]</td>
<td>[13, 14]</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>[10, 12, 14]</td>
</tr>
</tbody>
</table>

Table 4.2. Results from the Mincut module for Test System 1a.

<table>
<thead>
<tr>
<th>Load point</th>
<th>Minimal cut set vector</th>
<th>Normally open path vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>[1, 7, 3, 5, 9 + 11, 9 + 16, 9 + 12, 15 + 11, 15 + 16, 15 + 12, 10 + 11, 10 + 16, 10 + 12]</td>
<td>[5 18 6 4 13 17 14 2 8]</td>
</tr>
<tr>
<td>6</td>
<td>[4, 13, 17, 14, 6, 2, 8]</td>
<td>[5 18 6 3 9 15 10 1 7, 5 18 6 3 11 16 12 1 7]</td>
</tr>
</tbody>
</table>
### Table 4.3. Results from the MinCut module for Test System 1b.

<table>
<thead>
<tr>
<th>Load point</th>
<th>Minimal cut set vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>[ 5, 3 + 18, 3 + 6, 3 + 4, 3 + 13, 3 + 17, 3 + 14, 3 + 2, 3 + 8, 1 + 18, 1 + 6, 1 + 4, 1 + 13, 1 + 17, 1 + 14, 1 + 2, 1 + 8, 7 + 18, 7 + 6, 7 + 4, 7 + 13, 7 + 17, 7 + 14, 7 + 2, 7 + 8, 7 + 2, 7 + 8]</td>
</tr>
<tr>
<td>6</td>
<td>[ 6, 4 + 5, 4 + 18, 4 + 3, 4 + 1, 4 + 7, 13 + 5, 13 + 18, 13 + 3, 13 + 1, 13 + 7, 17 + 5, 17 + 18, 17 + 3, 17 + 1, 17 + 7, 14 + 5, 14 + 18, 14 + 3, 14 + 1, 14 + 7, 2 + 5, 2 + 18, 2 + 3, 2 + 1, 2 + 7, 8 + 5, 8 + 18, 8 + 3, 8 + 1, 8 + 7]</td>
</tr>
</tbody>
</table>

### Table 4.4. Results from the Aafail module for Test Systems 1a and 1b.

<table>
<thead>
<tr>
<th>Test System</th>
<th>Load point</th>
<th>Additional active failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>5</td>
<td>[ 9, 10, 11, 12, 15 + S9, 15 + S10, 16 + S11, 16 + S12]</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>1b</td>
<td>5</td>
<td>[ 6, 10, 12, 14, 18, 15 + S10, 16 + S12, 17 + S14, 13 + S14, 9 + S10, 11 + S12]</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>[ 5, 10, 12, 14, 18, 15 + S10, 16 + S12, 17 + S14, 13 + S14, 9 + S10, 11 + S12]</td>
</tr>
</tbody>
</table>
4.7 Documentation and Validation

The development of the RADPOW computer program is well documented. Numerous reports have been presented and are contained in the publication list in Section 1.4.

Validation of the algorithms used in RADPOW has been done through intensive testing. In total, 43 different cases from nine test systems have been studied from simple radial systems based on typical radial networks (according to [1]), to larger systems like the reliability test system (RBTS), as defined in [77]. RADPOW provides appropriate results for all these test systems and the validation is extensively documented in [75]. For each of the validated modules, the documentation includes the results from the validation and the output from RADPOW [75].

4.8 Assumptions and Identified Weaknesses

4.8.1 Assumptions for Evaluation of Reliability Indices

The model of the failure events adopts the following assumptions.

1. The outage times for transient failures are negligible.

2. Different restoration processes can be made simultaneously for overlapping voltages for example repairing two components at the same time.

3. The time taken to change the supply to a load point from one supply point to another is negligible.

4. When a load point is supplied via a normally open point that is reclosed, this supply is assumed to be totally reliable and that it only continues until the service is restored for the original supply line.

5. Minimal cut set failure modes for orders higher than two are not included.
4.8.2 Dummy Load Point

To solve a weakness found in RADPOW, a dummy load point representation has been included. In RADPOW, the failure modes are deduced via the minimal paths to each load point in the system. This implies that all components that are included in any minimal path will be included in the analysis. However, there are cases when a path will be used for supply but not be included in any minimal path. This will occur when a normally open path is used. The weakness will occur for failure in any component in a path not included in any minimal path since these components are not seen by RADPOW as possible causes of failures. To solve this weakness, dummy load points have been introduced into RADPOW. With the introduction of these load points, all components in the paths leading to them have been included in the analysis and the effect of failures of such components on other load points have now been correctly modelled. To prevent these additional load points from being analyzed, they are declared “dummy load points”, and RADPOW neglects them when indices are deduced and calculated. An example of this has been provided for the application study presented in Section 10.2.1.

4.9 Evaluation of Reliability and Cost

The module for cost evaluation in RADPOW has not yet been completed. However some cost analysis has been conducted and the results presented in [78]. The following paragraph constitutes a preliminary discussion on the topic. The same topic has however been analyzed in greater detail in the RCM application studies, and an extensive cost and benefit analysis has been done and is presented in Chapter 12. However, these defined cost evaluation formulae have been implemented in MATLAB, which uses output from RADPOW for the analysis as discussed in Chapter 12.

Reliability levels and economics are interdependent. There are two different costs related to the reliability of supply: (i) the investment cost required to achieve a certain level of reliability that can be fairly easily defined, and (ii) the cost for outages that consist of the part seen by the utility and the part seen by the customer or society. The cost of these outages is however not so easily defined, since the perception of reliability differs between the
utilities and the customers. This is highlighted in [79] and given as the reason why the value of reliability has to be included in power system planning. However in order to define the value of reliability for the customers, an outage cost needs to be defined and the translation between reliability indices and customer outage costs needs to be studied. Extensive surveys and analyses have been conducted in the UK [79], [80] and Canada [81]. These techniques have been used in [78], where the decrease in the unavailability of supply by the increase of automation has been studied. From the results of that study, it can be seen that customer outage costs reflect the change in system design that leads to increased reliability. The outage costs decrease when more equipment is introduced that lowers the outage time.
Chapter 5

Maintenance Procedures

This chapter introduce various maintenance procedures and discuss changes in trend of and requirements for maintenance methods.

5.1 Introduction

5.1.1 Generally about Maintenance

Maintenance procedures are an integrated part of the planning, construction and operation of a system. Moreover they are of central and crucial importance to the effective use of available equipment. The aim of maintenance activities is to continuously meet performance, reliability and economic requirements, while also adhering to the constraints set by system and customer requirements [82].

The concept maintenance refers to all actions undertaken to keep or restore equipment to a desired state. The electrical power system must abide by the regulations and norms for heavy current and maintenance, and in Sweden must follow the EBR trade standard. The EBR standard is a system governing the planning, building and maintenance of power distribution systems for 0.4 – 145 kV. The first EBR trade standards were created in the 1960s and new handbooks have recently been developed to support more effective maintenance [83],[84].

The cost of maintenance must be taken into consideration when handling system assets to minimize the lifetime costs of the system. However some
5.1. Introduction

maintenance activities must be undertaken even if they are not profitable, such as inspections and earth-plate-metering inspections stipulated in the power regulations ELSÅK-FS [85].

There are two types of maintenance: preventive, and corrective. Preventive maintenance can be planned and scheduled, but corrective maintenance occurs unpredictably, when failures are detected. This thesis focuses on preventive maintenance (PM).

5.1.2 Changing Maintenance Trends

The association of International Council on Large Electric Systems (Cigré) is a permanent non-governmental and non-profit-making organisation with its headquarters in France. The core of Cigré’s mission are issues related to the planning and operation of power systems, as well as design, construction, and maintenance of the plants. Technical work is being carried out within 15 study committees.

On of these working group set up a questionnaire in 1997 to obtain more information about trends in future substation planning, design, operation, maintenance, extension and refurbishment. An executive summary can be found in [19], based on the 49 responses obtained from utilities, manufactures and consultants. Some results of particular relevance to this context have been pointed out in the following paragraphs.

It is evident in the results that utilities have changed their organization in response to deregulation. The primary changes of note include the privatisation of companies and splitting up of transmission and production activities. The pressure to reduce operational and maintenance costs has already been felt. Maintenance, design, construction and some of the operating is increasingly being contracted out. The driving forces behind these changes are more aligned with institutional, business and economic factors than technical considerations. Another projected trend identified in the results is that manufacturers will become increasingly incorporated into the maintenance systems.

The following are some of the figures presented in the report.

- Some 39% of the utilities undertake their maintenance activities at fixed time intervals, and 30% on monitoring conditions. Many utilities
falling into the first category are evolving towards condition or system-reliability based maintenance, or both.

- About half the utilities and all the manufactures have performed reliability studies to optimize their maintenance. These reliability studies resulted in introducing more flexibility and diversity into the maintenance intervals.

- In the past, utilities have strived to achieve maximum reliability. However, according to the responses, some 80% thought that striving for optimal and thereby "more specific" reliability in different parts of the system is the trend for the future.

- Data concerning the times for repair and maintenance were stated to be available, but data on failure modes were claimed to be more difficult to find.

This study provided a similar picture of the maintenance issue to that identified in the Introduction of this thesis (see Chapter 1) that is it portrays a changing situation with increasingly complicated systems that are driven by economic rather than technical factors, and with the overall objective of achieving cost effective expenditures rather than maximum reliability.

### 5.1.3 Changing Requirements for Maintenance Methods

Change in the way maintenance is being managed has been identified. This change implies greater requirements on maintenance procedures. For example, maintenance decisions have been traditionally based on experiences and measurements which could be supported by diagnostics methods. The increase in the expectations of maintenance have kept pace with the increasing knowledge about the dynamic characteristics of the power system. These higher expectations are due to the increasingly complex systems and higher demands on cost-effective use of resources. The increasing knowledge about the system has been gained primarily by an understanding of the relationships between failure frequency, reliability and maintenance, and by methods and techniques provided by continuous measurements.
5.1.4 Maintenance Specifications and Performance

In June 1998, a seminar was held at KTH with the aim of gathering and presenting experience, concepts and ideas within the area of RCM [86]. Future demands for applying RCM within the electricity distribution system were discussed, and the need to develop models and techniques, and increase data availability for applying RCM were also identified. Participants and lecturers at the seminar brought with them their experiences from the specification and realization of maintenance activities and reliability analysis. The following presents a short review of one of the lectures from the seminar.

One of the lecturers, Marketeg [87] discussed why the grid is maintained and how maintenance is performed at the Swedish National Grid (Svk). Marketeg also presented the problems of finding optimal maintenance polices and the changing ways of working and the influence this has on maintenance. Svk is a state-owned company responsible for the Swedish national power grid, and it has no personnel working on maintenance and operation. Instead, these duties are performed by contractors in accordance with established maintenance policy.

The following factors were summarized as reasons why the grid should be maintained:

- to maintain a high level of safety for personnel,
- to maintain a good level of availability (required by customers),
- to prevent the grid from aging too quickly,
- to postpone reinvestments or new investments,
- to preserve the environment,
- to maintain good knowledge about the status of the grid,
- if possible, to assist personnel (the contractors) maintain a high level of competence, and
- to respond to changing environmental aspects (for example tree growth).

The following factors were summarized as constituting problems in maintenance:
5.2 Preventive Maintenance (PM)

The aim of PM is to extend the lifetime of the components. Component lifetimes can be prolonged when the causes of component failure and therefore component failure rates themselves reduce. This is of course dependent on the nature of the causes. One way of understanding the relationship between maintenance and reliability would be to study these causes. Moreover, the cost-effective planning of a system implies that the correct components are maintained, at the correct time and with the correct maintenance activity. In this context, this means focusing maintenance on the critical components that is those that have a significant impact on system reliability and to reduce the dominant causes.

Essentially there are four tasks in a scheduled maintenance program [22]:

- inspection of an item to detect a potential failure,
- reworking an item before a maximum tolerable age is exceeded,
5.2. Preventive Maintenance (PM)

- discarding an item before a maximum tolerable age is exceeded, and
- inspecting an item and finding failures that have occurred but were unknown.

For each failure type, an RCM program should be able to determine the type of maintenance task, if any, that should be applied and how frequently. Decision diagrams assist in this process.

The following are some typical maintenance questions.

- What efforts are required for this maintenance?
- Is the maintenance performed too little or incorrect?
- Is preventive maintenance done on the correct items?
- What is the relationship between failure and maintenance costs?

Applying RCM methodology would be one way of providing answers to these maintenance questions.
Chapter 6

Reliability-centred Maintenance (RCM)

*This chapter presents an RCM method as well as experience using the same method. The chapter also summarizes the formulation of the RCM framework and introduces the application studies that led to the resulting generic RCM methodology.*

6.1 RCM in General

6.1.1 RCM Concepts

The term RCM identifies the role of focusing maintenance activities on reliability aspects. The RCM methodology provides a framework for developing optimally-scheduled maintenance programs. The aim of RCM is to optimize the maintenance achievements (efforts, performance) in a systematic way. This method requires maintenance plans and leads to a systematic maintenance effort. Central to this approach is identifying the items that are significant for system function. The aim is to achieve cost effectiveness by controlling the maintenance performance, which implies a trade-off between corrective and preventive maintenance and the use of optimal methods.
6.1.2 The Emergence of RCM

The RCM concept originated in the civil aircraft industry in the 1960s with the creation of the Boeing 747 series of aircraft (the Jumbo). One prerequisite for obtaining a licence for this aircraft was having in place an approved plan of preventive maintenance (PM). However this aircraft type was much larger and more complex than any previous aircraft type, thus PM was expected to be very expensive. Therefore it was necessary to develop a new PM strategy. United Airlines led the developments and a new strategy was created. This was primarily concerned with identifying maintenance tasks that would eliminate the cost of unnecessary maintenance without decreasing safety or operating performance. The resulting method included an understanding of the time aspects in reliability (aging) and identifying critical maintenance actions for system functions. The maintenance program was a success. The good outcome raised interest and the program spread. It was further improved, and in 1975 the US Department of Commerce defined the concept as RCM and declared that all major military systems should apply RCM. The first full description was published in 1978 [22], and in the 1980s the Electric Power Research Institute (EPRI) introduced RCM to the nuclear power industry. Today RCM is under consideration by, or has already been implemented by many electrical power utilities for managing maintenance planning.

6.1.3 Different Versions of RCM

There are different versions and concepts of the RCM approach currently in use. Firstly there is the MSG-3 concept used by the civil aviation industry, which is a development of the initial MSG-1 version. Secondly there is the original version of RCM defined in [22]. In the 1980s, environmental questions became important issues, which led to a change in the RCM decision diagram, and a separate treatment of environmental aspects of failures was defined. This addition changed the decision diagram, and according to Moubray [24] the change was enough to warrant adopting a new name that is RCM2. Attempts to develop the RCM methodology further have been made by EPRIGEN (a subsidiary of EPRI), with the adoption of a reliability-centred maintenance process called streamlined RCM (SRCM),
which is a simplified version of RCM aiming at lowering the cost of performing RCM. The reason behind this development was EPRI’s concern that the classical RCM resource requirements were too great for an average system [88]. However, the concept and fundamental principles for these different versions of RCM remain true to the original definitions. Finally an RCM with the objective of realizing the inherent reliability characteristics of the equipment at a minimum cost [22] is the RCM concept of today. Its implementation must reflect current needs and resource capacity.

6.1.4 The RCM Method

RCM provides a formal framework for handling the complexity of the maintenance issues but does not add anything new in a strictly technical sense. RCM principles and procedures can be expressed in different ways [22], [23], [24] and [88], however the concept and fundamental principles of RCM remain the same.

The following features originate from the first definition of RCM [23], and define and characterize the RCM method. The RCM method facilitates the:

- preservation of system function,
- identification of failure modes,
- prioritizing of function needs, and
- selection of applicable and effective maintenance tasks.

There are several different formulations of the process of creating an RCM program and achieving an optimally-scheduled maintenance program found in the literature [89]. Three formulations have been addressed in this section. The first two have both been derived from the original RCM definition, and the third is an approach based on a set of questions rather than steps.

**Smith**

Smith defined a systematic process for RCM by implementing the following features that have been defined above [23].
6.1. RCM in General

1. System selection and information collection.
2. System boundary definition.
5. Failure mode and effects analysis (FMEA).
7. Selection of maintenance tasks.

Nowlan

The process of developing an initial RCM program when the information required is lacking, consists of the following steps: [22]:

- partitioning the equipment into object categories in order to identify those items that require intensive study,

- identifying significant items that are those that have essential safety or economic consequences and hidden functions that require scheduled maintenance,

- evaluating the maintenance requirements for each significant item and hidden function in terms of the failure consequences and selecting only those tasks that will satisfy these requirements,

- identifying items for which no applicable or effective task can be found, then either recommending design changes if safety is involved, or assigning no scheduled maintenance tasks to these items until further information becomes available,

- selecting conservative initial intervals for each of the included tasks and grouping the tasks in maintenance packages for application,

- establishing an age-exploration program to provide the factual information necessary to revise initial decisions.
6.1. RCM in General

The first step is primarily an activity for reducing the problem to a manageable size. The following three steps are the essence of RCM analysis, constituting the decision questions, as the seven questions listed below.

Moubray

To analyse the maintenance aspects of a system and its components, the first step is to identify the system items, and which of these ought to be analysed. Thereafter the RCM process can be formulated into seven questions for each of the selected items [24]. The seven general questions are:

1. What are the functions and performances required?
2. In what ways can each function fail?
3. What causes each functional failure?
4. What are the effects of each failure?
5. What are the consequences of each failure?
6. How can each failure be prevented?
7. How does one proceed if no preventive activity is possible?

6.1.5 Maintenance Management

Power utilities use computerized maintenance management systems to manage more intensive utilization of the network, extended length of usage time for system assets, and to minimize maintenance efforts [18].

There is broad interest in the benefits and applicability of the RCM method to transmission and distribution systems. As the majority of the maintenance and replacement costs are associated with power transformers and circuit-breakers, it is expected that RCM would be applied to these types of equipment. This matter has been studied within a Cigré working group, which resulted in a report presenting experiences from a number of power utilities: EdF (France), BPA (USA), HQ (Canada), and TEPCO (Japan).

The results from one of these studies are presented in more detail in the following. At EdF the first method of incorporating the aspect of failure
modes into maintenance plans was already done in 1985. This method was applied to switchgear. The main disadvantage with the method was that it did not take into account that components could be of the same type but have different criticality in the system. Therefore in 1995-1996, an RCM pilot study was carried out on a 400 kV line and related terminal equipment. This RCM analysis resulted in three maintenance plans for each component, representing three alternative levels that are reinforced, regular and light for different so-called outage blocks. A method utilizing data from experience for a quantitative analysis was also suggested. However the method used for the RCM analysis is based on a quantitative method. The conclusion was that this method enhanced the maintenance planning as the means for motivating more maintenance on a component of greater importance, even though that would result in taking that component out of the system more frequently for maintenance. However it is not clear whether the effect of this solution on reliability has been investigated.

From these different experiences, it can be summarized that the distribution system components have not been treated, and that a quantitative method for relating failure rate and PM was not used. Furthermore, it can be seen that the RCM concept has been used in a broad sense, sometimes excluding the main feature, that of relating the component and system levels, and a tendency exists for defining RCM in numerous different ways without significant reasons.

6.1.6 RCM Applications

As discussed previously, electrical power utilities are implementing new strategies for maintenance planning, and the application of RCM provides one candidate strategy [25]. EPRI initiated RCM application in the power industry in the US, and the approach has also been applied in Europe, for example in France, Ireland and Scandinavia [90].

Experience from RCM application including experience supporting RCM application is discussed in the following subsections.

RCM Applied to Hydroelectric Powerplants

RCM has been applied for maintenance planning for hydroelectric powerplants in Norway. The experience gained from this application and the
essential features of RCM and the RCM program is presented in the report [91].

In hydroelectric powerplants, the level of maintenance is often reasonably well adapted to operations due to many years of operational experience. Reliability is well controlled and the operational costs are so low that decreases produce only minor cost reductions. An analysis of maintenance must therefore be relatively simple to be profitable [91]. A conclusion from the study is that it is more important to achieve dynamic maintenance planning than to design the perfect maintenance programme.

**Experience at KTH Supporting RCM Application**

Identifying the status of electrical installations is of fundamental interest to power utilities, and an ultimate aim would be to be able to determine the remaining lifetime of the equipment. Operations could then be planned in the optimal way. A method for the diagnosis of the status of XLPE cables has been developed at KTH and proven successful [92]. The central problem identified is being able to detect water trees in a cable. A water tree is a slowly growing structural change within cable insulation, the effect of which is a decrease in the breakdown strength of the insulation. Certain cable parameters are measured, and from this the status of the cable can be classified. Laboratory and field measurements reveal that this method that is voltage dielectric spectroscopy is a good method for the diagnosis of XLPE cables. These studies are presented in greater detail in Chapter 9.

The competence developed in diagnostics characterized by well documented expertise, would provide excellent input and supporting knowledge about the component behaviour for an RCM analysis. Therefore, it has been identified that the maintenance handling of cables, primarily by replacement, could constitute a specific case study for RCM.

**Probabilistic Asset Management and RCM in substations**

Electrical power utilities are changing their activities to increase their competitiveness and reduce costs. Tools are needed that can be used to quantify costs associated with the whole life cycle of their equipment. However to enable taking full advantage of techniques like RCM, it is necessary to predict the remaining life cycle of an item and to quantify the effect of changes in
maintenance or operating policies on the remaining lifetime and associated costs.

One methodology for doing this has been developed by Ontario Hydro Technologies [93]. A generic technology called Asset Management Planner is used, which was originally applied to rotating machines. This method is described in a paper entitled Probabilistic Asset Management and RCM at sub-stations [93]. This method enables decisions to be made based on quantitative analyses, which is desirable in this context. The results demonstrate the importance and merit of modelling maintenance policies for power system equipment.

One problem identified is that numerous pieces of equipment in distribution networks (low voltage and medium voltage) are not well documented. There are no international standards, and these are needed to form a basis for specifications.

It is probable that a lack of data is one reason why an heuristic approach to RCM is commonly used.

6.2 The RCM Framework Developed

6.2.1 Why is the Maintenance Question not yet Solved?

The electrical utilities' need for improved maintenance strategies and understanding their effects on reliability has been identified. Furthermore, it has been shown that there are methods available for reliability analysis, maintenance optimization and more, and that these have been available but not fully utilized. Therefore, a reasonable question is why is the maintenance issue not yet solved?

To answer this question it is interesting to reflect on the origins of the techniques. Probability theory is the fundamental tool for handling the abstract (and stochastic) mathematical models in this thesis. This theory originates from the 1500-1600s in Italy and France, and was developed to support the handling of hazard games [59]. In the beginning of the 1930s, probability methods were introduced in quality control of manufacturing. However it was not until after the Second World War that these methods became widespread. During the Second World War, new sophisticated weapons were introduced, amongst these were the so-called flying bombs.
6.2. The RCM Framework Developed

The outcome of these was not accurately predictable as detonation occurred too early. Mathematicians were consulted to solve this problem, and the application of reliability theory to complicated technical systems was introduced. The next area to come into focus for probability theory was space research in the 1950s and 1960s. Following this, reliability theory was introduced into the nuclear power plants in the 1970s [58]. Consequently, it can be seen that the origin of probability theory came from an important need to predict unknown future events. It should be noted that all these examples are capital-intensive systems with a significantly high level of safety and reliability requirements.

In a similar way, methods like RCM and LCC (life cycle cost) originate from applications in complicated technical systems where the need for systematic methods has been necessary to maintain costs and the correct level of reliability.

It can therefore be seen as natural, that in electric power systems able to be divided into generation, transmission, and distribution, that the distribution system traditionally the least capital intensive of all three has been the last to embrace such sophisticated methods. However provided with sufficient incentive, these techniques could be fully adopted and introduced into distribution systems. Management could invest in sophisticated reporting systems and suitable personnel for handling and analysing the data, if the benefits to be gained by this were clearly visible. The required effort must be balanced by the benefit received.

A plausible answer to the question heading this section could be that in the same way as probability theory developed to support solutions for the popular game of hazard, and RCM developed to facilitate the development of Jumbo jets, then improved strategies for maintenance of distribution systems could become commonplace when the incentive is right. Furthermore, the present restructuring of the electric power systems in many countries indicates that those incentives will be available in the foreseeable future.

Adopting another point of view, it could be said that the techniques currently available are not very well adapted to power systems, as evidenced by their lack of use. Consequently, another answer to the question posed could be that existing methodologies lack the ability to clearly show the benefits gained for the PM efforts required, and are not simple to implement.
6.2.2 The RCM Framework

An RCM framework has been formulated based on an understanding of RCM concepts ([89]) and experience gained from simple RCM application studies [94],[95],[96]. This framework identifies the central role of defining the relationship between component behaviour and system reliability that is made through evaluation of the causes of failures. Table 6.1 presents this RCM framework that includes the main procedures for developing RCM plans, and consequently is also the first result in the development process in accordance with Figure 1.2.

Table 6.1 also identifies the following issues: (i) the logical order of the different procedures required, (ii) the need for interaction between the system and the component levels, and (iii) an indication of the different input data needed.

The following three main stages can be identified for the procedures.

Stage 1 System reliability analysis (system level analysis): defines the system and evaluates critical components for system reliability (Steps 1 and 2).

Stage 2 Evaluation of PM and component behaviour (component level analysis): analyses the components in detail and with the support of necessary input data, a quantitative relation between reliability and PM measures can be defined (Steps 3 to 5).

Stage 3 System reliability and cost/benefit analysis (system level analysis): puts the understanding of the component behaviour gained in a system perspective. The effect of PM on components is analysed with respect to system reliability and benefit in cost for different PM strategies and methods (Steps 6 and 7).

Figure 6.1 illustrates these three stages giving an overall picture of the RCM method.

The central part of this work, and the greatest challenge is the definition of a relationship between reliability and preventive maintenance, that is Stage 2 in the RCM analysis discussed above. This could be done through a generic approach involving the steps to be processed, or a generic theory involving mathematical relations to be solved. Whether the latter is possible to achieve is unclear at this point.
### Table 6.1. The RCM framework developed.

<table>
<thead>
<tr>
<th>Step</th>
<th>Procedure</th>
<th>Level</th>
<th>Data required</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Reliability analysis</td>
<td>syst.</td>
<td>comp. data</td>
<td>reliability indices</td>
</tr>
<tr>
<td>2</td>
<td>Sensitivity analysis</td>
<td>syst.</td>
<td>comp. data</td>
<td>critical comp.</td>
</tr>
<tr>
<td>3</td>
<td>Analysis of critical components</td>
<td>comp.</td>
<td>failure modes</td>
<td>critical comp. affected by maint.</td>
</tr>
<tr>
<td>4</td>
<td>Analysis of failure modes</td>
<td>comp.</td>
<td>failure modes causes of failures etc.</td>
<td>frequency of maint.</td>
</tr>
<tr>
<td>5</td>
<td>Estimation of composite failure rate</td>
<td>comp.</td>
<td>maint.</td>
<td>composite failure rate</td>
</tr>
<tr>
<td>6</td>
<td>Sensitivity analysis</td>
<td>syst.</td>
<td>frequency of maint.</td>
<td>relationship between indices and PM schedules</td>
</tr>
<tr>
<td>7</td>
<td>Cost/Benefit analysis</td>
<td>syst.</td>
<td>costs</td>
<td>RCM</td>
</tr>
</tbody>
</table>

syst. - system, comp. - component, and maint. - maintenance
6.2. The RCM Framework Developed

![Diagram showing System Reliability Analysis, Preventive Maintenance and Component Behaviour, System Reliability and Cost/Benefit Analysis, Reliability indices, Critical components, Alternative PM plans, RCM.

Figure 6.1. The three main steps in the RCM Analysis.

6.2.3 Input Data Required for RCM Analysis

One observation from the RCM framework is that in order for an RCM analysis to be possible, comprehensive knowledge about the system and its components is required, together with suitable input data to support a quantitative analysis. This matter is discussed further in this section.

Data Requirements

The input data required for achieving an RCM analysis are extensive. Therefore a central part of RCM analysis is how to collect, select and define these data.

A summary of the different data requirements is given below.

At the system level, the following data are required:

- system descriptions,
- system drawings,
• PM and control programs, and
• commitments or requirements for existing programs.

At the component level the following data are required:

• a list of components, and
• component maintenance history data.

For the cost/benefit analysis, the following data are required:

• the cost of reliability that are investment cost and outage cost,
• the cost of undertaking maintenance that are the cost of manpower, materials, components and so on, and
• the cost of not undertaking maintenance that involves outage costs for the utility and for the customers.

Issues that Need to be Discussed with the Utilities

At the system level, there is a need to form an understanding of the overall procedures involved in maintenance planning. Additionally, a dialogue is needed with the utilities to get to know the relationship between maintenance and reliability.

At the component level, the following issues need to be discussed:

• failure modes of components and their ranking,
• which modes can be affected by maintenance,
• the relationships between failures and lifetimes, and
• whether maintenance can affect “constant” failure rates or wearing out.

For the cost/benefit analysis, it is critical that the following issue be discussed:

• what the factors are that need to be balanced.
6.2.4 Introduction to the RCM Application Studies

Application of the defined RCM framework (see Table 6.1) constitutes the next step in the development of the generic RCM methodology. Application studies have been made on two different distribution systems: (i) a rural system of overhead power lines (the Flymen System), and (ii) an urban underground cable system (the Birka System).

These application studies have been performed using a simple approach called Approach I, and a comprehensive approach called Approach II. The differences between these two lies in the way they deal with the issue of relating reliability and the effect of PM activities defined as follows.

**Definition 6.1.** Approach I implies that a PM activity results in a percentage reduction in the causes of failures for affected components. Furthermore, it assumes that the failure rate is also reduced by the equivalent percentage. The resulting model of the relationship between failure rate and PM is referred to as \( \lambda(PM) \).

**Definition 6.2.** Approach II implies that a functional relationship is established between failure rate and PM activities. This must be based on detailed knowledge and understanding of the condition of the components as well as the failure rate characteristics. The resulting model of the relationship between failure rate and PM is referred to as \( \lambda(t, PM) \).

Both distribution systems mentioned above have been run through all the procedures in the RCM framework in Approach I except for the last one (the cost and benefit analysis), and the results are presented in Chapter 10.

The Birka System has been run through the complete RCM framework in Approach II, which is the failure rate modelling approach \( (\lambda(t, PM)) \). This study is referred to as the Cable Application Study.

Consequently, both Approaches I and II have been applied to the Birka system.

Section 7 through to and including Chapter 12 all relate to the application studies. Chapter 13 then summarizes the complete RCM application study (the Cable Application Study), and the resulting generic RCM methodology.
6.3 Computer Routines Developed for the RCM Analysis

6.3.1 General Remarks about the Implementation

The RCM analysis includes several sensitivity studies of the distribution systems analysed, involving repeated analyses using different sets of input data. To support this process, some simple routines for creating output data tables have been implemented in RADPOW, though the output data has almost exclusively been handled using MATLAB.

Graphical representation has been used for analysis of the output from RADPOW (RADPOW output consists of a series of reliability indices for different input values such as failure rates for components). This is supported by MATLAB and several program routines have been developed for that purpose.

6.3.2 Using the RADPOW Computer Program

The RADPOW computer program developed was presented in Chapter 4, and evaluates reliability indices for an electrical power network. The purpose of this tool in developing methodology for RCM is to illustrate the effect that preventing component failures has on system reliability.

In the basic RADPOW program, the evaluated reliability indices are based on analytical methods where average values for example for component failure rates are used as input data. This method is applicable in Approach I for analysing the effect of preventive maintenance, however in Approach II the model developed for relating failure rate and maintenance includes the change of functions over time.

In order to evaluate the resulting change in reliability indices over time, RADPOW has to be run repeatedly for varied reliability input data files. In doing this, the C ++ RADPOW program would not need to be compiled between runs, and it would be tempting to convert RADPOW into a function that could be called on repeatedly. However, the intention has been to apply this computer program to RCM rather than rewriting the program.
6.3.3 Computer Routines Developed for RCM Analysis

The following list summarizes the different computer routines that have been developed and implemented in the program, as well as the various steps featured in the Cable RCM Application study.

1. Modelling of general life distribution functions (as presented in Chapter 3).

2. Evaluation of cable component behaviour (as presented in Chapter 11).
   (a) Modelling the failure rate function over time \( \lambda(t) \).
   (b) Modelling cable component parameter behaviour \( \lambda(t, PM) \).

3. System effect analysis (as presented in Chapter 12).
   (a) Estimation of the composite failure rate for a cable component.
   (b) Evaluation of reliability indices.
      i. Repeated running of RADPOW.
      ii. Translation of results into functions in time.
   (c) Analysis of the effect of different strategies and maintenance methods.

4. Cost and benefit analysis (as presented in Chapter 12).
   (a) Modelling cost functions.
   (b) Annual cost and present value analysis.

6.3.4 Implementation of the RCM Approach in MATLAB

The algorithm developed for RCM methodology has been implemented in MATLAB. This includes modelling of the failure rate (Approach II) in the Cable RCM Application Study. The resulting program uses RADPOW for producing some of the results for the reliability analysis. The resulting evaluation process is not completely systematic due to the interconnection between the RADPOW program and the MATLAB program developed. The complication that has not been overcome relates to managing of running RADPOW for different sets of input data and transferring output to the
MATLAB program. The complication occurs in the handling of input data files which are read differently.

MATLAB is a technical computing environment for high-performance numeric computation and visualization [97]. The name MATLAB is an abbreviation of matrix laboratory, and was originally used for educational purposes in linear algebra. MATLAB version 5.2 has been used in this thesis. Programming has been performed in the word-processing program *xemacs* on a UNIX platform. Moreover the MATLAB toolboxes used here have been primarily those for handling graphics and numerical data analyses, such as for interpolation and polynomials.

The RCM algorithms implemented require input data from seven files. Five of these files relate to the component behaviour, and the other two to: (i) the reliability input data for the system for RADPOW, and (ii) the input data for the cost and benefit analysis. Appendix C these data for the Cable Application Study.
Chapter 7

Distribution System Components

This chapter introduces the different components in the distribution system and focuses on the underground cable component. It also presents different sources and results for component statistics and in particular the causes of failures. Results presented in this chapter provide input data for the analysis of the Flymen System (see Section 10.2), and for comparing this with the resulting data from the Birka system analysis.

7.1 Components in General

The main components in a distribution system include:

- lines (lines, poles and related items),
- cables (cables, junctions and related items),
- breakers,
- transformers,
- disconnecters,
- load disconnecters,
7.2. The Underground Cable Component

- fuses, and
- bus bars.

For further presentation of the individual components the reader see literature in the field. For the purpose of this study one component is analysed in greater detail that is the cable component.

7.2 The Underground Cable Component

The main reference for the general description of the cable component in this section is the *Electrical Engineer’s Reference Book* [98].

7.2.1 Introduction to the Cable Component System

Cable component systems contain two essential components: (i) the metallic conductor with low resistance to carry the current, and (ii) the insulation to provide a dielectric medium for isolating conductors from one another and from their surroundings.

In order to specify suitable insulation and construction for the service performance required, the design voltages are quoted in the form $U_0/U$, that is voltage-to-earth (phase-to-ground voltage)/voltage between phases [98]. For example power distribution to end users that is usually distributed in three-phase lines with a zero conductor [99], provides voltage levels of 230/400 V. Moreover, the voltage range extends from automobile cables of 6 – 12 V to the highest transmission voltages reaching around 800 kV [98].

Cables are normally grouped in either of two ways: (i) by design voltage or (ii) by usage. The first way typically uses the traditional categories of low, medium and high voltages, while the second typically uses for example: (i) wiring and general, (ii) power distribution, and (iii) transmission. Traditionally these cables had different insulation types and production places, which is no longer true for new cable types [98]. It is however important to bear in mind that system analysis as undertaken in this thesis, includes system components that have been in operation for long time. Many systems are more than 30 years old and due to deregulation, are expected to operate close to maximum length [21]. These demarcations may however
vary over years and between countries, and are therefore in themselves not a significant source of differentiation.

This thesis focuses on power distribution system analysis, and consequently relates to power distribution cables, or equally to the medium voltage cables, which are also the object of study in the main references [100], [101], [102], and [103]. Furthermore, the focus of the analysis is on the underground cable component, which is presented further in Chapters 9 and 11, and relates to failures in the cable insulation. Therefore, the insulation part of the cable is presented in greater detail in the following section. There are two main types of insulation material Figure 7.1 shows a piece of cable length of the both types. For a thorough description of the cable component, please refer to specific literature. A comprehensive literature reference is provided in [98].

![Diagram of cable components](image)

**Figure 7.1.** Two different types of underground cables, with (a) XLPE (b) Impregnated paper insulation respectively, which are in use for the 11 kV distribution in Stockholm City network.
7.2.2 Cable Insulation

Underground cable insulation can be either polymeric material (thermoplastic and elastomeric material) or impregnated paper. These types of insulation are discussed further below. The latter is representative of the first types of cables and the former of more modern material. From about the 1960s onwards, polymeric materials have become increasingly preferred in insulation because of their potentially higher operating temperature.

Polymeric material

The properties of good insulation material are flexibility and the ability to withstand high temperatures. Natural rubber fulfils the first but not the second, and therefore other materials have been used. This shortcoming of rubber can be solved by using for example synthetic polymeric materials.

Elastomeric material returns rapidly to approximately its initial dimensions and shape after deformation at room temperature caused by a weak stress. Under such conditions thermoplastic material shows permanent deformation. Conventional elastomeric compounds need to be cross-linked by vulcanisation generally by chemical methods to provide them with characteristics akin to rubber compounds. Two most common elastomeric materials are ethylene propylene rubber (EPR) and cross-linked polyethylene (XLPE). These combine the flexibility and electrical properties of natural rubber with a higher operating temperature and easier strippability. Examples of thermoplastic materials are polyvinyl chloride (PVC), polyethylene (PE) and polypropylene (PP). [98]

One of the disadvantages with PVC in cabling relates to its use in buildings or tunnels. Although PVC is basically flame retardant, if a serious fire does develop it can transmit flame and decompose generating noxious acidic fumes and dense smoke. [98]

Compared with paper insulation, XLPE has the main advantages of not needing metallic sheathing, and being much cleaner and easier to handle in laying and jointing [98].

The most important single problem with XPLE insulation is that like paper insulation, internal partial discharges occur at voltages of 5 kV upwards at any irregularities within or at the surface of the insulation.
While it was recognized that the XLPE insulation must be extremely clean and free from voids, and that screening at both surfaces of the insulation was necessary, many cables were put into service without adequate testing to ensure freedom from discharging. It was not until the mid 1970s that ideal forms of screening were developed that could be readily removed for jointing and could adequately deal with thermal expansion and contraction. In the years that followed, the final problem was to identify and find solutions to problems caused by the effects of water-insulation contact. Tree-like structures were found in the insulation and it was eventually established that these could lead to electrical breakdown [98]. This phenomenon is called water treecing and is further discussed in Chapter 9.

Many of the early cable failures were due to imperfections resulting from the use of semi-conducting fabric tapes for conductor screens. A thin layer of extruded semi-conducting polymeric material is now mandatory, and to ensure a clean interface it is normally extruded in tandem with the main insulation and cured with it.

Impregnated paper

Impregnated paper insulation as the name implies, consists of layers of paper tapes overlapping the conductor. The cable is dried and impregnated before application of a metal sheath, which is required to keep the insulation dry and undamaged. The impregnation of the paper by a mass-impregnating process is carried out before the application of the metallic sheath. Moreover, the paper consist of a felted matting of long cellulose fibres derived from wood pulp. An important factor in the control of the properties of the paper cables is the washing of the fibres. Large quantities of water are used for this, and with paper intended for the highest voltage cables this water has to be deionized to ensure a minimum power factor [98].

From its introduction at the end of the 1800s, impregnated cables have provided excellent service to the cable industry. Under normal conditions, users have been able to install cables and then simply forget about them. Ultimate lifetimes of 50 – 60 years have been common, and the majority of cables have been replaced only because they became too small for their loads. While the basic dielectrics have changed little throughout the years, there have been considerable improvements in the quality of materials and
7.3. Review of Component Statistics

7.3.1 The Swedish National Outage Data Bank

Introduction to the reporting system

National disturbance statistics for the Swedish distribution system have been summarized annually by Swedenergy AB (formerly the Association of Swedish electrical power utilities (Sve), from the DAR reporting system, and its precursor FAR (see for example [105]). DAR is a system for compiling and analyzing information about disturbances, supply interruptions and failures in the power distribution system. Statistics are collected for the voltages levels 22 – 0.4 kV [46]. DAR was developed to provide the utilities with statistics about complications due to disturbances and failures in their equipment, and to provide the authority with reliability indices to compare the utilities and illustrate levels of power availability to customers. In the future, the need for collecting such data is expected to increase. The authority is introducing strategies to control and reward utilities in respect to supply availability and outage costs suffered by customers [17]. To meet these new requirements, a new generation of reporting systems called DAR-WIN is being developed [106].

The output from DAR is presented in relative values to facilitate the comparison of statistics between different utilities. The following list summarizes some of its features.

- Data is provided at the individual voltage levels.
7.3. *Review of Component Statistics*  

- Faults are allocated by specific types of components.
- Fault type is identified, along with how and when the fault is cleared.
- How and when the failed component is isolated and identified.
- The number and types of causes of faults are provided and classified as either:
  - weather,
  - damage
  - material/method,
  - personnel, or
  - other.

Within each group a more specific cause can be stated. Note that only one cause is reported for a failure, this being the primary and initial cause of the failure.

An understanding of the fundamental concepts in the reporting system is required for the correct reporting and analysing of the disturbance data. These are as presented in [46] and the glossary [47] (see also Section 2.1.3).

**Analysis of disturbance data from the DAR reporting system**

Distribution system statistics from the DAR system for the years 1995–1997 are summarized in [105]. This includes a survey of the interruption of supply incidents for different voltage levels and geographical locations. The survey includes the following voltage levels: 22 kV, 11 kV, less than 10 kV and 0.4 kV. The results show that the 11 kV distribution system contributes some 35 – 40% of all the interruptions at the voltage levels studied here.

Table 7.2 presents an outline and overview of interruptions to supply (not forced outages) for these years. The interruptions are shown as both the total number of reported interruptions (voltage interruptions) and those that lead to supply interruptions. The results illustrate that the 11 kV range is responsible for most of the unavailability of supply for the voltage levels studied here.
7.3. Review of Component Statistics

The report [105] provides a comparison of causes of failure between two rural networks and two urban networks for the period 1990-1997. These rural networks are located in the south of Sweden (RuralS) and the north of Sweden (RuralN). The urban networks are located in the middle of Sweden (UrbanM) and in the north of Sweden (UrbanN). Table 7.3 presents the results from the 11 kV level. For the rural networks, the most marked difference is in the failure caused by lightning. This may be due to the higher frequency of lightning in the south due to regional meteorological effects. For the urban networks, the most marked difference is seen in other weather. However since the unknown causes in the UrbanM network are as high as 30%, no relevant conclusions can be made about this difference. The major reason for registering an unknown cause is because the interruption has not been analysed correctly [107]. By comparing the rural and the urban networks it can be seen that other weather shows the greatest diversity. This is probably an effect of the more frequent use of overhead lines in rural networks, and underground cables in urban networks. It can be concluded from the statistic analysis that the cause of failures are closely connected to where the distribution system is situated, in regards to both geographical and environmental conditions. It has also been identified that there is a problem with reporting, evident by the significant number of unknown causes reported.

Table 7.3.1 presents average values for causes of failure for the complete study performed in [105]. These values are based on interruptions to supply for the period 1995-1997. Other weather makes up about 40% of the causes of failures in all the networks together, which is the same level as for the rural networks.

It has been shown that the 11 kV voltage level contributes significantly to failures in the distribution systems, and that the causes of these failures depend on geographic location and impacts from the surrounding environmental. Therefore, it would be of great interest to analyse distribution systems that are spread across the country and represent both a rural and urban system. Chapter 10 presents results from such an analysis of two different systems, one rural and one urban network.
### Table 7.1. Causes of failures leading to interruption of supply in distribution systems in Sweden 1995-1997 [105].

<table>
<thead>
<tr>
<th>Cause of failure</th>
<th>Estimated average Number</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Lightning</td>
<td>343</td>
<td>12.3</td>
</tr>
<tr>
<td>- Other weather</td>
<td>1199</td>
<td>43.1</td>
</tr>
<tr>
<td>- Wind</td>
<td>242</td>
<td>8.7</td>
</tr>
<tr>
<td>- Snow</td>
<td>213</td>
<td>7.7</td>
</tr>
<tr>
<td>- Rainwater</td>
<td>36</td>
<td>1.3</td>
</tr>
<tr>
<td>- Salt</td>
<td>5</td>
<td>0.2</td>
</tr>
<tr>
<td>- Tree (wind)</td>
<td>485</td>
<td>17.4</td>
</tr>
<tr>
<td>- Tree (snow)</td>
<td>218</td>
<td>7.8</td>
</tr>
<tr>
<td>Damage</td>
<td>283</td>
<td>10.2</td>
</tr>
<tr>
<td>Material/method</td>
<td>453</td>
<td>16.3</td>
</tr>
<tr>
<td>Personnel</td>
<td>62</td>
<td>2.3</td>
</tr>
<tr>
<td>Overloading</td>
<td>62</td>
<td>2.2</td>
</tr>
<tr>
<td>Returning load</td>
<td>5</td>
<td>0.2</td>
</tr>
<tr>
<td>Unknown</td>
<td>371</td>
<td>13.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2778</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

### Table 7.2. Disturbance statistics for Swedish distribution systems [105].

<table>
<thead>
<tr>
<th>Year</th>
<th>Voltage levels</th>
<th>Total interruptions</th>
<th>Supply interruptions</th>
<th>Energy not supplied [MWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1995</td>
<td>All</td>
<td>6364</td>
<td>6220</td>
<td>6506</td>
</tr>
<tr>
<td></td>
<td>11kV</td>
<td>2632 (41%)</td>
<td>2565 (41%)</td>
<td>5561 (85%)</td>
</tr>
<tr>
<td>1996</td>
<td>All</td>
<td>7342</td>
<td>7209</td>
<td>9519</td>
</tr>
<tr>
<td></td>
<td>11kV</td>
<td>2755 (38%)</td>
<td>2698 (37%)</td>
<td>7655 (80%)</td>
</tr>
<tr>
<td>1997</td>
<td>All</td>
<td>11078</td>
<td>10939</td>
<td>5574</td>
</tr>
<tr>
<td></td>
<td>11kV</td>
<td>3745 (34%)</td>
<td>3668 (34%)</td>
<td>4432 (80%)</td>
</tr>
</tbody>
</table>
Statistics for underground cables from the DAR and FAR systems.

Table 7.4 presents statistics from the DAR and FAR systems, and primarily for the Stockholm City network (Birka Nät AB). These data were prepared in connection with the study reported in [108].

### 7.3.2 Data from the National Fault and Interruptions Reporting System (NAFIRS) in the UK

Data based on the National Fault and Interruptions Reporting System (NAFIRS) from the UK are presented in Table 7.5. This table presents results for high voltage (11 kV) distribution systems and separates the information according to different component types. Note that in this table "Line" refers to overhead lines, and "Cables" refers to underground cables.

Maintenance can have an impact on some of these causes but not others. The cause of failures in Table 7.5 that are assumed to be influenced by maintenance are: wind-borne materials (detected by inspection and then resolved by for example removal), corrosion, vibration, trees, vermin, farm animals, wilful damage, faulty construction and installation, aging and wear, faulty manufacture and design. Other weather includes: lightning, rain, snow, ice and gales. In practice however, maintenance may overcome none, some or all of these causes of failures.

<table>
<thead>
<tr>
<th>Cause of failure</th>
<th>RuralS</th>
<th>RuralN</th>
<th>UrbanM</th>
<th>UrbanN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightning</td>
<td>23 [%]</td>
<td>5 [%]</td>
<td>0 [%]</td>
<td>3 [%]</td>
</tr>
<tr>
<td>Other weather</td>
<td>45 [%]</td>
<td>50 [%]</td>
<td>1 [%]</td>
<td>29 [%]</td>
</tr>
<tr>
<td>Wilful damage</td>
<td>7 [%]</td>
<td>11 [%]</td>
<td>13 [%]</td>
<td>24 [%]</td>
</tr>
<tr>
<td>Material/method</td>
<td>11 [%]</td>
<td>12 [%]</td>
<td>37 [%]</td>
<td>21 [%]</td>
</tr>
<tr>
<td>Personnel</td>
<td>1 [%]</td>
<td>0 [%]</td>
<td>19 [%]</td>
<td>9 [%]</td>
</tr>
<tr>
<td>Overloading</td>
<td>1 [%]</td>
<td>5 [%]</td>
<td>1 [%]</td>
<td>3 [%]</td>
</tr>
<tr>
<td>Unknown</td>
<td>13 [%]</td>
<td>18 [%]</td>
<td>30 [%]</td>
<td>11 [%]</td>
</tr>
</tbody>
</table>
Table 7.4. Statistics for underground cables from the DAR and FAR systems.

<table>
<thead>
<tr>
<th>Component type</th>
<th>Voltage level [kV]</th>
<th>Total length [km]</th>
<th>Failures/year and km</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DAR - national statistics 1990-1996</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>132</td>
<td>2341</td>
<td>0.00564</td>
</tr>
<tr>
<td>Total</td>
<td>33</td>
<td>582</td>
<td>0.01279</td>
</tr>
<tr>
<td>Total</td>
<td>11</td>
<td>16704</td>
<td>0.00902</td>
</tr>
<tr>
<td>Total</td>
<td>0.4</td>
<td>132315</td>
<td>0.00128</td>
</tr>
<tr>
<td><strong>DAR - internal statistics, Birka 1990-1994</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>11</td>
<td>2298.8</td>
<td>0.01201</td>
</tr>
<tr>
<td>XLPE</td>
<td>11</td>
<td>819.9</td>
<td>0.01638</td>
</tr>
<tr>
<td>Impregnated paper</td>
<td>11</td>
<td>1478.9</td>
<td>0.00427</td>
</tr>
<tr>
<td><strong>FAR - internal statistics, Birka 1982-1990</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>110</td>
<td>126</td>
<td>0.00088</td>
</tr>
<tr>
<td>Total</td>
<td>33</td>
<td>594</td>
<td>0.00937</td>
</tr>
<tr>
<td>Total</td>
<td>11</td>
<td>2069</td>
<td>0.03057</td>
</tr>
<tr>
<td>Total</td>
<td>0.4</td>
<td>5173</td>
<td>0.05475</td>
</tr>
</tbody>
</table>
### Table 7.5. Faults per cause in the UK, from NAFIRS [43].

<table>
<thead>
<tr>
<th>Cause of failure</th>
<th>Line</th>
<th>Cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weather</td>
<td>52.3</td>
<td>3.6</td>
</tr>
<tr>
<td>Wind-borne materials</td>
<td>2.6</td>
<td>0.3</td>
</tr>
<tr>
<td>Condensation</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>Corrosion</td>
<td>1.3</td>
<td>0.7</td>
</tr>
<tr>
<td>Vibration</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Fires</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Trees</td>
<td>10.6</td>
<td>0.1</td>
</tr>
<tr>
<td>Birds</td>
<td>3.5</td>
<td>0.1</td>
</tr>
<tr>
<td>Vermin</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Farm animals</td>
<td>0.7</td>
<td>0</td>
</tr>
<tr>
<td>Wilful damage</td>
<td>1.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Other utilities</td>
<td>0.2</td>
<td>21.8</td>
</tr>
<tr>
<td>Farming activities</td>
<td>1.1</td>
<td>0.7</td>
</tr>
<tr>
<td>Individuals</td>
<td>1.3</td>
<td>11.6</td>
</tr>
<tr>
<td>Builders and developers</td>
<td>5.3</td>
<td>20.3</td>
</tr>
<tr>
<td>Utility personnel</td>
<td>0.4</td>
<td>2.9</td>
</tr>
<tr>
<td>Faulty construction and installation</td>
<td>1.3</td>
<td>4.4</td>
</tr>
<tr>
<td>Aging and wear</td>
<td>13.1</td>
<td>29</td>
</tr>
<tr>
<td>Operational restrictions</td>
<td>3.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Faulty manufacture and design</td>
<td>0.2</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Window Rule for the Collection of Data

When using statistics to predict the future it is important to consider which time interval is relevant to the specific analysis. For example, if the aim is to predict the lifetime function of a component type for which significant changes in design have recently been introduced, then when predicting the behaviour of this component, use only a short interval, or question whether these statistics should be used for the purpose of prediction at all. Generally however, changes happen over time, both with the introduction of new techniques as well as resulting trends in the statistics. Therefore the data used should cover a reasonable length of time to achieve adequate statistical significance, but not be too long, as the aging data would not be relevant to new data. A reasonable data-collection time of 10 years has been used as guideline in the UK [43].

7.3.3 Other Sources Available

This section presents a selection of different sources of reliability component and system data, and indicates what types of information these include.

Nordel

Fault statistics covering the Scandinavian countries (Denmark, Finland, Norway, Sweden and Island) are compiled within the Nordel reports. These statistics refer to faults causing disturbances in 100 – 400 kV power systems. The total number of faults in 1999 came to 2204, and the loss of energy was 10.9 GWh [109]. The Nordel data include:

- component type,
- number of components,
- number of disturbances, and
- percentage breakdown of the causes of failures for the period 1990 – 99 into lightning, other weather, damage, personnel, technical equipment and other.)
New guidelines for the classification of disturbances and failures, that provide greater detail and are common for all these countries are currently being prepared [110].

Svenska Kraftnät, owns and operates the Swedish transmission system and provides Nordel with the Swedish statistics. Other information is available but not published yet in the Nordel reports, and covers component types, reporting on: (i) the failure frequency (from 1997), and (ii) the unavailability of supply per disturbance and assorted probabilities for failure of function [111]. Moreover, Statnett provides Nordel with the Norwegian statistics, for example those presented in [112].

**Canadian Electricity Association**

The Canadian Electricity Association (CEA) was founded in 1891 and is a national forum for the evolution of electricity enterprises in Canada. The CEA’s mission is to provide a comprehensive database for component and system reliability and performance data to assist its member utilities. The first stage of this system was implemented in 1977, covering reliability data from the generation system. These data are still being presented annually (see for example from 1998 [113], and include both generating units and outage data. Moreover, transmission equipment data are published for example for lines, transformers with failure causes, and more [114]. The only part missing are the statistics for the distribution system.

**Cigré**

Cigré, as earlier introduced, is an international association, registered in France and founded in 1921. Technical work is undertaken within its various study committees, and whose activities have resulted in some very interesting reports, including disturbance statistics. For example, a comprehensive survey of circuit-breaker failures can be found in [115], and data from service experience in high voltage gas-insulated substations (GIS) can be found in [116].
T-book

The T-book [117] provides a comprehensive presentation of reliability data on components in Nordic nuclear power plants. This collection of statistics started in the mid 1970s and the first edition of the book was released in 1982, and included operational statistics from 21 reactor years. The most recent edition of the book includes data from a total of 108 reactor years. Reliability data are presented for different failure modes and the failure rates are presented for different confidence intervals.

The long tradition of careful collection and management of statistics by the nuclear power plants in the generation of power, is exemplary in the power transmission and distribution industry.

A concluding remark

As can be seen from the data sources presented above, there are a lack of distribution system data. However some data from Sweden were presented in Section 7.3.1, and from the UK in Section 7.3.2, that relate to the distribution system level. Nonetheless, the conclusion is that future work requires international efforts to generate statistics for distribution-level component and system data. One of the reasons for not compiling and publishing data may be the competitive nature of the relationships between power utilities. However it would in the common interest of all the parties to provide support for improving their systems.
Chapter 8

Causes of Failures in Underground Cables

This chapter summarizes results from a survey of the causes of failures based on knowledge from both a disturbance reporting system and practical experience from maintenance. This information focuses on the underground cable component and relates experience from one Swedish electrical power utility that owns and operates the Stockholm City network, namely Birka Nät AB. The results presented provide input data for the analysis of the Birka System following in Section 10.3 through to Chapter 12.

8.1 Introduction

One observation from the RCM framework was that in order to make an RCM analysis possible, comprehensive knowledge about the system and its components is required together with suitable input data to support a quantitative analysis. This issue has been analysed in detail in this chapter. The results of a survey have been presented which identify the knowledge and data required, should they be or become available. The results from the survey also provide input data for the RCM analysis of the Cable Application Study that follows.
The material used here comes mainly from the report [20], which includes a comprehensive presentation of the statistical survey. Results have also been published in an RCM perspective in [5].

8.1.1 Cooperation with an Electrical Power Utility

In the first stage, different possible sources of data and contacts where investigated. The aim was to find data that could provide detailed knowledge about the system and its components, and to support the objective of defining a relationship between reliability and PM. It was identified that the best approach was to focus the communication on one utility, which would capture deep rather than broad knowledge, though also specific to the actual utility. The utility chosen was the owner of the Stockholm City network, Birka Nät AB (which also includes the former Stockholm Energi).

Cooperation with Birka Nät was a good choice for several reasons, including: (i) the availability of good long-term disturbance data, (ii) the previous contacts were good, (iii) close proximity to both head office and the network, facilitating visits to the actual distribution systems and simplified meetings, and (iv) good contact possibilities with maintenance personnel (Birka Service was now contracted to undertake the maintenance of the network as a separate business unit within the same company (Birka Nät), however they share a history with Stockholm Energi which implies close relationships between the interests). The utility (Birka Nät), on the other hand has an interest in evaluating methods for improving the management of maintenance with the aim of achieving more cost effective PM.

8.1.2 Problem Formulation

The driving forces for the utilities are changing from technical to economical and management factors. The sorts of issues being looked at are whether maintenance is correct, whether it can be made more effective, and in which parts of the system would it be of most value to focus the maintenance activities. Consequently, the main questions from the perspective of the utility are: "Where do the failures appear that cause the system to fail?" and "How could the PM be planned to prevent these failures more effectively?". The experience at Birka Nät [20] suggests that the 11 kV underground cables represent the greatest source of failure in the distribution system.
8.1. Introduction

From the RCM methodology point of view (the main problem formulation of this thesis), the problem is to find out data that supports detailed knowledge about a distribution system component and how that information could be used for defining the impact of PM on system reliability.

For solving these issues a survey of the available disturbance statistics was performed.

8.1.3 Approach to and Summary of the Survey

1. System statistics analysis
   
   • Disturbance reports for the Stockholm City network were analysed.
   
   • The conclusion was that for system reliability the critical voltage level is the 11 kV, and the critical component type is the underground cable.

2. Cable component analysis

   (a) Analysis of specific cable system data
   
   • Disturbance reports for a specific 33/11 kV Substation were analysed.
   
   • Faults due to the 11 kV underground cable were identified and analysed in great detail.
   
   • The conclusion was that causes of failures denoted material and method is predominant in cable system failure, and that more information is needed to relate causes of failure to PM activities.

   (b) Discussions with maintenance personnel
   
   • Several meetings were held with people from both the utility (Birka Nät) and the PM contractor (Birka Service). The focus of the discussion was on the causes of failures of the 11 kV underground cables and how these could be prevented by maintenance.
   
   • Outcomes from the discussions were presented in a report that has been used in the discussion and other sections that follow.
3. The results were put into an RCM framework for the failure mode and effect analysis that is the deduction of the causes of the failures. This provides input data for the following RCM analysis.

All the analysed disturbance reports imply voltage interruptions, and not forced outages.

8.2 System Statistics Analysis

Failure reports within the period 1982 – 1990 and also from the reporting system FAR, have been analyzed for the whole Stockholm City distribution system. These reports refer to voltage interruptions for which the supply interruptions have also been defined. A total of 3980 reports have been investigated.

8.2.1 The Stockholm City Network

Figure: 8.1 provides an overview of the distribution system in Stockholm City. This distribution system includes different types of stations, from the complex constructions for the transmission voltage at 220 kV, down to the simpler designs for households at 400 V. The end customers are defined by the number of annual subscriptions, being 450,000 at 400V. Some of the end customers are however so-called high voltage customers, which in this system include: 17 customers at the 33 kV level, and 329 customers at the 11kV level. This group consists mainly of the underground railway system (33 kV), industries and hospitals. The customer data is further discussed in detail for the system analysis presented in Section 10.3.3.

Table 8.1 summarizes the different feeder lengths in the system, which are laid out in tunnels, the ground, or overhead. It can be seen that underground cables constitute 90% of the Stockholm City system. About 70% of these are 11 kV feeders. Consequently, the Stockholm City distribution feeders are dominated by the 11 kV underground cable.

8.2.2 System Level Statistics

Failure reports state the system voltage at the actual failure point. In this survey, the reports were sorted into three voltage groups: HV (220, 110, 33
8.2. *System Statistics Analysis*

**Figure 8.1.** Illustration of the distribution system in the Stockholm City network. The boxes represent substations.

**Table 8.1.** Feeder lengths used in the distribution system in Stockholm City.

<table>
<thead>
<tr>
<th>Feeders</th>
<th>Tunnel</th>
<th>Underground</th>
<th>Overhead</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>220 kV</td>
<td>20.3 km</td>
<td>5.4 km</td>
<td>0 km</td>
<td>25.7 km</td>
</tr>
<tr>
<td>110 kV</td>
<td>30.6 km</td>
<td>103.6 km</td>
<td>0 km</td>
<td>134.2 km</td>
</tr>
<tr>
<td>33 kV</td>
<td>67.3 km</td>
<td>465.0 km</td>
<td>0 km</td>
<td>532.3 km</td>
</tr>
<tr>
<td>11 kV</td>
<td>199.1 km</td>
<td>2101.6 km</td>
<td>14.2 km</td>
<td>2315.0 km</td>
</tr>
<tr>
<td>Total</td>
<td>317.4 km</td>
<td>2675.6 km</td>
<td>14.2 km</td>
<td>3007.2 km</td>
</tr>
</tbody>
</table>

(Source: Birka Nät statistics 1998 – 12 – 31)
kV), 11 kV, and other. It should be mentioned that the distinctions between voltage levels is not completely systematic in the reporting system, for example auxiliary voltages are included in the one category but belong to different voltage levels.

Table 8.2 compares the three categories of reports, referred to as HV (220, 110, 33 kV), 11 kV, and other. It can be seen that few interruptions occur for the first category (HV), however they do affect a large number of customers with an average outage time of about half an hour. Furthermore, 35% of the failures occur at the 11 kV level. The number of customers affected is somewhat lower than for the higher voltages, but the average outage time is about one hour. The highest number of failures (about 58%) occurs within the voltage group referred to as other voltage levels, which consists mainly of lower voltages. However of these, some 48% are related to auxiliary voltages which are not considered to be relevant component types in this context [118]. The conclusion is that the 11 kV voltage level is critical to the system regarding the number of interruptions and the effect on customers.

<table>
<thead>
<tr>
<th>Class</th>
<th>Quantity of reports</th>
<th>Custom. affected</th>
<th>Total cust. outage time [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV</td>
<td>262 ≈ 7%</td>
<td>455,501</td>
<td>208,955</td>
</tr>
<tr>
<td>11 kV</td>
<td>1392 ≈ 35%</td>
<td>419,602</td>
<td>420,134</td>
</tr>
<tr>
<td>Other</td>
<td>2326 ≈ 58%</td>
<td>386,762</td>
<td>243,044</td>
</tr>
<tr>
<td>Total:</td>
<td>3980 = 100%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 8.2.3 Component Level Statistics

In the next step of the survey, the reports were sorted by failed component type and cause of failure, for both the entire Stockholm City system and the different voltage classes.

Tables 8.3-8.4 present results for the whole Stockholm City network. The tables shows the different components (failure causes) and their individual impacts on failures of the power delivery system. It can be seen that the
cable component contributes about 36% of the total supply interruptions at all voltage levels. Another significant result is that the causes of failures reported as unknown was almost 50%.

The disturbance statistics were further analysed for the different voltage levels separately. Tables 8.5 and 8.6 show the results for the 11 kV level. These tables confirm the hypothesis that the dominant contribution to failure is made by the cable system components. The cable system consists of the cable itself (including insulation and conductor), terminations and joints. The cable system causes about 30% of the failure reports, 60% of the interruptions, and 80% of the affected customers. Moreover, these affected customers experienced an average outage time of about one hour due to cable system failure. The dominant failure causes, as shown in Table 8.6 are attributable to "manufacturing and material", which contributes about 20% of total failures. However "other equipment” has been reported as causing 40% of failures.

8.2.4 Conclusions

The conclusion from this analysis is that the underground cable system constitutes the most significant contribution to failures in general for the Stockholm City network and specifically for interruptions of supply at 11 kV, which means that the critical component for the system has been identified. However, the results have also shown a lack of reporting detail about causes of failures. Therefore it was decided to continue the analysis of a specific system where more detailed data could be provided.

8.3 Cable Component System Analysis

8.3.1 Statistics from the 11 kV Station Liljeholmen (LH11)

The previous analysis of statistics for the complete Stockholm City system could not provide enough detailed information about causes of failures. Therefore the survey continued by studying one particular station in the system, the Liljeholmen station (LH11) to see whether additional data could be provided for this specific station.
Table 8.3. Failed component types for voltage disturbances in the Stockholm City network 1982 – 1990.

<table>
<thead>
<tr>
<th>Failed component</th>
<th>Numbers of voltage supply affected</th>
<th>Custom. outage time(^1) [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus bar</td>
<td>21 14 5404</td>
<td>7590</td>
</tr>
<tr>
<td>Circuit breaker</td>
<td>211 76 63,453</td>
<td>12,622</td>
</tr>
<tr>
<td>Load disconnector</td>
<td>255 51 19,750</td>
<td>14,102</td>
</tr>
<tr>
<td>Disconnector</td>
<td>62 16 130,704</td>
<td>112,236</td>
</tr>
<tr>
<td>Earthing switch</td>
<td>12 9 15,760</td>
<td>3712</td>
</tr>
<tr>
<td>Power transformer</td>
<td>519 144 36,129</td>
<td>26,956</td>
</tr>
<tr>
<td>Reactor</td>
<td>3 0 0</td>
<td>0</td>
</tr>
<tr>
<td>Power capacitor</td>
<td>81 69 0</td>
<td>0</td>
</tr>
<tr>
<td>Measuring transformer</td>
<td>15 8 92,600</td>
<td>88,530</td>
</tr>
</tbody>
</table>

*Fuse*
- Fuse apparatus                  | 20 12 1523                        | 2791                            |
- Incorrect fuse                   | 46 18 22                         | 59                              |
- Incorrect automatic fuse         | 12 1 0                           | 0                               |

*Overhead line*
- Pole                             | 1 1 75                           | 304                             |
- Insulator                        | 13 10 1,750                      | 1078                            |
- Other material                   | 4 4 550                         | 395                             |
- Clear line path\(^2\)             | 5 5 552                         | 1265                            |

*Cable system* \(\approx 14\% \approx 36\% \approx 35\%\)
- Conductor                        | 175 166 101,719                   | 163,609                         |
- Conductor insulation             | 262 236 152,916                   | 139,214                         |
- Joint                            | 60 57 163,960                     | 90,721                          |
- Terminations non-protected       | 6 6 9050                         | 2764                            |
- Terminations protected           | 20 14 11,262                     | 12,729                          |

Surge diverter                    | 1 1 0                            | 0                               |
Charging rectifier                | 75 14 0                          | 0                               |
Power rectifier                   | 298 192 0                       | 0                               |
Battery                           | 18 4 0                           | 0                               |
Other current supply              | 76 19 11,200                     | 3275                            |

*Control equipment*
- Incorrect relay protection      | 140 60 212,561                    | 108,180                         |
- Incorrect relay                 | 97 21 130,850                    | 50,277                          |
- Control equipment               | 79 16 9500                       | 9317                            |
- Computer equipment              | 50 10 11,100                     | 6660                            |
- Other control equipment         | 462 35 69,800                    | 5204                            |
Compressed air                    | 200 13 0                         | 0                               |
Building, other                   | 414 32 13,600                    | 14,633                          |
Total                             | 3714 1335 1265,790               | 878,223                         |

\(^1\sum N_a \cdot r\) where \(N_a\) = number of affected customers and \(r\) = outage time.
\(^2\) e.g. cleared from close trees.
8.3. *Cable Component System Analysis*

<table>
<thead>
<tr>
<th>Cause of failure</th>
<th>Numbers of affected inter.</th>
<th>Supply inter.</th>
<th>Custom outage time [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overvoltage</td>
<td>170</td>
<td>108</td>
<td>12,958</td>
</tr>
<tr>
<td>Returning load</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Dirt</td>
<td>11</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Lightning</td>
<td>85</td>
<td>27</td>
<td>12,060</td>
</tr>
<tr>
<td>Wind</td>
<td>16</td>
<td>14</td>
<td>2202</td>
</tr>
<tr>
<td>Snow, ice</td>
<td>25</td>
<td>12</td>
<td>3801</td>
</tr>
<tr>
<td>Rain</td>
<td>102</td>
<td>13</td>
<td>2250</td>
</tr>
<tr>
<td>Other weather</td>
<td>30</td>
<td>6</td>
<td>3050</td>
</tr>
<tr>
<td>Digging</td>
<td>88</td>
<td>83</td>
<td>34,177</td>
</tr>
<tr>
<td>Falling tree</td>
<td>2</td>
<td>2</td>
<td>650</td>
</tr>
<tr>
<td>Animal</td>
<td>11</td>
<td>11</td>
<td>2532</td>
</tr>
<tr>
<td>Traffic injury</td>
<td>5</td>
<td>3</td>
<td>201</td>
</tr>
<tr>
<td>Fire</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Other damage</td>
<td>68</td>
<td>46</td>
<td>22,881</td>
</tr>
<tr>
<td>Incorrect operation</td>
<td>25</td>
<td>21</td>
<td>132,311</td>
</tr>
<tr>
<td>Incorrect handling</td>
<td>39</td>
<td>16</td>
<td>78,300</td>
</tr>
<tr>
<td>Incorrectly adjusted protection</td>
<td>49</td>
<td>18</td>
<td>26,850</td>
</tr>
<tr>
<td>Lack of surveillance</td>
<td>18</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Incorrect installation</td>
<td>62</td>
<td>21</td>
<td>77,851</td>
</tr>
<tr>
<td>Contractor</td>
<td>6</td>
<td>3</td>
<td>3000</td>
</tr>
<tr>
<td>Other personnel</td>
<td>122</td>
<td>51</td>
<td>67,304</td>
</tr>
<tr>
<td>Manufact./material</td>
<td>565</td>
<td>196</td>
<td>340,719</td>
</tr>
<tr>
<td>Lack of PM</td>
<td>204</td>
<td>35</td>
<td>12506</td>
</tr>
<tr>
<td>Dimension fault</td>
<td>31</td>
<td>12</td>
<td>2000</td>
</tr>
<tr>
<td>Falling trees (lack of PM)</td>
<td>1</td>
<td>1</td>
<td>200</td>
</tr>
<tr>
<td><strong>Other equipment</strong></td>
<td>1976</td>
<td>628</td>
<td>427,987</td>
</tr>
<tr>
<td></td>
<td>≈ 53%</td>
<td>≈ 47%</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>3714</td>
<td>1335</td>
<td>1265,790</td>
</tr>
</tbody>
</table>
### Table 8.5. Failed component type in voltage disturbances in the Stockholm City network at the 11 kV level during the period 1982 – 1990.

<table>
<thead>
<tr>
<th>Failed component</th>
<th>Numbers of voltage supply affected</th>
<th>Custom. outage time [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>inter.</td>
<td>inter.</td>
</tr>
<tr>
<td>Bus bar</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>Circuit breaker</td>
<td>79</td>
<td>21</td>
</tr>
<tr>
<td>Load disconnector</td>
<td>244</td>
<td>46</td>
</tr>
<tr>
<td>Disconnector</td>
<td>19</td>
<td>7</td>
</tr>
<tr>
<td>Earthing switch</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Power transformer</td>
<td>174</td>
<td>69</td>
</tr>
<tr>
<td>Reactor</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Power capacitor</td>
<td>60</td>
<td>52</td>
</tr>
<tr>
<td>Measuring transformer</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td><strong>Fuse</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-Fuse apparatus</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>-Incorrect fuse</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>-Incorrect automatic fuse</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td><strong>Overhead line</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-Pole</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>-Insulator</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>-Other material</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>-Clear line path</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td><strong>Cable system</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>≈ 31%</td>
<td>≈ 62%</td>
</tr>
<tr>
<td>-Conductor</td>
<td>147</td>
<td>143</td>
</tr>
<tr>
<td>-Conductor insulation</td>
<td>212</td>
<td>207</td>
</tr>
<tr>
<td>-Joint</td>
<td>54</td>
<td>51</td>
</tr>
<tr>
<td>-Terminations non-protected</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>-Terminations protected</td>
<td>19</td>
<td>13</td>
</tr>
<tr>
<td>Surge diverter</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Charging rectifier</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td><strong>Control equipment</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-Incorrect relay protection</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>-Incorrect relay</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>-Control equipment</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>-Other control equipment</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Power rectifier</td>
<td>298</td>
<td>0</td>
</tr>
<tr>
<td>Building, other</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1093</td>
<td>669</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cause of failure</th>
<th>Numbers of voltage inter.</th>
<th>Numbers of supply inter.</th>
<th>Numbers of affected custom.</th>
<th>Custom. outage time[h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overvoltage</td>
<td>38</td>
<td>33</td>
<td>11,057</td>
<td>14,860</td>
</tr>
<tr>
<td>Dirt</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Lightning</td>
<td>11</td>
<td>10</td>
<td>5760</td>
<td>16,228</td>
</tr>
<tr>
<td>Wind</td>
<td>14</td>
<td>13</td>
<td>2202</td>
<td>8853</td>
</tr>
<tr>
<td>Snow, ice</td>
<td>8</td>
<td>7</td>
<td>3801</td>
<td>5471</td>
</tr>
<tr>
<td>Rain</td>
<td>3</td>
<td>1</td>
<td>600</td>
<td>280</td>
</tr>
<tr>
<td>Other weather</td>
<td>13</td>
<td>6</td>
<td>3050</td>
<td>4533</td>
</tr>
<tr>
<td>Digging</td>
<td>73</td>
<td>70</td>
<td>34,177</td>
<td>51,540</td>
</tr>
<tr>
<td>Falling tree</td>
<td>2</td>
<td>2</td>
<td>650</td>
<td>440</td>
</tr>
<tr>
<td>Animal</td>
<td>7</td>
<td>7</td>
<td>2532</td>
<td>1718</td>
</tr>
<tr>
<td>Traffic injury</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Other damage</td>
<td>29</td>
<td>26</td>
<td>19,570</td>
<td>16,066</td>
</tr>
<tr>
<td>Incorrect operation</td>
<td>15</td>
<td>14</td>
<td>7311</td>
<td>3689</td>
</tr>
<tr>
<td>Incorrect handling</td>
<td>8</td>
<td>5</td>
<td>4200</td>
<td>1504</td>
</tr>
<tr>
<td>Incorrectly-adjusted protection</td>
<td>7</td>
<td>7</td>
<td>4600</td>
<td>3191</td>
</tr>
<tr>
<td>Lack of surveillance</td>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Incorrect installation</td>
<td>30</td>
<td>12</td>
<td>18,851</td>
<td>4191</td>
</tr>
<tr>
<td>Contractor</td>
<td>2</td>
<td>1</td>
<td>3000</td>
<td>1700</td>
</tr>
<tr>
<td>Other personnel</td>
<td>32</td>
<td>21</td>
<td>20604</td>
<td>14863</td>
</tr>
<tr>
<td>Manufact./material</td>
<td>312</td>
<td>131</td>
<td>121,318</td>
<td>75,961</td>
</tr>
<tr>
<td></td>
<td>( \approx 29% )</td>
<td>( \approx 20% )</td>
<td>( \approx 29% )</td>
<td></td>
</tr>
<tr>
<td>Lack of PM</td>
<td>91</td>
<td>23</td>
<td>11706</td>
<td>8083</td>
</tr>
<tr>
<td>Dimension fault</td>
<td>9</td>
<td>7</td>
<td>2000</td>
<td>900</td>
</tr>
<tr>
<td>Falling trees (lack of PM)</td>
<td>1</td>
<td>1</td>
<td>200</td>
<td>470</td>
</tr>
<tr>
<td>Other equipment</td>
<td>378</td>
<td>271</td>
<td>142,337</td>
<td>185,585</td>
</tr>
<tr>
<td></td>
<td>( \approx 35% )</td>
<td>( \approx 40% )</td>
<td>( \approx 34% )</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1093</td>
<td>669</td>
<td>419527</td>
<td>420134</td>
</tr>
</tbody>
</table>
A system for the case study has been defined as shown in Figure 8.2. This system is based on the Liljeholmen-Bredäng area (220 – 11kV) and is considered to be sufficiently delimited to enable an adequate RCM analysis.

Disturbance reports on interruptions to supply during the period 1982 – 1999 have been studied. These reports come from the two reporting systems FAR (1982 – 1990) and DAR (1991 – 1999).

FAR provided 23 interruptions and DAR 35 interruptions at Liljeholmen. These led to the disconnection of the 11 kV main breaker, which implies a fault on the redundant 11 kV underground cable system. This redundancy system features two cables in parallel and loop feeding.

Consequently, about 60 interruptions occurred during a 20 year period. There are about 30 similar stations in the Stockholm City area. This gives $30 \times 60 / 20 = 90$ int./yr, or 2 int./wk, which is considered to be in good agreement with real supply disturbances (which could also be validated by comparison with the $69/9 \approx 75$ int./yr in Table 8.5 from the FAR system). Furthermore, the network consists of about 2000 km of underground cable, which is $90/2000 \approx 0.05$ int./yr and km. This value can be compared with the average value for cable faults, being about 0.051 int./yr and km, in Norway for the period 1967 – 1983 [64]. This shows that the cable fault data is significant. Furthermore, in [105] an average value is given for the failure rate of 11 kV cables for 1995 – 1997, being about 0.03 int./yr and km. Finally, [119] shows that the failure rate for mass impregnated cables is about 0.02 int./yr and km. The conclusion is that the failures reported in the cable system give a realistic value for interruptions to the Stockholm City system and therefore validate the data used in the survey.

**Causes of Failures**

Table 8.7 shows the results of the failure and disturbance reports from FAR and DAR. These results show the interruptions due to cable faults for the LH11 system. Materials or methods cause 59% of these faults. Furthermore, it can be seen that within the Material/Method cause, failures by manufacture and material predominate with about 14%. No failures were caused by weather, which is a typical behaviour for underground cables. The conclusion from these statistics is that materials and methods are the most significant
Figure 8.2. Illustration of the case system LH11, used in the RCM study at Birla Nāt.
causes of failures for cables. However, the statistics do not provide enough
details about the failure causes, to relate these to PM measures.

<table>
<thead>
<tr>
<th>Cause of failure</th>
<th>Supply interruptions</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Digging</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>- Sabotage</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td>- Other damage</td>
<td>–</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Personnel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Incorrect manoeuvre</td>
<td>–</td>
<td>3</td>
</tr>
<tr>
<td>- Incorrect installation/ laying</td>
<td>–</td>
<td>3</td>
</tr>
<tr>
<td>- Other personnel</td>
<td>1</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material/Method</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Manufac./material</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>- Lack of PM</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>- Other material/method</td>
<td>14</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Unknown</td>
<td>–</td>
<td>8</td>
</tr>
<tr>
<td>Total</td>
<td>23</td>
<td>35</td>
</tr>
</tbody>
</table>

**Table 8.7.** Supply interruptions caused by cable system failures at Sub-
station LH11 in the Stockholm City network from the two periods from the
reporting systems FAR and DAR.

**Cable-specific Information**

Information reported about failed cables has been studied in more detail here
relating to cable-specific information (for example manufacturer or size), and
the parts of the failed components (for example joint, conductor or other).
In both reporting systems (DAR and FAR), a detailed classification of the
failed component can be reported. In FAR, the identity of the components
can be included which is not the case for DAR. However, the reporting of
this information is imperfect. In DAR, failure reports were made in 31% of cases, and in FAR, only three of 23 cases were reported with detailed cable-specific information, but information about which part of the component that caused the interruption was provided in 13 of the 23 cases.

The cable-specific data could provide information to illustrate the trend of failures in a certain type of cable. The DAR data shows that the types of cables exposed to failure are equally divided between the two main cable types, XLPE insulation and mass impregnated cable. The FAR data was too poor to support any conclusions.

The reporting frequency supporting the question about which part of the cable system fails is quite poor. Such reports have been made in only 24 of the 58 cases (41%). Results from both reporting systems indicate that the cable itself is the major contributor to failure rather than joints and terminations. This result does not correspond with the expected outcome for Birka Nät, which estimates that the joints provide the greatest contribution to failure [120]. The result is however, emphasized by [119], which indicates that mass impregnated cables when divided into their constituent parts (being the cable itself, the terminations and the joints), contribute 0.014, 0.005 and 0.003 int./yr and km respectively.

**Failure Location**

The cable failures were studied in regard to failure location. All the failures were pinpointed on a geographical map showing the cable layout. It could be deduced that the failures were geographically scattered over the area, and that some critical areas featured repeated failures between stations. These critical areas contained three different stations with a total of 16 failures, which implies about 28% of the failures during the period. In all of these cases, repetitive faults were overcome by re-connections, which implied that another cable was used as a feeder. In addition, one of the stations was taken out of service.
8.3.2 Maintenance Personnel Experience

Introduction

In this part of the survey, the statistics have been compared with practice the experiences from the 11 kV underground cable faults in the Stockholm City system. The aim here has been to identify what additional information is available and what the present reporting systems do not tell, plus to provide recommendations for how the reporting systems and the maintenance routines could be improved.

The information in Table 8.7 shows the causes of failures for the 11 kV underground cable system at LH11. The table shows what has happened but not why or how. This consequently leads to questions such as: "What further information can be identified?", and "What additional details can be reported in the present and future reporting systems?" From these, a discussion document was prepared for interviews with maintenance personnel. The focus of these discussions can be summarized as: "Experience of the causes of failures and PM in 11 kV underground cables".

The first meeting resulted in a working document that was discussed further in two subsequent meetings. Participants came from Birka Service Operation Planning Group, and also involved the actual electricians that performed the re-couplings, repairs and similar work. This section provides a brief summary of the outcomes from these discussions that in turn resulted in recommendations. It is worth noting that the survey was presented in a 59 page report, and that the material here is very much reduced.

General Aspects

The power delivery system in the Stockholm City area is a mixed network where the feeders consist of several types of cables and installation years, and are joined together in many different combinations. Working and failure-free cables exist that were put into operation in 1902. On the other hand, cable joints from 1970 – 1991 have been shown to be prone to failure.

In general, no direct relationship exists between commissioning year and failure occurrences, but experience shows that when work is performed near to cables, the probability of cable failure increases. However, these particular failures are likely to be primarily caused by digging, which in some areas and
time periods could be the dominant cause of failures. In this paper, the main focus is on the cause of failure due to material or method. These have been illustrated in Table 8.7, and can be seen to be a significant cause of failure and may be preventable by maintenance.

"Materials and Method" as a cause of failure

*Material and method* has been reported as the cause of failure in more than half the cable system faults. It is difficult to confirm whether this value is correct or reasonable. These failures are more complicated to deduce than failures caused for instance, by digging. Nonetheless the following can generally be said about the failures caused by *material and method*: (i) the classifications are not sufficiently developed to allow individual judgments about (i) the cause of failure, and (ii) the cause of aging. However aging could in turn be related to different causes and would therefore probably not be a suitable cause for a reporting system.

One main focus for the discussions was to identify what the cause denoted as *material and method* means. The following list presents a summary of the results from the discussions.

- **Cu and Al contacts**: contact between the different materials, copper and aluminium, which can occur in joints and could lead to a short circuit.

- **Water trees**: a tree-like phenomenon which allows water penetration through the insulation, and which occurred primarily in XLPE insulation cables produced in the mid 1970s.

- **Corrosion** of the screen or jacket.

- **Lack of oil insulation** due to poor refilling of oil in joints or terminations of cables laid up and down hillsides.

- **Bending damage** can occur because of digging holes too shallowly when laying.

- **Scratches in the insulation**, for example in XLPE insulation because of the incorrect method or handling during laying.

The discussions showed that more useful information is known about the cable system failures than is actually being reported, which could help in identifying and preventing failures. Information revealed at the failure
8.4. Results

location, but not reported includes for example: (i) repeated laying of the
cable, (ii) signs of aging or earlier repair, (iii) dry insulation paper, (iv)
stones in the filling material, (v) fractures in the jacket, (vi) new asphalt,
(vii) joint close to failure, (viii) taped cable, (ix) convolution and more.
The recommendation is to make a checklist to report what is seen at the
failure location. These lists could be evaluated after a test period to support
further planning of cable maintenance. An important point is that several
individuals are often involved in the actions following a failure. Observations
by all these individuals could be useful inclusions in the reporting system.

8.3.3 Conclusions

Disturbance reports for a specific 33/11 kV substation have been analysed.
These reports include statistics from the 18-year period 1982-1990 in the
FAR system, and 1991-1999 in the DAR reporting system. Supply interrup-
tions that are caused by the 11 kV underground cable have been identified
(that is those failures that trip the breaker at the 11 kV level). The resulting
supply interruptions numbered 58. The identified underground cable faults
have been analysed in great detail. The individual reports for each fault have
been studied and all possible and useful information, primarily the causes of
failures, has been analysed and compiled.

8.4 Results

8.4.1 Summary of the Results from the Survey

Table 8.8 presents a summary of the results from the statistic analysis. The
statistics used for the first set of analysis came from the FAR system (1982—
1990) and for the second set of analysis from the FAR and DAR system
(for 1991 — 1999). The last results, that is for the type of insulation that
contributed most to failures was only supported by the DAR data due to
lack of reported information in the FAR reports.

Figure 8.3 presents a summary of the results from the survey and also
the logic of the approach. The knowledge gained can be divided into three
levels:

Level 1 , the system and its components,
8.4. Results

Level 2, failure causes based on statistics, and

Level 3, details about failure causes based on experience from maintenance personnel.

Firstly, statistics that would support the RCM analysis were studied and deduced for both the whole system (the Stockholm City power delivery system), and for a critical voltage level (the 11 kV network system). Secondly, the focus was placed on the cable system component and a specific station LH11. Available data was extracted. The results showed that the data was not sufficient and specifically that causes were not sufficiently broken down into detail. To achieve a deeper level of understanding of the causes of failures, discussions with maintenance personnel were conducted. This resulted in a deeper level of knowledge about the causes of failure for the 11kV cable component.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Result</th>
<th>Supporting statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical area</td>
<td>11 kV network</td>
<td>1982 – 1990</td>
</tr>
<tr>
<td>Critical component</td>
<td>underground cable</td>
<td>1982 – 1990</td>
</tr>
<tr>
<td>Cause of failure</td>
<td>material and method</td>
<td>1982 – 1999</td>
</tr>
<tr>
<td>Part of cable</td>
<td>cable</td>
<td>1982 – 1999</td>
</tr>
<tr>
<td>Type of insulation</td>
<td>about half of XLPE and impregnated paper</td>
<td></td>
</tr>
</tbody>
</table>

8.4.2 Recommendations for the Documentation System

The need for and benefits of reporting more as well as better information have been identified, and could lead to for example a more complete use of the reporting system.

The following list summarizes some of the resulting recommendations from discussions with maintenance personnel as well from the investigation of the current reporting system.
• Report information for components treated individually. This would help to easily identify trends and possible actions, for example replacement of a type of joint that appeared to be prone to failure.

• Use a checklist and visual inspection during failure events. Include useful information about the environment to further support the reporting of failure incidents (see Section 8.3.2).

• Incorporate several information systems to create a comprehensive understanding of the system and its components, for example include information about: material, maintenance times, remarks and actions.

• Improve feedback and communication within the different active parts of the reporting procedures, for example by sharing and discussing the statistics resulting from the reporting systems.

• Provide the necessary support for the organization to assist in long-term work with documentation led by their own expertise.

In summary it was proposed that an extensive documentation system be created to provide decision-making support for maintenance planning, and furthermore that long-term responsibility for this system be prioritised in the organization. The motivation for this is and must be based on economics. This paper has shown the benefit of such a system in providing decision support for taking the right maintenance actions for components (RCM). This in turn would help make optimal use of the economic resources that would be an incentive in regard to requirements from authorities and owners.

8.4.3 Application of the Results in RCM

The data and knowledge obtained from the survey can be put into an RCM framework with the aim of achieving an optimal maintenance strategy. The results from this cable application study are shown in Figure 8.3. This application follows the RCM method as represented by the RCM framework in Section 6.2.2, and relates reliability performance and PM through causes of failures. It should be noted that the intention is not to suggest this as the only solution for the cable component, but to provide one possible solution for a real component based upon real data.
Figure 8.3. Results from the survey as input data for an RCM analysis. Note that the boxes shown with dashed lines are those that could be considered to be affected by PM. Note also that the percentage of the causes of lower-level failures do not add up to that of the higher-level failures because some items (specifically unknown), have been omitted.
The cable application study can be summarized as follows. The cable system has one main function, being to deliver electrical power. This function can fail in one of two failure modes: (i) short circuit (for example one/two phase/s to earth), or (ii) open circuit (for example interruption in supply). Furthermore, a failure event leads to failure of function. A short circuit is caused by imperfections in the insulation, in other words by insulation failure. A failure event occurs due to a failure cause. An insulation failure is due to deterioration in the insulation, and could for example be caused by water treeing in XLPE cables.

The results show the logic between detailed knowledge about failure causes and system function failure. In this application using an 11 kV cable system, the conclusion is that 50% of causes of failure are due to material and method and of these 34% have known causes. These failure causes were further identified in detail based on knowledge from maintenance personnel, which would suggest that these could be reduced by PM. Consequently, the application of these results could be used to show the benefit of preventing component failures with the right maintenance activity.

A reliability analysis of the 11 kV system defined (LH11) was made and presented in [121]. The results clearly demonstrate the system reliability benefits obtained by focusing maintenance on the critical components, and on the dominant causes of failures on which maintenance can have an impact. This forms a significant input to achieving cost-effective maintenance programs. Furthermore, this was supported by the use of data and information about the specific system as a result of the comprehensive survey of causes of failures as presented in this paper. Consequently, this survey has shown a contribution for improving PM plans.

8.4.4 An Analysis of the Maintenance Situation

As a result of the cooperation with the power utility Birka Nät, an understanding of today’s maintenance situation has been gained and is presented in the following analysis. It is also interesting to note that this discussion provided the motivation for this work, and therefore also appeared in the introductory chapter.

The following three major parties are involved in this provision of service.
8.4. Results

1. The authority that regulates the market and supervises the utilities’ in their fulfilling certain requirements.

2. The customer who receives energy supplied via the electric distribution system.

3. The utility that owns, operates and maintains the distribution system.

The following points summarize the changing situation they face.

• Deregulation ⇒ market conditions ⇒ requirements for effectiveness, for example the benefit in reliability of a PM measure must balance the cost of applying the same.

• Market conditions ⇒ new ways of handling a company effectively, for example ⇒ larger utilities mean more assets resulting in the employees no longer know their systems, instead face new routines and systematic approaches ⇒ subcontracting out maintenance; a need to specify in detail what the needs and benefits are.

• Customers and society require generally higher levels of availability than experienced in the past but also clearly visible incentives in receiving a certain availability at a certain cost, that is production of cost incentive goods.

• Authority supervises, and compensates or penalizes the utilities depending on how they meet their requirements and fulfill their obligations towards their customers.

• Power demand in most Western countries is on the increase but not at the same rate as before, which implies a decline in the rate of extension of power systems and the increasing age of the existing ones.

Conclusions about the maintenance situation:

• requirements for PM measures will increase in the future,

• there is a requirement for quantifying the benefit of expenses made, for example PM in cost and reliability, and

• a systematic methodology is required to support PM strategy decisions.
8.5. Conclusions

Objectives:

- formulate RCM methodology, and
- develop theories and tools to support a quantitative measure of the relationships PM, cost and reliability.

8.5 Conclusions

The main conclusion from the data survey is that data exists that could support an RCM analysis, but that it is inadequate. RCM analysis requires a deeper level of information, as well as the efficient use of the reporting system.

The conclusion from the statistical analysis for the Stockholm City system (1982-1990) is that the critical voltage level for system reliability and the number of affected customers is the 11 kV network. Furthermore, the critical component type was identified as the cable, which dominated the system with 70% of the feeders and availability for customers. After system analysis, the cable component was studied in greater depth. The significant causes of failures were identified from 1981-1999 data, and it was found that material and method was reported as the cause of 59% of the total number of failures. Moreover, it was found that these faults originated equally often from cables and the joints on the one hand, and from XLPE insulation cables and mass-impregnated cables on the other.

Furthermore, from interviews with maintenance personnel about the causes of cable faults, it was concluded that due to the complicated nature of the process of identifying causes of failures, not all the questions currently posed can be fully answered. However, it can be stated that useful information is available which is not presently reported, for example information about the environment surrounding the cables. This could be overcome by the use of a checklist so that all the parties involved in the relevant activities could be able to contribute to the data. Furthermore, it has been concluded that the feedback on the information reported has been relatively poor, for example the lack of distribution of the resulting statistics from the reports. If communication and feedback improved, this would be reflected in an overall improvement in the quality of the statistics.
Chapter 9

XLPE Cable Insulation Behaviour

This chapter presents cable component behaviour focusing on the degradation of the insulation due to the water-tree phenomenon, and also on the diagnosis and PM methods used to characterize, measure and prevent these. Consequently the polymeric insulation material that they occur in is also focused on, especially XLPE. The understanding of and the supporting data for component behaviour presented in this chapter provides input data for the modelling and analysis of cable component behaviour presented in Chapter 11.

9.1 Introduction

The main objective of the analysis in this thesis is to support an effective PM plan. At this point of the analysis this issue relates to cable insulation and defining an optimal choice of PM method to prevent failures caused by water treeing. This chapter aims to provide a short introduction to the area of cable insulation in XLPE cables, though enough detail to support the following analysis that uses these results. For a comprehensive presentation of the different phenomena and relevant research, the reader is referred to more specific literature.
9.2. Aging Mechanisms

Electrical insulation as indicated in the introduction to the cable system component (Chapter 7), is both a crucial and a complex area for the understanding of the cable behaviour. Moreover, cable insulation failures are the effects of different aging mechanisms in the insulation material. This matter has been the subject of detailed studies and research, for example Cigré has published several reports on the subject of aging factors and diagnostics of cable systems [122], [123] and [124].

Extensive research has been undertaken by the Electric Insulation Group at KTH. The original aim was to develop a method for defining the remaining lifetime of XLPE cables. The project resulted in the development and implementation of a tool, where permittivity and losses are measured as a function of voltage and frequency. This technique is suitable for measuring cables in the field as well as samples in the laboratory. Field-aged cables have been analyzed both in laboratory and field. In addition, a method for growing and analyzing water trees in small XLPE samples has also been developed. The aim is to continue the research, and for the techniques developed to be put to practical use by the power utilities. The following thesis and publications summarize the results: [100], [101], [125], [102], [33] and [126].

9.2 Aging Mechanisms

9.2.1 Aging Factors and Effects

An overview of different aging mechanisms and diagnostic methods for both XLPE and paper-insulated cables can be found in [21]. That study suggested that aging factors that affect cable insulating include the following (examples of each are provide in brackets): thermal (temperature cycling), electrical (voltage), environmental (humidity) and mechanical (example bending). Moreover, an attempt has been made to define possible aging mechanisms for the cable system relating to these four different aging factors. One of these is the phenomenon of water treeing which is said to be caused by either electrical or environmental factors. Moreover these aging factors are said to cause the aging mechanisms of electrical treeing, water treeing and partial discharging (PD).
Important to note here is that some of the aging mechanism may take several years to develop while others may occur within days or weeks [21]. Another issue to note here is that this area is very complicated, which has led to a number of different theories, and no single correct model for aging exists.

9.2.2 The Water-Tree Phenomenon

Water treeing is considered to be the most important aging phenomenon in polymeric insulated cables [100],[98],[21].

The water-tree concept

The concept of a water tree is used to refer to structures in the polymeric insulation said to resemble the shape of a tree. Two types of water trees can be distinguished, referred to as bow-tie and vented trees, and are described below.

Bow-tie trees start to grow within the insulation and grow along the electrical field lines. The initiating point is usually a void or impurity in the insulation. The growth is rapidly from the initiating point, but decreases dramatically and can almost stop at the end. This growth process implies there is a limited length of bow-tie trees and therefore these trees are seldom considered to be the cause of insulation failure.

Vented trees (also referred to as boundary or bush trees) start to grow from the interfaces between the insulation and the semi-conducting screens. Consequently these trees are in contact with the screens so water and impurities can easily diffuse into the water-tree structure. The initiating point is often difficult to find. Possible initiating causes of these include mechanical damage to the insulation surface, voids and irregularities or heterogeneities in the semiconductor screens. The growth of vented trees can be described in three stages: (i) the inception stage before growth begins, (ii) a rapid growth stage, and (iii) a slowing down in growth stage. This growth pattern can allow water trees to grow through the entire thickness of the insulation. Therefore, the vented trees are considered to be the more dangerous of the two types of water trees.
9.2. Aging Mechanisms

The following analysis and discussion sections of the thesis refer to vented trees, unless stated otherwise. Figure 9.1 shows an example of vented water-trees.

![Image of water-trees](image)

**Figure 9.1.** An example of a cable exhibiting vented water-trees, where some of these have grown through the complete thickness of the cable insulation [100].

**Properties of water trees**

It has been observed and is generally accepted that water trees reduce the 50 Hz, 0.1 Hz, DC, and impulse breakdown strength [100]. Though the water itself appears as an insulating material, cable samples with water trees bridging the whole insulation, still exhibited a breakdown strength above service stress $\approx 2 \text{kV/mm}$ [21], [100].

The breakdown voltage of water-tree-deteriorated cables can be restored by drying the insulation. Breakdown voltages of up to approximately 50% of the original level have been reported. However the trees do not disappear, and when water returns the breakdown voltage reduces again [100].

**Water-tree mechanisms**

The following are the two most commonly presented water-tree growth mechanisms.
1. The electro-chemical mechanism assumes that the water treeing is a result of chemical reactions that are strongly enhanced by electrical stress. The initiating process is caused by water entering the regions of the polymer. This is followed by chemical reactions and electrolysis reactions at the border of the PE and water that lead to the degradation of the PE. This degradation causes oxidation and polar groups are created which enhance diffusion and further degradation take place.

2. The electro-mechanical mechanism assumes that water treeing is caused by Maxwell's forces which are high enough to damage the PE.

Artificial aging

Water treeing under service-voltage conditions is a very slow process. This means that accelerated or artificial aging is required in measurement studies. Application of such a procedure that accelerates the aging must also result in conditions that reflect the effects that would normally occur during service conditions. The parameters normally used to accelerate aging include application of electric stress, frequency and temperature. Internationally proposed and generally accepted artificial aging factors include for example 30 degrees Celsius and $2.5U_0$ [100].

9.3 Diagnostic Measurements

The purpose of diagnosis is to evaluate and locate degradation phenomena causing cable failure [21]. Diagnostic measurements can be done using either destructive or non-destructive tests, depending on whether the measured object is destroyed by the test or not. Furthermore, these can be made either on-site or in the laboratory (where accelerated aging can be achieved). Diagnostic tests measure or monitor one or more properties of the insulation that are related to aging or failure, for example, a failure occurs when the property reaches a critical level after a certain age or aging period.
9.3.1 Diagnostic Methods

Non-destructive method

Figure 9.2 provides a simple illustration of both (i) the problem, and (ii) the method used to measure the status of water-tree affected cable insulation. Furthermore, this figure summarizes the method that has been developed and implemented by the Insulation Research Group at KTH.

The upper part of the same figure (the process) can be summarized as follows. Due to the entry of water into the insulation, the phenomenon of water-treeing is initiated. Water trees start to grow through the cable insulation, which in turn leads to a decrease in the breakdown voltage in the cable. The resulting effect is therefore a deterioration in the condition of the cable. To achieve effective maintenance and operation of the cable system, it is desirable to predict the remaining lifetime of the cable. For example, when a cable faults the decision has to made to either replace or repair the cable, and this decision is influenced by the overall condition of the cable. Consequently, there is a need for a method able to diagnose cable condition.

The lower part of the same figure illustrates the diagnosis method that uses dielectric diagnostics of the insulation to gain an understanding of the condition of the insulation. Therefore, information has to be gathered to determine this, which is done by exciting the insulation and measuring the response. Importantly a property that reflects the general status of the insulation should be used for these measurements. It has been proven that a change in the insulation has dielectric properties [125]. Moreover, these properties can be effected by dielectric polarization. If the polarization is changed in time it gives rise to an electric current. This current could be measured in a diagnosis technique to indicate insulation status.

The electric field that the insulation is subjected to can of course be any of a number of different types. Two of the most commonly used are, voltage by a step function (for example Heaviside’s step function [61], and voltage by a sinusoidal function [125]. Moreover, for these two different assumed functions, the two different methods for measuring the current are obtained in either the time domain or the frequency domain. Just as the name suggests, these methods are either performed as functions of time or frequency.
9.3. Diagnostic Measurements

The frequency domain method has been discussed further here, and the results have been used in the analysis found in Chapter 11.

The resulting response current (which has phase and amplitude) can, after some mathematical analysis [100], [101], [125] be measured through the use of the permittivity \( \varepsilon \), which is defined in complex form as follows:

\[
e(\omega) = \varepsilon_0(\varepsilon_r + i\varepsilon_i) = \varepsilon_r - i\varepsilon_i \tag{9.1}
\]

where \( \varepsilon_r \) is the real part of the relative permittivity, therefore \( \varepsilon/\varepsilon_0 \) - \( \varepsilon_i \) is the imaginary part of the relative permittivity \( \varepsilon/\varepsilon_0 \). The imaginary part of the relative permittivity is also referred to as dielectric loss. Furthermore, the ratio between the loss part and the capacitive part is given by:

\[
tan\delta = \frac{e^\prime\prime(\omega)}{e^\prime(\omega)}, \tag{9.2}
\]

which is defined as the loss factor.

This method has been developed, implemented and used for experiments utilizing the frequency domain method, in high voltage applications \( U_0 = 12\text{kV} \), with the frequency interval \( 0.0001 - 100 \) Hz, as presented in [125], [100], and [101]. The resulting method is called dielectric spectroscopy.

Results from these experiments showed that non-water-treed cables had low losses and linear responses. However the water-treed cables had increased losses and significantly non-linear responses both in capacitance and losses [100]. This method can consequently be used for distinguishing between non-water-treed and water-treed cables, and how to relate this effect to insulation status.

The method has been further developed and implemented as presented in [100] and [101]. The following relationship is presented for the analysis of the non-linear response:

\[
\Delta e^\prime_{n\text{onlin}} = e^\prime(U_0) - e^\prime(0.5U_0) = \Delta e^\prime(0.5U_0) - \Delta e^\prime(U_0), \text{ and} \\
\Delta e^\prime\prime_{n\text{onlin}} = e^\prime\prime(U_0) - e^\prime\prime(0.5U_0). \tag{9.3}
\]
Fig. 9.2. Illustration of the dielectric diagnostics of water-tree affected electric insulation, with two alternative functions for the electric field applied.
Destructive methods

Two generally used "destructive" methods have been presented in following paragraphs.

*Electrical breakdown testing* can be done using AC, DC or impulse voltages. This is a simple method and one of the most widely used. The most common tests are done using impulse and AC impulses at 50 Hz. A limitation with this method is that it requires many samples [21].

*Water-tree testing* is done on thin slices of cable, about 0.1-1 mm in thickness. Before doing the analysis, the trees must be made visible. In the method used in [100], the slices are stained and then investigated using a stereo microscope, or with the aid of image analysis using a video camera connected to a computer. To simplify the tedious measuring work, an evaluation method based on the assumption that it is the length of the longest water-tree that is of critical importance, has been developed [100], [127].

All investigations in [100] where made on field-aged water-trees. One reason for this was that it had been noted when using the previously presented non-destructive method and the breakdown-test method, that these gave different results in laboratory-aged water-trees.

9.4 Preventive Maintenance in Cables

9.4.1 Replacement Schemes Based on Diagnosis Methods

The non-destructive diagnosis method presented earlier and summarized in Figure 9.2, has been used together with a criterion for the condition of the cable, to define replacement schemes for cables. This means that the result from the diagnostic measurements together with the resulting loss factor was used for classification of the status of the cables. Results from these studies are presented in [126] and [101]. This method is now a commercial product. Table 9.1 summarizes these criteria.

A report by Elforsk [128], presents a comparison of four commercial methods based on the diagnosis of the condition of the insulation and water-tree aging for different cable types. The report also indicated which type of information that is essential to be collected in a system for a continuous diagnosis of component condition.
9.4.2 Rehabilitation Method for Water-treed Cables

It has been shown that deterioration of cable insulation due to water treeing can be prevented by a rehabilitation method. This method for rehabilitation of XLPE cables with long water-trees has been developed and patented in the USA [129]. A large amount of XLPE cables have been rehabilitated using this method in both Europe and the USA, totaling some 700 – 800 km of three-conductor cable. The utilities that have utilized the method have also to a large extent continued to use it in their installations and infrastructure [129].

This method has also been applied and evaluated in by the Foundation for scientific and industrial research at the Norwegian Institute of Technology (SINTEF) in Norway as presented in [130]. The same study includes application studies from the field and laboratory, and evaluation of the water-tree growth after rehabilitation (laboratory study). A full-scale failure test done at Sandnes Energi, provides useful experience and results for the method. An aging process been studied two years after PM activities in laboratory studies. It has been verified that rehabilitation leads to a significant improvement in both AC and impulse voltages.

Rehabilitation by Silicon Injection

The main principle in this rehabilitation method involves injecting a silicone-based liquid between the wires in the conductor. It is therefore not possible to rehabilitate cables with massive conductors, or cables with swallow powder in the conductor.

Table 9.1. Diagnostic criteria for defining cable status [100], [101].

<table>
<thead>
<tr>
<th>Category</th>
<th>Normalized breakdown voltage [V]</th>
<th>Comment about the cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>( U_{bd}/U_0 ) &gt; 4</td>
<td>No measures necessary</td>
</tr>
<tr>
<td>Risk</td>
<td>( 2.5 \leq U_{bd}/U_0 \leq 4 )</td>
<td>Risk zone keep for observation</td>
</tr>
<tr>
<td>Bad</td>
<td>( U_{bd}/U_0 ) \leq 2.5</td>
<td>Poor condition replaced ASAP</td>
</tr>
<tr>
<td>Bad/leakage</td>
<td>( U_{bd}/U_0 ) \leq 2</td>
<td>Very poor condition replaced ASAP</td>
</tr>
</tbody>
</table>
Rehabilitation is brought about when the component in the silicon-based liquid diffuses in and is absorbed into the semiconductor and the XLPE insulation. With heating during current loading, this rehabilitation measure works quicker since the diffusion speed increases with temperature.

When the rehabilitation liquid comes into contact with water from the water-tree in the insulation, a chemical polymerization reaction takes place, and the liquid consumes the dampness and the diffusion of the molecules becomes slower [130].

**SINTEF Experience with this Rehabilitation Method**

Results from the rehabilitation of three major water-tree-aged XLPE cables (24 kV 3x150mm²) performed at Sandnes Energi are presented in [130]. The cables were manufactured and installed in 1975. One of the lengths experienced a supply interruption. Using water-tree analyses on pieces of the cable near the failure, it could be ascertained that it contained vented water-trees from the outer semi-conductor of tape that equated to some 95–99% of the insulation strength over a 5.5 mm distance. The cables that were rehabilitated were consequently strongly water-tree-aged. To obtain the best possible rehabilitation outcome, the cable was heated in DC current.

The results from the voltage strength testing of the cable at different points of time after the rehabilitation have been presented using for example a 5 m length of cable containing water trees that was tested at a strength of $U_{gj} = 30$ kV. After the rehabilitation, a cable with water trees could carry $\bar{U}_{gj} = 156$ kV, which implies that the electrical strength had been improved by 380%.

A common procedure used to evaluate the condition of an XLPE cable is to repair the first and often also the second failure without making any special arrangements. As a rule, failures in XLPE cables produced after 1982 are one-off occurrences. If the cable continues to fail, the utility evaluates other alternatives such as sampling for water-tree analysis, replacement, rehabilitation.

It is desirable to develop secure non-destructive methods for diagnosis of cables for rehabilitation [130].

Laboratory aging of XLPE cables has shown that water-tree growth begins again after rehabilitation.
Rehabilitation liquid has a positive effect on the impulse strength, the initial voltage of partial discharges, and electrical trees.

The dielectric losses increase at rehabilitation. This can have an impact on the performance criterion of non-destructive tests on rehabilitated cables. This is further discussed in Chapter 11.

**Economical benefits of rehabilitation**

The costs of rehabilitation compared to renewal of cable have been evaluated in two practical cases: (i) the Sandnes Energi case, and (ii) a Fredrikstad Energiverk installation [130]. The utilities have provided costs for these relatively dissimilar installations, shown in Table 9.2. It can be seen that the rehabilitation cost is less than the replacement cost in both cases.

These calculations do not consider differences in quality, manufacturing and installation methods between cables manufactured in the mid 1970s and those of today and in other words the loss in profit by having to install new cables.

The conclusion here is a recommendation to the utilities to adopt the rehabilitation method, because after evaluation, it has been shown to be an economically and technically beneficial method.

**Table 9.2.** Cost values for the SINTEF evaluation of the PM method for water-treed XLPE cables [130].

<table>
<thead>
<tr>
<th>Utility</th>
<th>Cable length</th>
<th>Cost for rehabilitation</th>
<th>Cost for renewal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandnes</td>
<td>1700</td>
<td>500,000</td>
<td>770,000</td>
</tr>
<tr>
<td>Fredrikstad</td>
<td>650</td>
<td>170,000</td>
<td>370,000</td>
</tr>
</tbody>
</table>

SEK 1.5 ≈ NKR 1 and SEK 10 ≈ Euro 1
9.5 Survey about XLPE Cables Affected by Water Treeing

Introduction

In 1981, a working group was established with the objective to collect and analyze data on damaged XLPE cable stations. This working group delivered a report at the end of 1985, which included all known types of faults on XLPE cable in 12 and 24 kV systems, that had occurred during the period 1965 to the beginning of 1985. This report established that the failure rate was at an acceptable level, and that “the expected lifetime was essentially in excess of 15 years”. Furthermore, it recommended the continued evaluation of the XLPE cables. In January 1988, another working group was appointed with the objective to determine lifetimes and the uses of XLPE cables, and to recommend any steps that needed to be taken. This section introduces the main features of this survey [104], from which data has been used for further analysis.

Collection of basic data

As discussed earlier on in Section 7.3.1, it was established that the disturbance statistics available from Swedenergy (formerly the Swedish Power Utility Association) were too incomplete to be used as a source of data for the investigation. Therefore the working group decided to perform a national data collection procedure for failures occurring in XLPE cable systems, that would include failures at joints and terminations. Furthermore, it was considered that all failures should be included, even though they were caused by for example digging, and that it would include operation voltage levels of 12 kV and higher.

In March 1988, the request for information was sent out to 257 utilities. Of these, some 251 responded. The utilities that had reported failures received a questionnaire asking for a detailed description of these failures. The quality of the failure descriptions were of course varying, and in some instances failure descriptions were not received at all.
9.5. Survey about XLPE Cables Affected by Water Treeing

Remarks about the data collection procedure

It is interesting to compare this XLPE data survey above with the survey performed in this thesis on the causes of failures of a cable system presented in Chapter 8). In both these surveys, it was realized initially that the nationally collected statistics (introduced in Section 7.3.1), were too incomplete for the objectives. However in the survey of the cause of failures (the thesis) it was then decided to focus on gaining more data by contacting one utility, rather than as was done in the study above, by contacting several utilities. Another interesting difference is that in the survey above, the utilities were asked about data that they had already made a special effort to obtain, though in the thesis survey generally available data was identified. Both these surveys show in a simple way, how to collect statistics that could be used for the prediction of reliability, which is a significant contribution.

Analysis of the Statistics

A cable system is assumed to consist of a three-conductor cable or three one-conductor cables, joints and terminations. A failure is defined as one or several failures that occur in the same cable system, and implies voltage interruptions. Furthermore, the cable faults where grouped into the two different causes of failures described below.

1. Insulation material failure caused by treeing including:
   - faults established by the manufacturer as treeing,
   - repeated inexplicable faults of a cable system, and
   - occasional inexplicable faults where the cable system had been in operation for more than one year and the working group considered the likelihood of tree faulting as high.

2. Other cable faults considered including:
   - manufacturing faults that include faults established by the manufacturer such as production faults, as well as inexplicable faults occurring within less than a year after being put in operation.
• inexplicable faults that include faults occurring after a year in operation and that were considered not to be insulation material failure caused by treeing.
• failure caused by damage that includes digging and skewing and such like, and handling and laying not following the appropriate norms.

Results
The average failure rate of the XLPE cable systems in total has been shown to be somewhat more than half of that of the impregnated paper cables. The failure rate for modern XLPE cables developed after 1975 is only one seventh of the failure rate of the total XLPE cables in the study. With this background, it is concluded that the XLPE cable is expected to reach the same lifetime expectancy as impregnated paper cables.

This also shows that the inclusion of the extruded outer conducting layer that protects the insulation from water penetration has been able to significantly reduce the number of failures. Consequently, the results indicate that the problem with water trees was significantly reduced with the introduction of extruded layers.

An interesting question is, "What was the cost of this benefit?" However the issue has not been treated in the study.

These statistics have been analysed further and used in the modelling of failure rate presented in Chapter 11.

Conclusions and further analysis
The conclusions from the Svel study are that treeing occurs primarily in failures in cables that were manufactured before 1974 and that have an outer semiconductor of tape (this is before the introduction of the extruded layer), are low loaded and have dampness or water in the conductor; and that these often occur in connection with overvoltages in the network, for example due to lightning.

Another report was presented analysing the same issue in 1995 [131], where statistics for the improved XLPE cables where evaluated. The result showed during a five years period no water treeing failures for these new type of cables, with the extruded outer layer.
Chapter 10

RCM Application Studies using Approach I

This chapter presents the results of a reliability analysis on two different power distribution systems: (i) a rural system referred to as Flymen and dominated by overhead lines, and (ii) an urban system referred to as Birka with mainly underground cables. This analysis focuses on relating system reliability to the preventive maintenance (PM) of the included components such as lines or cables. In the approach presented, referred to as Approach I, it has been assumed that the impact of maintenance results in a percentage reduction in the causes of component failure.

10.1 Approach

The approach used in the RCM analysis of the two case distribution systems has been presented below. This approach involves running through all the steps defined in the RCM methodology presented in Table 6.1 (see page 94), except for the last step, which is the cost and benefit analysis analysed in detail in Section 6.2. The overall approach is has been outlined below.

1. Choose and define a system to analyze, consisting of a

(a) boundary, and
(b) included components.
2. Collect, select and define input data:
   (a) system network data,
   (b) customer and power data, and
   (c) component reliability data.

3. Evaluate system and load-point reliability with RADPOW:
   (a) identify critical components, and
   (b) identify critical load points, voltage levels and so on.

4. Evaluate component behaviour:
   (a) conduct a failure mode and effect analysis, and
   (b) collect statistics and experience about the causes of failures.

5. Model the effect of PM on reliability
   Approach I has been used in accordance with Chapter 6, and can be described as follows. It is assumed that a PM activity results in a percentage reduction in the causes of failures for affected components. Furthermore, it is also assumed that the failure rate is reduced by an equivalent percentage. The resulting model of the relationship between failure rate and PM is referred to as $\lambda(\text{PM})$.

6. Evaluate the effect of PM on system reliability.

10.2 Flymen - a Rural Overhead Line System

This section describes the analysis and presents the results of a reliability and maintenance study done on a rural Swedish distribution system called Flymen. Results from this study have been published in: [96], [95], [94] and [70].

10.2.1 Definition of the Flymen System

The Flymen Network

The Flymen network is a 10 kV distribution system located in Blekinge in southern Sweden, and belongs to the Sydkraft Elnät distribution area.
network. The Flymen network supplies just over 900 customers at 112 load points, with a total energy demand per year of 8890 MWh. The Flymen distribution system is supplied via two 4 MVA 20/10 kV transformers, which constitute a reciprocal reserve for each other. The system consists of four outgoing feeders, normally fed radially from the transformer station in the Flymen network. This network has coupling possibilities via disconnectors (see Figure 10.1). The Flymen network includes manual and automatic disconnectors. Moreover, it is a simple country distribution system compared with the more complicated urban networks.

The maintenance policy covering the Flymen network follows the investment and maintenance policy for local networks in Sydkraft [132]. The maintenance of the overhead lines in streets are included in a separate document [133]. The aim of the maintenance efforts is to keep the equipment in a state that fulfills the requirements for operation and personnel safety at the lowest possible cost [132]. According to Sydkraft, there are no special maintenance problem areas or where failure occurrences are especially high in the Flymen system. However, there are major changes underway in maintenance planning at Sydkraft and at other utilities. This could indicate that there are weaknesses in the existing procedures for maintenance planning. A new process-oriented approach to this work is being developed at Sydkraft, and a new policy for maintenance is being drafted. Life-cycle cost (LCC) is to be used as a tool for analysing the inspection results according to the policy [132].

The Flymen Model

As can be seen in Figure 10.1, the Flymen network can be separated into northern and southern parts, which are independent of one another in respect to reliability. Therefore distribution in these two parts can be analyzed separately. Since it is desirable to make the analysis on a limited system, one of these parts has been chosen for this analysis, being the northern part referred to as FlymenN (see Figure 10.3). The system is modelled from the supply point to the load points, and the Flymen station is not included in the analysis. Figure 10.2 illustrates the components included in the analysis. Note that the component type referred to earlier as a bus (in Chapter 4) is called a junction here. The system is defined by its load points and included
components (as illustrated in Figures 10.4 and 10.5). All these points have been identified by a number.

As can be seen in Figure 10.3, two load points (denoted 295 and 296) have been introduced that are not included in the Flymen network. These load points are the dummy load points referred to previously for ensuring correct deduction of failure events for other load points, but are not themselves included in the reliability analyses. By introducing these two load points, the failure of any component in the normally open path between the subsystems FlymenNW and FlymenNE (via branches 80 and 137) has been included in the analysis (see also Chapter 4 and Section 4.8.2 about dummy load points).

10.2.2 Network, Power and Customer Input Data

The network, power and customer input data for the reliability analysis of the Flymen system has been provided by Sydkraft, and are presented below.

1. Connection diagram of the network for the Flymen station including:
   - load points with individual notations, and
   - section (switching) points with disconnectors.

2. Operation diagram showing the topology of the network including:
   - load points with individual notations, and
   - section (switching) points with disconnectors.

3. Data for the overhead lines including:
   - connection points,
   - length,
   - type, and
   - impedance data.

4. Table of the included load points including:
   - name and number,
   - number of customers, and
Figure 10.1. The Flymen system.
• yearly energy consumption (kWh).

• Type of customers connected to each load point by:
  – NE: bungalows, summer cottages, small farms, poultry farm, and
  – NW: bungalows, summer cottages, small farms, country shop.

The network topology input data for RADPOW can be summarized as follows:

• 140 branches and 296 components,
• two supply points (components 69 and 70),
• one normally open point (component 142), and
• component types (according to Figure 10.2).

The customer and power data-topology-input-data for RADPOW can be described as follows. The customers are mainly residential, but as can be seen in the input data from Sydkraft presented above, there are also other categories of customers. From the Flymen input data (see Appendix B), it can be seen that four load points have a distinctly higher power demand per customer than the other load points. Therefore it has been assumed that these load points (6, 7, 24 and 68) are industrial customers. These data have been divided into different categories of customer (see Appendix B for a summary of these).

Further information of interest from Sydkraft is, that there are two proposed switching points in the northern part of the network:
Figure 10.3. The FlymenN system.
Figure 10.4. The FlymenNW system.
Figure 10.5. The FlymenNE system.
10.2. Flymen - a Rural Overhead Line System

- NW: cn 280 (F14-2870) and cn 142 (F142875),
- NE: cn 287 (F14-2880).

These proposed points could possibly effect the future reliability of the Flymen system.

10.2.3 Reliability Input Data

Sydkraft has provided reliability data for the Flymen system which has been summarized below.

1. Switching time:
   - manual switching - 1 h,
   - remote control - 10 sec \( \approx 0.17 \) h,
   - automatic switching - 5 sec \( \approx 0.083 \) h.

2. Failure rate:
   - line - 1.8 f/yr per feeder,
   - breaker - 0.005 f/yr,
   - manual disconnectors - 0.05 f/yr,
   - equipment for remote control - 0.0005 f/yr, and
   - equipment for automatic switching - 0.001 f/yr.

3. Repair times:
   - line - 3 h,
   - breaker - 12 h,
   - manual disconnectors - 3 h, and
   - remote or automatic disconnectors - 6 h.

4. Probability of non-function via:
   - remote - 0.0005, and
   - automatic - 0.0014.
Further input data required by RADPOW have been defined based on the following assumptions.

- Based on the failure rate for the disconnectors, the following assumptions have been made for the failure rates, (i) remote disconnectors $0.05 + 0.0005 = 0.0505 \text{ f/yr}$, and (ii) automatic disconnectors $0.05 + 0.001 = 0.051 \text{ f/yr}$.

- Failure statistics for the load points have been estimated as follows. During a period of three years (1996-1998), 900 failures for Sydkraft’s total number of load points (approximately 17,000) have been registered. This gives $900/(17000 \cdot 3) \approx 0.018 \text{ f/yr per load point (bus bar type)}$.

The statistics Sydkraft have today are not broken down to component level. This will be changed in their future maintenance planning, since it is necessary for providing correct analyses.

### 10.2.4 Definition of Failure Rates for Overhead Lines

This section analyses and defines some additional reliability input data for the Flymen system, including different failure rates.

**Evaluation of permanent failure rates for overhead lines**

The failure rates for overhead lines have been provided by Sydkraft as the average failure frequency per feeder. However, input data for RADPOW for failure rates are for each component, that is for each line. Therefore this average value has had to be converted into failure rates per km for each feeder. Since the feeders are of different total lengths, the result is a different failure rate per km and feeder. A more correct way statistically, would have been to use the same failure rate per km for both feeders, since the statistics are known to be very limited. It should however be remembered that these failure rates are an overall average, and there will be differences occurring in the actual rates of different feeders due to differences in terrain, tree coverage, weather patterns and so on. Therefore, it is reasonable to incorporate this effect by having different values for different feeders, which was the approach used in this analysis of the Flymen system.
10.2. Flymen - a Rural Overhead Line System

Assuming that the failure rate for the feeders is proportional to its length, then the following Sydkraft data are known:

- the average failure rate per feeder is 1.8 failures per year, and
- the lengths of individual overhead lines.

With this information, calculations have then been made to obtain an average failure rate for different lengths of overhead lines. FlymenN consists of two main feeders, (i) the north eastern (NE) and (ii) the north western (NW). The total length for these feeders were deduced and the resulting average failure rates per year and kilometer were evaluated as follows.

NW: total length 39 km $\Rightarrow 1.8/39 \approx 0.046$ f/yr and km.
NE: total length 28 km $\Rightarrow 1.8/28 \approx 0.064$ f/yr and km.

Furthermore, assuming that all the overhead lines in the NW and NE subsystems have the appropriate average failure rate, then if one average value would have been used for all the overhead lines, the resulting rate would have been 0.054 f/yr and km.

To obtain failure rates for individual overhead lines, all overhead lines were grouped according to length. The overhead line lengths vary between 10 – 1700 m. Six groups have been chosen in increments of 250 m. For each feeder, six groups have been defined and average failure rates calculated. The results are summarized in Tables 10.1 and 10.2. Consequently, the groups with length $l$ have been grouped as follows:

- Line 1, $0 < l \leq 0.25$ km,
- Line 2, $0.25 < l \leq 0.50$ km,
- Line 3, $0.50 < l \leq 0.75$ km,
- Line 4, $0.75 < l \leq 1.00$ km,
- Line 5, $1.00 < l \leq 1.25$ km, and
- Line 6, $1.25 < l$ km.

The average length for each group has been used when calculating the average failure rate. The failure rates were then rounded off to obtain the total average value of 1.8 f/yr per feeder.

**Permanent failure rates for junctions**

There was one component type included in the system model for which no data was provided by Sydkraft the junctions. A junction is a connecting link
10.2. *Flymen - a Rural Overhead Line System*

**Table 10.1.** Failure rates for overhead lines and feeder in the NW subsystem with 0.046 f/yr and km.

<table>
<thead>
<tr>
<th>Line type</th>
<th>Average length [km]</th>
<th>Average failure rate [f/yr]</th>
<th>Number of lines</th>
<th>Resulting failure rate [f/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line1W</td>
<td>0.125</td>
<td>≈ 0.006</td>
<td>33</td>
<td>0.198</td>
</tr>
<tr>
<td>Line2W</td>
<td>0.375</td>
<td>0.017</td>
<td>15</td>
<td>0.255</td>
</tr>
<tr>
<td>Line3W</td>
<td>0.625</td>
<td>0.029</td>
<td>13</td>
<td>0.377</td>
</tr>
<tr>
<td>Line4W</td>
<td>0.875</td>
<td>0.04</td>
<td>10</td>
<td>0.4</td>
</tr>
<tr>
<td>Line5W</td>
<td>1.125</td>
<td>0.05</td>
<td>3</td>
<td>0.15</td>
</tr>
<tr>
<td>Line6W</td>
<td>1.375</td>
<td>0.06</td>
<td>7</td>
<td>0.42</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>81</td>
<td>1.8</td>
</tr>
</tbody>
</table>

**Table 10.2.** Failure rates for overhead lines and feeder in the NE subsection with 0.064 f/yr and km

<table>
<thead>
<tr>
<th>Line type</th>
<th>Average length [km]</th>
<th>Average failure rate [f/yr]</th>
<th>Number of lines</th>
<th>Resulting failure rate [f/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line1E</td>
<td>0.125</td>
<td>0.008</td>
<td>19</td>
<td>0.152</td>
</tr>
<tr>
<td>Line2E</td>
<td>0.375</td>
<td>≈ 0.026</td>
<td>18</td>
<td>0.468</td>
</tr>
<tr>
<td>Line3E</td>
<td>0.625</td>
<td>0.04</td>
<td>7</td>
<td>0.28</td>
</tr>
<tr>
<td>Line4E</td>
<td>0.875</td>
<td>0.06</td>
<td>7</td>
<td>0.42</td>
</tr>
<tr>
<td>Line5E</td>
<td>1.125</td>
<td>0.07</td>
<td>3</td>
<td>0.21</td>
</tr>
<tr>
<td>Line6E</td>
<td>1.375</td>
<td>0.09</td>
<td>3</td>
<td>0.27</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td>57</td>
<td>1.8</td>
</tr>
</tbody>
</table>
in the system. This component could be a simple bus-bar construction or be more complicated including several components.

Input data for the failure rate have therefore been based on other sources of statistics, which were introduced in Chapter 7. The selected data were obtained from statistics from SvI (Swedish electrical power utilities) and the Swedish National Outage Data Bank (DAR). The failure rate used was 0.014 f/yr and refers to the component named \textit{kopplingskäp} (switchbox) at 11 kV [105].

**Passive and active failure rates**

The input data for failure rates discussed earlier in this section relates to permanent failure rates. The permanent failure rate ($\lambda_t$) is a total failure rate for passive and active failure rates (see the definitions in Chapter 2)

$$\lambda_t = \lambda_p + \lambda_a$$

(10.1)

However input data for RADPOW also include active and temporary failure rates, which have been defined below.

- For all static components (overhead lines, transformers and such like) the number of passive failures is generally negligible, therefore $\lambda_p \approx 0 \Rightarrow \lambda_t \approx \lambda_a$.

- Switching devices (particularly breakers and automatic or remote devices) can be prone to operate when not required, hence $\lambda_p > 0 \Rightarrow \lambda_t > \lambda_a$. For manual switches however, $\lambda_p \approx 0$ [43].

Conclusions from the above discussion are hence: (i) that for all components, except the breakers and disconnectors, the active failure rate approximately equals the permanent failure rate, and (ii) that for the breakers and disconnectors, the active failure rate is lower than the passive. Appendix B contains the assumed values for active and temporary failure rates.

**Maintenance Frequency Data**

RADPOW includes one set of reliability input data for maintenance ($\lambda_m$), as presented earlier in Chapter 4. However this input data set relates to
the outage frequency and average time for scheduled maintenance. These activities are planned and therefore the outage will be known in advance and the customers concerned can be informed. Consequently, a scheduled outage is not usually included in the evaluation of a load point’s reliability if this activity causes disconnection [1] (see also Chapter 4). However where events overlap several systems, these cause interruption of supply. Therefore failures caused by a “maintenance outage followed by a component failure” must be analyzed. This aspect was analyzed by RADPOW. However the Flymen system does not include overlapping failure modes, and therefore these values will not have an impact on the results for this system. Therefore a detailed analysis of the maintenance procedures at has been omitted at this stage, and \( \lambda_m \) has been set to zero for all components in the Flymen system model.

10.2.5 Cost Input Data

The following cost data presented in thousands of Swedish kronor (KSEK) were obtained from Sydkraft:

1. Installation costs for breakers:
   - material, KSEK 120, and
   - labour, KSEK 20.

2. Installation costs for manual disconnectors:
   - material, KSEK 20, and
   - labour, KSEK 10.

3. Installation costs for remote or automatic disconnectors:
   - material, KSEK 20 + 60 = 80 (namely the cost of the component plus surrounding equipment), and
   - labour, KSEK 10.

10.2.6 Reliability Analysis

Appendix B presents the load-point indices resulting from the RADPOW analysis of the Flymen system.
10.2. *Flymen - a Rural Overhead Line System*

**Failure Modes**

Figure 10.6 illustrates the deduced minimal cut sets for Load Point 1. Like all load points in the Flymen system, this load point has one radial path and one normally open path. Therefore the system only includes first order failure events. The minimal cut sets of the first order for Load Point 1 include components 69, 140, 143, 71, 144 and 1. The normally open path is connected by the closure of the normally open disconnector that is component 142. The second group of failure modes for Load Point 1 that is the primary system failure modes according with Section 4.5 includes all components that are connected with the load point but not included in its path.

![Diagram](image)

*Figure 10.6. Minimal cut set scheme for Load Point 1*

**Results from RADPOW**

Figure 10.7 shows the output from analyzing the FlymenN subsystem with RADPOW. Furthermore, Appendix B presents results for each individual load point. The following paragraph contains some remarks about these results.

The failure rate seems to be a straight line at two levels, one for the NW subsystem (Load Points 1 – 40) and the other for the NE subsystem (Load Points 41 – 68). The diversity between the subsystems reflects the assumption of using different failure rates for the feeders and the overhead lines in accordance with Section 10.2.4. The failure rate is however not constant for the load points, and this can be seen in a more detailed diagram (Figure 10.8) from the NW subsystem. In the FlymenNW system, the failure rate varied between 4.360 – 4.362 f/yr, and with an increasing failure rate
with the number of components from the supply point. In the FlymenNE system, the failure rate varied from 3.605-3.606 f/yr. It should be stressed that these differences were less than the accuracy in the input data, however they provide information about the different behaviours in the system, which is the aim of the analysis. Furthermore, the almost constant failure rate occurred because all the component failures would result in an outage at all load points. This is in turn the result of the characteristics of the system; for example it is a serial system, has one normally open path that can be used when failure occurs, and two breakers situated at the supply points. Figure 10.9 illustrates the different categories of the failure rate, which in total provide the nearly constant rate. This further illustrates that when the number of permanent failures increases, the active failures decrease, and that the number of temporary failures are constant. However the outage time caused by these failures varies for different restoration activities.

The outage time varies between 0.8380–1.1132 hours, where Load Points 24 and 25 exhibit the maximum values, and 26, 35 and 40 exhibit the minimum values. Unavailability varies between 3.121–4.8559 h/yr, where Load Points 41–44 and 67–68 have the lowest values, and 24 and 25 the highest.

The results for the energy not-supplied indicate two exceptionally high values for the Load Points 6 and 58. As can be seen from the input data in Appendix B, this reflects divergent customer and power data for these two load points compared with the other load points; for Load Point 58 because of a large number of customers, and for Load Point 6 because of a combination of high total active power and large numbers of customers.

**Validation of the Results**

The correctness of the results can be checked using a number of estimations. Consider for example Load Point 1, which has the minimal cut sets of components 69, 140, 143, 71, 144 and 1. All other components in the system constitute additional active failure modes. The same reasoning can be applied to all of the load points. The temporary failure events occur as both minimal cut sets and additional active failures. According to the input data (see Appendix B), the permanent failure rate equals the active failure rate for all components except the two breakers and the disconnectors that are automatically operated ($\lambda_t = \lambda_d$) (see also the discussion about passive
Figure 10.7. Load-point indices for the FlymenN subsystem.
**Figure 10.8.** A close-up view of the failure rate in the FlymenNW subsystem.

**Figure 10.9.** Failure rate categories for the FlymenN subsystem.
10.2. Flymen - a Rural Overhead Line System

and active failure rates in Chapter 2.) This system only contains first order failure modes and the breakers have no "stuck probability".

According to the above discussion, by letting \( n_{\text{type}} \) be the total number of components in the system of a certain type, then an estimate of the failure rate for a load point can then be evaluated by:

\[
\lambda_{lp} \approx \sum_{\text{type}} n_{\text{type}} \cdot (\lambda_t + \lambda_{te}),
\]

where \( \text{type} = \) load point, junction, breaker, manual disconnectors, automatic disconnectors and overhead lines.

**Table 10.3.** Data used in the validation of the RADPOW result for the Flymen system.

<table>
<thead>
<tr>
<th>Component type</th>
<th>Number of components</th>
<th>( \lambda_t ) [f/yr]</th>
<th>( \lambda_{te} ) [f/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUSL</td>
<td>40</td>
<td>0.018</td>
<td>0.01</td>
</tr>
<tr>
<td>BUST</td>
<td>40</td>
<td>0.014</td>
<td>0.01</td>
</tr>
<tr>
<td>BREAK</td>
<td>1</td>
<td>0.005</td>
<td>0.02</td>
</tr>
<tr>
<td>DISCM</td>
<td>6</td>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>DISCA</td>
<td>3</td>
<td>0.051</td>
<td>0</td>
</tr>
<tr>
<td>Line1W</td>
<td>33</td>
<td>0.006</td>
<td>0</td>
</tr>
<tr>
<td>Line2W</td>
<td>15</td>
<td>0.017</td>
<td>0</td>
</tr>
<tr>
<td>Line3W</td>
<td>13</td>
<td>0.029</td>
<td>0</td>
</tr>
<tr>
<td>Line4W</td>
<td>10</td>
<td>0.04</td>
<td>0</td>
</tr>
<tr>
<td>Line5W</td>
<td>3</td>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>Line6W</td>
<td>7</td>
<td>0.06</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 10.3 summarizes data used for the validation. Moreover, with data from Appendix B, an estimate of the failure rate in the Flymen system NW can be evaluated according to the following:

\[
\lambda_{NE} \approx 40 \cdot (0.018 + 0.01) + 40 \cdot (0.014 + 0.01) + 1 \cdot (0.05 + 0.02) + 6 \cdot 0.05 + \]
\[
6 \cdot 0.05 + 3 \cdot 0.051 + +33 \cdot 0.006 + 15 \cdot 0.017 + 13 \cdot 0.029 + \\
+ 10 \cdot 0.04 + 3 \cdot 0.05 + 7 \cdot 0.06 = 4.358 \text{f/yr}
\]

Equivalent evaluations for the NE subsystem result in 3.607 f/yr. Comparing these results with the output from RADPOW, which are 4.36 - 4.362 f/yr and 3.605 - 3.606 f/yr (see Appendix B), leads to the conclusion that the evaluated failure rates from RADPOW seem to be correct.

The unavailability in this system model is caused by three types of failures: permanent, temporary and active. The outages for the permanent failures consist of repair time for the component if the normally open path cannot be used or the switching time of one hour. The outage time for an active failure is also the switching time. The unavailability for the load point is the sum of the unavailables for each failure mode. The contributions from the temporary failures to the uncertainties are small (no more than 8/100 h/yr), and these can be ignored when making an estimate.

Continuing on with Load Point 1, the major contribution to the unavailability is caused by the permanent and the active failures. The restoration activity for a minimal cut set failure mode \((69, 140, 143, 71, 144 \text{ and 1})\), is either repair or re-closure of the normally open disconnectors (with switching time of one hour). The additional active failures are restored by switching. All components that are not a minimal cut set constitute an additional failure. Consequently, Load Point 1 has \(171 - 6 = 165\) additional failures (see also Section 4.5). The failure rate for the total components in the subsystem is calculated to be 4.358 f/yr with the temporary failures. An estimate of the unavailability at Load Point 1 can then be estimated as follows:

\[
U_{lp} \approx \sum U_{active} + U_{permanent},
\]

and where

\[
U_{active} \approx (\lambda_{lp} - \lambda_{te} - \lambda_t) \cdot r_s.
\]

Note that the permanent failure rate \((\lambda_t)\) refers to the actual minimal cut sets for the load point that is analyzed.
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Active failures:

\[
(4.358 - (40 \cdot (0.01 + 0.01) + 0.02) - (0.018 + 2 \cdot 0.014 + 0.017 + \\
+0.04 + 0.004)) f/\text{yr} \cdot 1h/f = 3.431 \text{ h/yr.}
\]

Permanent failures:

\[
0.014 \cdot 2 + 0.04 \cdot 3 + 0.018 \cdot 2 + 0.017 \cdot 1 + 0.005 \cdot 1 + 0.014 = 0.22 \text{ h/yr.}
\]

Total failures:

\[
U_{lp} \approx 3.41 + 0.22 = 3.651 \text{ h/yr.}
\]

This value for the total failures compared with the result from RADPOW (3.72016 h/yr) confirms that the results seem correct. The results for unavailability vary from 3.65 h/yr up to 4.85 h/yr for load points in the NW subsystem. The divergence reflects the difference in the number of components that are needed to be repaired when the load point fails, which in turn reflects the number of components in a minimal path to the load point. For example Load Point 25 has 27 components that when they fail, need to be repaired to achieve restoration of supply. Load Point 25 has an unavailability of 4.85 h/yr.

The other load-point indices resulting from RADPOW (the average outage duration, average energy not-supplied and load not-supplied) are evaluated based on earlier calculations together with customer input data.

The conclusion is that the RADPOW results for the FlymenN subsystem seem to be correct.

### 10.2.7 Identifying the Critical Components

The first step in deducing an effective maintenance plan is to decide which parts of the system to maintain, and how to perform the maintenance activities. To achieve this, a sensitivity analysis is performed for the system with the aim of identifying the critical components that are the components that have a large influence on system reliability.

The approach that has been used is described in the following. The components were categorized according to their type, then the failure rates were varied for one type at a time, and the resulting indices then evaluated. The different cases have been listed below:
c1 base case,
c2 junctions,
c3 breakers,
c4 disconnectors, and
c5 overhead lines.

If in Cases c2–c5 the associated component category was assumed to be 100% reliable, then the resulting load-point indices presented in Figures 10.10 - 10.12 were obtained.

Results have been provided for Load Points 25, 6 and 58, which strongly indicate that the overhead lines have the primary impact on system reliability. The overhead lines show a significant contribution to the overall failure rate, unavailability and energy not-supplied. The overhead lines have a minor impact on the outage time since all components have a similar repair time. This result is however a logical conclusion since the system consists mainly of overhead lines.

The apparent impact of the junctions that can be seen from the figures is somewhat more surprising. For a distribution system, these components are generally very simple and therefore do not have a large impact on system reliability. However the result depends on the assumed failure rates. The failure rate that is assumed for the junctions is an average value from the DAR statistics, being 0.014 f/yr. This value has been comparable with many other overhead lines. A reasonable conclusion would therefore be that the assumed failure rate for the junctions is too high.

Note that the average outage time increases when the junctions are assumed to be totally reliable that is in Case c2. This reflects the fact that these events have repair times that are shorter than the majority of the other components, particularly the overhead lines which have a dominant effect.

10.2.8 Analysis of Critical Load-points

The Load Points 6 and 58 were identified as having a much higher "not-supplied energy" value than the other load points. It could also be seen from the results that the differences were not due to lower unavailability at
Figure 10.10. Identifying critical components showing results for Load Point 25.
Figure 10.11. Identifying critical components showing results for Load Point 6.
Figure 10.12. Identifying critical components showing results for Load Point 58.
these points. However the energy not-supplied could of course be decreased at these points if the unavailability was decreased. According to the statistics from Svel and Table 7.3.1, it can be seen that failures caused by trees falling is dominant, representing (17 + 8 ≈ 25%) of the causes of failures. Therefore one effective way to improve the unavailability would be to eliminate failures caused by falling trees.

Assuming that maintenance activities are performed to prevent trees from falling, and assuming that this leads to "no failures caused by falling trees", this would then imply that the failure rate would decrease by 25%. Now assume firstly that in Case c6, only overhead lines connected to the Load Points 6 and 58 from the supply point through the minimal path are maintained, then this would then imply a prioritizing of the maintenance for critical load points. Secondly assuming in Case c7 that all overhead lines in the system were maintained with the same effect, and with Case c1 being the base case, then the different cases can then be summarized as follows:

c1 denotes the base case,

c6 denotes the maintained overhead lines in minimal paths (Load Points 6 and 58), and

c7 denotes all the maintained overhead lines.

The results have been presented in Figures 10.13 and 10.14. Because all overhead lines contribute to the failure rate, and most are not affected by line maintenance in Case c6, the benefit in this case is not significant. Case c7 however shows considerable improvement.

10.2.9 The Benefits of Maintaining the Overhead Lines

As discussed previously, one way to reduce the unavailability of supply is to reduce the frequency of interruptions, and this in turn can be achieved by focusing on the causes of failures. One way to gain an understanding of the relationship between maintenance and reliability would then be to study the causes of failures. This however requires knowledge about the behaviour of components, and that can be gained from statistics, as discussed earlier in Chapters 7 and 8.
Figure 10.13. Failure rate decreases for overhead lines for Load Point 6.
Figure 10.14. Failure rate decrease for overhead lines for Load Point 58.
10.2. Flymen - a Rural Overhead Line System

Statistics based on the NAFIRS from the UK was provided in Table 7.5. This table shows the causes of failures for 11 kV distribution systems and overhead lines.

The causes that may be affected by maintenance have been identified and studied further in the following.

Reducing Causes of Failures in Overhead Lines

Assume here that maintenance is performed on overhead lines to reduce certain causes of failures categorized into the following cases:

a base case,
b wind-borne materials,
c corrosion,
d vibration,
e trees (for example falling trees),
f vermin,
g farm animals,
h wilful damage,
i faulty construction and installation,
j aging and wear, and
k faulty manufacture and design.

Furthermore, assume that these causes of failures are eliminated by the maintenance activities. The corresponding failures will then be eliminated and the reliability indices influenced accordingly.

Figure 10.15 reveals the benefit to system indices attributable to the different cases, and Table 10.4 provides a ranking of these results. It can be seen that two causes of failures have a major impact on system reliability, namely trees (Case e) and aging and wear (Case j). Importantly, the different causes of failures have been studied separately here, though in reality more
Figure 10.15. Sensitivity analyses for determining the benefit of maintaining overhead lines.
than one set of causes of failures could be affected by maintenance. Therefore combinations of causes have been studied to observe the cumulative effect of maintenance.

Table 10.4. Ranking of the case study for overhead lines.

<table>
<thead>
<tr>
<th>Case</th>
<th>SAIFI [int/yr.cust]</th>
<th>SAIDI [h/yr.cust]</th>
<th>CAIDI [h/int]</th>
<th>AENS [kWh/yr.cust]</th>
</tr>
</thead>
<tbody>
<tr>
<td>j</td>
<td>3.80506</td>
<td>3.43481</td>
<td>0.902695</td>
<td>3.24763</td>
</tr>
<tr>
<td>e</td>
<td>3.85027</td>
<td>3.4841</td>
<td>0.904898</td>
<td>3.29412</td>
</tr>
<tr>
<td>b</td>
<td>3.99312</td>
<td>3.6398</td>
<td>0.911517</td>
<td>3.4409</td>
</tr>
<tr>
<td>h</td>
<td>4.01046</td>
<td>3.65871</td>
<td>0.912292</td>
<td>3.45875</td>
</tr>
<tr>
<td>c</td>
<td>4.01732</td>
<td>3.6662</td>
<td>0.912598</td>
<td>3.46581</td>
</tr>
<tr>
<td>i</td>
<td>4.01732</td>
<td>3.6662</td>
<td>0.912598</td>
<td>3.46581</td>
</tr>
<tr>
<td>g</td>
<td>4.02845</td>
<td>3.67835</td>
<td>0.913093</td>
<td>3.47733</td>
</tr>
<tr>
<td>d</td>
<td>4.03307</td>
<td>3.68337</td>
<td>0.913293</td>
<td>3.48204</td>
</tr>
<tr>
<td>f</td>
<td>4.0352</td>
<td>3.6857</td>
<td>0.913387</td>
<td>3.48421</td>
</tr>
<tr>
<td>k</td>
<td>4.03707</td>
<td>3.68771</td>
<td>0.91346</td>
<td>3.48612</td>
</tr>
<tr>
<td>a</td>
<td>4.04071</td>
<td>3.6917</td>
<td>0.913625</td>
<td>3.48988</td>
</tr>
</tbody>
</table>

Reducing Causes of Failures by Trees and Aging and Wear in Overhead Lines.

From the analysis it can be seen that two causes of failures have a major impact on the reliability of the system: trees (Case e) and aging and wear (Case j).

Assuming that maintenance is performed and has the effect that failures caused by trees and aging and wear are eliminated, then according to Table 7.5, (page 112), it can be seen that the failures can be reduced by 10.6 + 13.1% = 23.7%. Therefore, the corresponding failure rate would be reduced by the same amount. If the failure rates for the overhead lines (permanent and active failure rates) were cut by 23.7%, then the failure rates would change according to Table 10.5.
Figure 10.16 presents the RADPOWER results for the NW subsystem. The results are shown for the base case and for when the failure rates for overhead lines are reduced. As can be seen in the figure, there is a significant decrease in unavailability. It can however be observed that the value of energy not-supplied decreases slightly due to the outage times that remain nearly unchanged.

The system indices for this system will also change with the decreased failure rate. Table 10.6 presents these changes.

### Table 10.5. Reduction of failure rates in overhead lines.

<table>
<thead>
<tr>
<th>Line type</th>
<th>Failure rate ([/\text{yr}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>old</td>
<td>new</td>
</tr>
<tr>
<td>Line1W</td>
<td>0.006</td>
</tr>
<tr>
<td>Line2W</td>
<td>0.017</td>
</tr>
<tr>
<td>Line3W</td>
<td>0.029</td>
</tr>
<tr>
<td>Line4W</td>
<td>0.04</td>
</tr>
<tr>
<td>Line5W</td>
<td>0.05</td>
</tr>
<tr>
<td>Line6W</td>
<td>0.06</td>
</tr>
<tr>
<td>Line1E</td>
<td>0.008</td>
</tr>
<tr>
<td>Line2E</td>
<td>0.026</td>
</tr>
<tr>
<td>Line3E</td>
<td>0.04</td>
</tr>
<tr>
<td>Line4E</td>
<td>0.06</td>
</tr>
<tr>
<td>Line5E</td>
<td>0.07</td>
</tr>
<tr>
<td>Line6E</td>
<td>0.09</td>
</tr>
</tbody>
</table>

### Table 10.6. System indices before and after a reduction in the causes of failure for overhead lines.

<table>
<thead>
<tr>
<th>Index</th>
<th>Unit [\text{int/yr and cust.}]</th>
<th>Old</th>
<th>New</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAIFI</td>
<td>4.04</td>
<td>3.63</td>
<td></td>
</tr>
<tr>
<td>SAIDI</td>
<td>3.69</td>
<td>3.24</td>
<td></td>
</tr>
<tr>
<td>CAIDI</td>
<td>3.69</td>
<td>3.24</td>
<td></td>
</tr>
<tr>
<td>AENS</td>
<td>3.49</td>
<td>3.06</td>
<td></td>
</tr>
</tbody>
</table>
Figure 10.16. Reduction in the causes of failure due to trees and aging and wear in the FlymenNW system.
10.2. A Summarizing Analysis

It must be emphasized that the information presented in Table 7.5 includes average values for all overhead lines including those for which falling trees may have no impact at all, and those where trees may have a major impact. It should also be noted that the statistics come from the UK, and in Sweden tree coverage is generally higher, and therefore the impact of trees is probably even more significant. Corresponding statistics from Sweden in Table 7.3.1, which are not separated for different component types, showed an average value of about 25% for causes of failures due to trees. The conclusion from both observations is that for those overhead lines that can be affected by trees, the percentage of faults due to this cause may be much greater than the average figure quoted in Table 7.5. To estimate the influence of this aspect, a number of calculations have been made using percentages of failures caused by trees varying between 5 – 95%. The results of this analysis are presented in Figure 10.17, which shows that the span between the system indices is significant. For SAIFI, the divergence is about 1.5 interruptions per year and customer.

Figure 10.18 provides a summary of results from the analyses for the NW feeder, where the base case is compared with two cases. It shows the cumulative effect of maintenance when reducing faults for overhead lines caused both by trees and aging. It also shows the effect of maintenance when the overhead lines have a cause of failure of 95% for trees. The latter shows that for those overhead lines that can be affected by trees, the percentage of faults by this cause may be much greater than the average figure quoted in the statistics. The conclusion is that the individual behaviour needs to be studied in order to understand the relationship between maintenance and failure rate.

10.2.11 Overhead Lines Replaced by Underground Cables

One way to improve the reliability of a distribution system is by using underground cables instead of overhead lines. This is however a very expensive solution. Therefore, it is interesting to study quantitatively what the values of this benefit in system reliability would be.

Assume here then that the network consists of underground cables instead of overhead lines. According to Svel’s statistics for 1995 – 1997, the
Figure 10.17. Benefits of maintenance with the causes of failures attributed to trees ranging from 5 – 95%.
Figure 10.18. Decrease in unavailability by preventing failures.
average value for failures in underground 11 kV cables is 0.0293 f/km and yr. This value should be compared to the corresponding value for overhead lines, which is 0.125 f/km and yr. However in the FlymenN subsystem, the average failure rates for overhead lines are 0.046 f/km and yr and 0.064 f/km and yr (in Section 10.2.4). Therefore it can be seen that the average failure rate for underground cables is significantly lower than for overhead lines.

If the same procedure used for overhead lines (see Section 10.2.4) is used, then the resulting failure rates for the different underground cables can be evaluated for example as follows: 0.0293 f/yr and km · 0.125 km ≈ 0.004 f/yr. The total length of the overhead lines according to Section 10.2.4, is 39 + 28 = 67 km. The resulting failure rate is then 0.0293 · 67 ≈ 1.963 f/yr. This value should be compared with the 1.8 f/yr and feeder, which is 2 · 1.8 = 3.6 f/yr. Consequently, the underground cables have approximately half the failure rate for the system. Table 10.7 presents the resulting failure rates per underground cable.

**Table 10.7.** Failure rates for underground cables in the FlymenN subsystem.

<table>
<thead>
<tr>
<th>Underground Cable</th>
<th>Number of cables</th>
<th>Failure rate [f/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable 1</td>
<td>52</td>
<td>0.004</td>
</tr>
<tr>
<td>Cable 2</td>
<td>33</td>
<td>0.011</td>
</tr>
<tr>
<td>Cable 3</td>
<td>20</td>
<td>0.018</td>
</tr>
<tr>
<td>Cable 4</td>
<td>17</td>
<td>0.026</td>
</tr>
<tr>
<td>Cable 5</td>
<td>6</td>
<td>0.030</td>
</tr>
<tr>
<td>Cable 6</td>
<td>10</td>
<td>0.041</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>138</strong></td>
<td><strong>1.963</strong></td>
</tr>
</tbody>
</table>

Figure 10.19 summarizes the resulting load-point indices for the FlymenN subsystem with underground cables instead of overhead lines. The large reduction in the failure rate when underground cables are used has a great impact on the load-point indices. For example the energy not-supplied at Load Point 58 is now 108.2 kWh/yr instead of 161.2 kWh/yr (see Figure 10.7. Figure 10.19 presents the resulting system indices for the same cases as used in the study of the overhead lines. As can be seen from the results,
and according to the statistics (see Table 7.5) aging and wear (Case j) are the primary causes of failure that can be reduced by maintenance.

![Graph showing failure rate, unavailability, and outage time across load points](image1)

![Graph showing energy not supplied across load points](image2)

**Figure 10.19.** Results for the FlymenN subsystem using underground cables.

### 10.2.12 Conclusions

This section of the thesis has presented the results from reliability analysis and the effects of maintenance on the Flymen rural distribution system. From sensitivity analyses, the effect of critical components has been determined. By the change in system indices the lines were identified to be the critical component reflecting the behaviour of a rural distribution system. The relationship between maintenance and reliability was studied through sensitivity analyses of the benefit when reducing causes of failures. Failures
Figure 10.20. System indices for the FlymenN subsystem using underground cables.
caused by trees and aging were identified to have the most significant impact on reliability indices.

The conclusion is that preventive maintenance can have a great impact on system reliability and the relationship between failure rate and maintenance should be investigated in more detail. Improvement in reliability indices must be compared with the investment costs required and the benefit in outage costs. Therefore the relationship between reliability levels and economics should also be investigated. The crucial need for appropriate data is another matter that needs to be recognized.
10.3 Birka - an Urban Underground Cable System

This section describes the analysis of and presents the results from a reliability and maintenance study of a Swedish distribution system belonging to the Birka Nät distribution system in the Stockholm City area. Some of the results from this study have also been published in: [121].

10.3.1 Definition of the Birka System

The Stockholm City distribution system supplies power to about 450,000 customers and belongs to the utility Birka Nät, which has the greatest number of customers of any power utility in Sweden [134]. A survey of disturbance statistics and maintenance practices, focusing on the causes of failure in underground 11 kV cables has been undertaken in cooperation with Birka Nät, in accordance with the approach presented earlier in Chapter 8. In this study a special part of the network has been defined and studied in greater detail as a case system. This special part of the network has been modelled and is referred to as the Birka System.

This case system includes the Birka Nät 220/110 kV Bredäng station and the 33/11 kV Liljeholmen station, which are connected to each other via two parallel 110 kV cables. From the Liljeholmen station (LH11) there are 32 outgoing 11 kV feeders that supply the southern part of central Stockholm City. The system is an urban network whose distribution feeders consist mainly of underground cables and is shown in Figure 8.2 (page 129).

Figure 10.21 presents the model of the case system called the Birka system. The simplified network consists essentially of bus bars where double bar arrangements are represented by single bus bars (note that this simplification is taken into account when defining the reliability input data as discussed in Section 10.3.5). Moreover, the customers are represented by two 33-kV load points, referred to as Högalid station (HD), and Statens Järnvägar railway line (SJ), and one 11-kV load point, referred to as Liljeholmen station (LH11). LH11 includes customers connected to a total of 32 outgoing 11-kV feeders, in parallel from the Liljeholmen station with a total of 14,300 customers. These distribution feeders are represented by the one "averaged" component. HD supplies a total of 23,400 customers. The
cable lengths and components in HD are of a mixture of mass-impregnated paper and XLPE cables. The 11 kV cable within the Liljeholmen station has been ignored since it is of minimal length compared with the 11 kV network. The resulting model of the Birka system has in total 58 components and 18 branches. The following components are included in the system model:

- 220, 33 and 11 kV bus bars,
- 220, 110, 33 and 11 kV breakers,
- 110, 33 and 11 kV underground cables,
- 220/110, 110/33 and 33/11 kV transformers, and
- 11/0.4 kV fuse.

The data defined above constitute the network input data for the RADPOW reliability analysis. These input data are discussed further in the following sections.

10.3.2 Sources of Input Data for the Birka System

The model of the Birka system has been provided with input data from the following data sources.

- Birka Nät:
  - results from the survey at Birka Nät presented in [20] and summarized in Chapter 8,
  - statistics collected in connection with a previous study presented in [135], in which the author participated in connection with some reliability evaluations,
  - estimated input data from an earlier reliability analysis presented in [108], and
  - verbal discussions with Kjell Gustafsson [136] (the customer and power data), Lars-Åke Gustafsson [118], Daniel Terranova [137] and Mats Åhlén [120].

- Other sources:
Figure 10.21. The model of the Birka system used in the RADPOW reliability analysis of the Birka Nat Case System.
10.3. Birka - an Urban Underground Cable System

- Nordel,
- DAR and FAR, and
- T-book,

which were introduced in Chapter 7.

10.3.3 Customer and Power Input Data

The Birka system introduced in Section 10.3.1, represents the distribution network from the Bredäng (BÅ) 220/110 station to the Liljeholmen (LH) 33/11 station. Furthermore, the HD and SJ 33 kV stations are connected with the network as shown in the Figure 10.21. The customers are represented by two 33 kV customers (HD) and (SJ), and one 11 kV customer (LH11). LH11 includes the customers connected to the roughly 30 outgoing 11 kV feeders leading from Liljeholmen station. HD supplies a number of customers.

The Stockholm City network was introduced in Section 8.2.1. This system includes stations and feeders from the 220 kV level down to the 400 V level that is from the transmission voltage to the household customer. Table 10.9 shows the number of stations of each type included in the Stockholm City system. There are for example 24 stations of the type denoted Fs (distribution stations or fördelningstation in Swedish) at 33 or 11 kV including the HD and LH11 stations. The table also includes the total number of customers for Stockholm City (450,000), LH11 (14,300) and so on. An average station at the 33 or 11 kV level has consequently about 315,500/24 ≈ 13,000 customers, which indicates the general size of the HD and LH11 stations, at Load Point LH 11.

Note that for the reliability analysis, one average 11 kV feeder connected to LH11 has been analyzed. This means that the average number of customers is about 14,300/32 ≈ 446.875 ≈ 447.

The power data for the load points have also been analyzed. Table 10.8 presents the resulting values. These data are partly based on estimations [136], since measurements are difficult to make at the actual point. For example power up to 2 MW may be back-fed to the network at SJ [136]. Furthermore, it is obvious that the number of customers changes (the values
used are from 2000), but this difference is considered to have little in this context and is therefore ignored.

For a reliability analysis, it is also of interest to divide the customers into different categories. This is for example useful when valuing the benefits from changes in not-supplied energy. The customers should be categorized into the following three different groups for RADPOW input data: industrial (ind.), commercial (com.) and residential (res.). Estimations about the percentage distribution between these groups have been made with knowledge about the system. Table 10.10 presents these results. It can be seen that LH11 shows a fair spread for different customers however, HD is dominated by residential customers and SJ is the sole commercial customer (the railway).

Table 10.11 present the resulting RADPOW customer and power input data for the Birka System. The input data for the reactive power is not considered in the analysis (\(irppc = inppc = rppp = crpp = 0\)), and therefore not included in the table.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>LH11</td>
<td>14,300</td>
<td>24.6</td>
<td>39.4</td>
<td>1.7203</td>
<td>2.7552</td>
</tr>
<tr>
<td>HD</td>
<td>23,400</td>
<td>23</td>
<td>37.8</td>
<td>0.9829</td>
<td>1.6154</td>
</tr>
<tr>
<td>SJ</td>
<td>1</td>
<td>0.8</td>
<td>4</td>
<td>0.8</td>
<td>4</td>
</tr>
<tr>
<td>Total:</td>
<td>37,701</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 10.3.4 More about the Input Data

For some of the components in the Birka case system the voltage levels belong to some extent to the transmission system instead of the distribution system. Therefore, additional statistics were obtained from Nordel and the Scandinavian transmission systems [109] (mentioned earlier in Chapter 7). Table 10.12 presents selected statistics for the actual components in the model system. In addition to the failure rates that would be used for RADPOW input data, causes of failures were also summarized. The results show that weather (excluding lightning), makes a small contribution to failures.
Table 10.9. Different types of stations and the number of customers in Stockholm City.

<table>
<thead>
<tr>
<th>Station type</th>
<th>Voltage levels [kV]</th>
<th>Total number of station type</th>
<th>Station name</th>
<th>Number of customers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fs</td>
<td>33 or 11</td>
<td>24</td>
<td>HD</td>
<td>23,400</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>LH</td>
<td>14,300</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total:</td>
<td>315,500</td>
</tr>
<tr>
<td>Tp</td>
<td>110</td>
<td>4</td>
<td>LH</td>
<td>37,700</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total:</td>
<td>155,500</td>
</tr>
<tr>
<td>Sn</td>
<td>220</td>
<td>5</td>
<td>BA</td>
<td>73,600</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total:</td>
<td>325,800</td>
</tr>
<tr>
<td>220Fs</td>
<td>220</td>
<td>4</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total:</td>
<td>114,100</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Total:</td>
<td>450,000</td>
</tr>
</tbody>
</table>

(Source: Birka Nat 2000)

Table 10.10. Estimates of customer categories for the Birka case system.

<table>
<thead>
<tr>
<th>Station</th>
<th>Customer</th>
<th>Active power</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH11</td>
<td>25% 50% 25%</td>
<td>40% 40% 20%</td>
</tr>
<tr>
<td>HD</td>
<td>10% 80% 10%</td>
<td>20% 70% 10%</td>
</tr>
<tr>
<td>SJ</td>
<td>0% 0% 100%</td>
<td>0% 0% 100%</td>
</tr>
</tbody>
</table>
Moreover, it can be seen that both the cables and breakers are dominated by failures due to equipment, being 67% and 64% respectively. However, failures due to damage make a dominant contribution to cable failures. It is interesting to relate these results to the results for the 11 kV cable presented in Chapter 8. For both of the cables weather has little or no impact, but damage and equipment (material/method) respectively have a significant impact. The only significant difference is for "personnel", where the results for the 11 kV cable show a contribution of about 12% for personnel, but the Table 10.12 shows a 0% contribution, which is difficult to draw any conclusions from.

**Table 10.11.** Customer and power input data for RADPOW for the Birka system.

<table>
<thead>
<tr>
<th>Load point</th>
<th>Number of customers</th>
<th>Active power [kW/cust]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH11</td>
<td>c35*</td>
<td>447</td>
</tr>
<tr>
<td>HD</td>
<td>c48*</td>
<td>23,400</td>
</tr>
<tr>
<td>SJ</td>
<td>c58*</td>
<td>1</td>
</tr>
</tbody>
</table>

*component number according with Figure 10.21

**Table 10.12.** Selected component statistics from Nordel (Sweden 1990 – 1999) [109].

<table>
<thead>
<tr>
<th>Component</th>
<th>Cable [kV]</th>
<th>Breaker [kV]</th>
<th>Transformer [kV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>char.</td>
<td>110 – 150</td>
<td>110 – 150</td>
<td>220 – 300</td>
</tr>
<tr>
<td>λ [f/yr and km]</td>
<td>0.0098</td>
<td>0.0087</td>
<td>0.0261</td>
</tr>
<tr>
<td>percentage</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| distribution of causes of failures
| Lightning       | 0%         | 15%          | 8%               |
| Weather         | 0%         | 1%           | 0%               |
| Damage          | 33%        | 0%           | 0%               |
| Personnel       | 0%         | 13%          | 16%              |
| Equipment       | 67%        | 64%          | 47%              |
| Other           | 0%         | 7%           | 29%              |
|                 |            |              | 28%              |
10.3. Birka - an Urban Underground Cable System

Some reliability input data have their origins in the T-book [117] that was introduced earlier in Section 7.3.3. However, the use of such data requires detailed knowledge about the faults and the system, and the data selected were collected by Birka Nät in connection with previous reliability studies [108].

10.3.5 Component Reliability Input Data

Table 10.13 summarizes the component input data for the Birka system. The collection and selection of input data are presented in more detail below.

- Input data for the permanent failure rate ($\lambda_{permanent}$) originate from the following sources: T-book [117], LH11 [20], Nordel99 [109] or FAR81 [108].

- The active failure rate is defined by: $\lambda_{permanent} = \lambda_{active} + \lambda_{passive}$

  - For all switching devices that is breakers and the fuse it is assumed that: $\lambda_{passive} = 0.01 \cdot \lambda_{permanent} \Rightarrow \lambda_{active} = 0.99 \cdot \lambda_{permanent}$.

  - For all other components it is assume that: $\lambda_{passive} = 0 \Rightarrow \lambda_{active} = \lambda_{permanent}$.

- Input data for the average time of repair ($t_{repair}$) equals that of a previous reliability analysis at Birka Nät, presented in [108], with the exception that one hour has been used for the bus bar repair time instead of 72 hours. The reason for this is the simplification in the RADPOW model system, in which the double bus bar arrangements have been represented by one single bus bar. To compensate for this, the repair times have been reduced to the estimated effective switching time to transfer load from one bus to the other following a bus failure.

- The effect of the cable component failure rate on the system unavailability was not as significant as had been expected. Furthermore, this was caused by the input data for the restoration times. To better model the system, input data was changed by including replacement times for some components for high voltage breakers and transformers. These components would most probably be replaced by spares, which means that the repair procedures would involve replacement rather
than repair. Replacement time of one day was considered to be a reasonable estimate. Consequently, replacement times of 24 hours have been used for the breaker and transformer input in RADPOW.

- A "stuck probability" of $P_{\text{stuck}} = 0.001$ has been assumed for the breakers.

The component reliability input data required by RADPOW that is not presented in Table 10.13 is either assumed to be zero or equal for all the components. The following contains some detailed comments about these.

- Short interruptions have not been included in the source statistics studied. Therefore the transient failure rates are assumed to equal zero.

- It has not been possible to identify temporary failure rates. These would either equal zero, since the component does not cause temporary forced outages, or these failures would be included in the assumed permanent forced outages. Therefore, the input data for the temporary failure rates are also assumed to be zero.

- The maintenance frequency input data has been set to zero. This might appear strange, but is just a reflection of an effect of using PM based on component reliability rather than predefined intervals. Firstly, it should be realized that this input data only has an effect on the reliability indices (with the logic implemented in RADPOW) for overlapping faults. This implies that the PM intervals with predefined times for PM only lead to system unavailability if first the PM activity is applied and then a fault randomly occurs but not the contrary (see also the discussion in Section 10.2.4).

- The re-closure time is assumed to be 5s and the switching time 1 h for all components.

The failure rates for the cables depend on both the length and the type of cable. Detailed information for the specific system (LH11) has been studied to define the input data for the actual system. The lengths of the different cables in the Birka system have been provided by Birka Nät. Table 10.14 illustrates the evaluation of the resulting failure rates.
### Table 10.13. Component reliability input data for the Birka case system used in RADPOW.

<table>
<thead>
<tr>
<th>Component</th>
<th>$\lambda_{\text{permanent}}$ [f/yr]*</th>
<th>Source</th>
<th>$\lambda_{\text{active}}$ [f/yr]*</th>
<th>$r_{\text{repair}}$ [h]</th>
<th>$r_{\text{replace}}$ [h]</th>
<th>$P_{\text{stuck}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>220 kV</td>
<td>0.00964</td>
<td>T-book</td>
<td>0.00964</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>33 kV</td>
<td>0.00964</td>
<td>T-book</td>
<td>0.00964</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>11 kV</td>
<td>0.00867</td>
<td>T-book</td>
<td>0.00867</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Breaker</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>220 kV</td>
<td>0.00870</td>
<td>Assume = 110</td>
<td>0.00861</td>
<td>168</td>
<td>24</td>
<td>0.001</td>
</tr>
<tr>
<td>110 kV</td>
<td>0.00870</td>
<td>Nordel99</td>
<td>0.00861</td>
<td>168</td>
<td>24</td>
<td>0.001</td>
</tr>
<tr>
<td>33 kV</td>
<td>0.00089</td>
<td>FAR81</td>
<td>0.00088</td>
<td>72</td>
<td>24</td>
<td>0.001</td>
</tr>
<tr>
<td>11 kV</td>
<td>0.00243</td>
<td>FAR81</td>
<td>0.00241</td>
<td>48</td>
<td>24</td>
<td>0.001</td>
</tr>
<tr>
<td>Cable</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>110 kV</td>
<td>0.00980-km</td>
<td>Nordel99</td>
<td>0.00980-km</td>
<td>168</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>33 kV</td>
<td>0.00937-km</td>
<td>FAR81</td>
<td>0.00937-km</td>
<td>48</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>11 kV</td>
<td>0.01242-km</td>
<td>LH11</td>
<td>0.01242-km</td>
<td>6</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Transformer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>220/110 kV</td>
<td>0.02610</td>
<td>Nordel99</td>
<td>0.02610</td>
<td>504</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>110/33 kV</td>
<td>0.02050</td>
<td>Nordel99</td>
<td>0.02050</td>
<td>504</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>33/11 kV</td>
<td>0.01989</td>
<td>FAR81</td>
<td>0.01989</td>
<td>504</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>11/0.4 kV</td>
<td>0.00331</td>
<td>FAR81</td>
<td>0.00331</td>
<td>48</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>Fuse</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 kV</td>
<td>0.01340</td>
<td>T-book</td>
<td>0.01340</td>
<td>4</td>
<td>0</td>
<td>0.001</td>
</tr>
</tbody>
</table>

* For cables the failure rate has unit [f/yr and km]

Sources: T-book [117], LH11 [20], Nordel99 [109], FAR81 [108]
10.3.6 Impact of the Length of the 11 kV Cable

As discussed earlier, the Birka case network has been modelled assuming that one 11 kV cable represents all the 32 outgoing 11 kV feeders leading from LH11. However in reality, these cables have different lengths and are a mixture of different types with XLPE or oil-impregnated paper insulation. The effect of these different lengths has been analyzed and some of the results presented in this section.

Detailed data for the cable lengths have been provided by Birka Nät and relevant information for this study are presented in the previous section For the 11 kV cables, these data can used in an analysis as follows.

1. Cable feeders:

   (a) total number = 32,
   (b) total length = 259.387 km,
   (c) average length = 259.387/32 ≈ 8.106 km,
   (d) minimum length = 0.838 km (Liljeholmen Ls), and
   (e) maximum length = 15.654 km (Tellusborgsvägen 34).

Table 10.14. Cable reliability input data from the Birka system model used in RADPOW.

<table>
<thead>
<tr>
<th>Cable id</th>
<th>Voltage [kV]</th>
<th>Failure rate [f/yr and km]</th>
<th>Length [km]</th>
<th>Failure rate [f/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>110 kV a)</td>
<td>110</td>
<td>0.00980</td>
<td>7.1555</td>
<td>0.07012</td>
</tr>
<tr>
<td>110 kV b)</td>
<td>110</td>
<td>0.00980</td>
<td>7.1745</td>
<td>0.07031</td>
</tr>
<tr>
<td>LH33 kV</td>
<td>33</td>
<td>0.00937</td>
<td>0.0300</td>
<td>0.00028</td>
</tr>
<tr>
<td>HDa)</td>
<td>33</td>
<td>0.00937</td>
<td>2.4445</td>
<td>0.02291</td>
</tr>
<tr>
<td>HDb)</td>
<td>33</td>
<td>0.00937</td>
<td>2.4375</td>
<td>0.02285</td>
</tr>
<tr>
<td>HDc)</td>
<td>33</td>
<td>0.00937</td>
<td>2.4170</td>
<td>0.02265</td>
</tr>
<tr>
<td>SJa)</td>
<td>33</td>
<td>0.00937</td>
<td>0.9210</td>
<td>0.00863</td>
</tr>
<tr>
<td>Sjb)</td>
<td>33</td>
<td>0.00937</td>
<td>0.8930</td>
<td>0.00837</td>
</tr>
<tr>
<td>LH11</td>
<td>11</td>
<td>0.01242</td>
<td>8.1058</td>
<td>0.10069</td>
</tr>
</tbody>
</table>
2. Cable insulation type and length

An estimation of cable type is made using an heuristic approach based on evaluation of the quotient ampere/kilometre (A/km). If the cable length contains mainly mass-impregnated cable insulation then the quotient is about 1 A/km, and with XLPE insulation is about 2-4 A/km (for 150-240 mm2) [136]. Based on this approach, the cable in the Birka case system has been evaluated as follows.

(a) Liljeholmen Ls: \(2.346/0.838 \approx 2.80\) A/km \(\Rightarrow\) XLPE cable.

(b) Hornstullstrand 4: \(8.091/15.654 \approx 0.5\) A/km \(\Rightarrow\) paper cable.

(c) 13 feeders are paper cables with a total length of 160.596 km, which gives an average length of 12.35 km.

(d) 19 feeders are XLPE cables with total length of 98.79 km, which gives an average length of 5.20 km.

3. Failure rates \(\lambda_{\text{permanent}} f/\text{yr}\) can be estimated based on knowledge about failure occurrences and cable lengths as follows:

(a) \(58\) failures/\(18\) yr \(\cdot 259.387\) km \(\approx 0.01242\) failures/yr and km.
   
i. \(\lambda_{\text{min length}} = 0.01041\) f/yr,
   
ii. \(\lambda_{\text{average length}} = 0.10069\) f/yr,
   
iii. \(\lambda_{\text{max length}} = 0.19446\) f/yr,
   
iv. \(\lambda_{\text{average paper length}} = 0.15342\) f/yr, and
   
v. \(\lambda_{\text{average pex length}} = 0.06460\) f/yr.

Consequently, the 11 kV cables leading out from LH11 have a length of \(l_{\text{LH11}} \in [0.838, 15.654]\) km and a failure rate of \(\lambda_{\text{LH11}} \in [0.01041, 0.19446]\) f/yr.

For the purpose of these studies, a single LH11 load point (Load Point LH11) has been assumed that represents an average cable and consequently is connected to the 11 kV station with a pair of cables, each about 8.1 km long. The real system has 32 such load points connected by cables varying in length from 0.84-15.7 km. Figure 10.22 shows the effect on system reliability resulting from varying this cable length. This figure shows the results from RADPOW analysis of Load Point LH11. It can be seen that the reliability does differ depending on which cable is modelled in regard to both length
and type of insulation, where for example the XLPE insulation was shown to result in fewer faults than the mass-impregnated paper cable. The average cable representation has been used in the following analyses.

Different sources of supply interruption statistics were introduced in Chapter 8. At this point it is important to assess whether or not the failure rate value found for the 11 kV cable in this study (about 0.01242 failures/yr and km) is reasonable compared with general statistics. Table 7.4 (page 111) presents national statistics from the DAR and FAR system, as well as internal statistics from Birka Nat. Comparison with the national values shows that the resulting value for this 11 kV cable has a higher failure rate than the corresponding results from DAR. However for higher voltage levels, the national statistics reach the same values, and for the 33 kV level, the national DAR statistics correspond with a value of about 0.01279 f/yr and km. For the internal Birka statistics that cover a larger area than the statistics analysed in Chapter 8 (the input data), there is good correspondence between the results. These provide a value of 0.01201 f/yr and km for the 11 kV cable. However using the corresponding data from FAR, the value is as high as 0.03057, which could indicate the use of inferior cable types as in earlier times, but may also indicate differences in the reporting systems. Consequently, it has been shown that the resulting average failure rate for the 11 kV cable (LH11) is a reasonable failure rate compared with the general statistics.

10.3.7 Reliability Analysis

Table 12.1 presents the base case results from the reliability analysis.

The failure rate is significant at the 11 kV level compared with the two 33 kV load points, with the average failure rate for an 11 kV customer being about 0.33 failures/yr. For the network, this would imply about 11 failures/yr, and for the system with 24 similar stations, about 5 failures/wk. Real statistics (see Chapter 8) and [5]) indicate about 2 failures/wk for this area. The reason for this is that the average length of the 11 kV cables in the case system (8.1 km) is considerably longer than the average for the total 11 kV network (1.6 km). The loads at the different load points vary significantly, which is partly caused by the different number of customers for each one (SJ is used by one and HD by 234,000), and partly by the
10.3. Birka - an Urban Underground Cable System

Figure 10.22. The effect of the individual cable failure rates on the system reliability, showing results from RADPOW for the Birka case system and Load Point LH11, where $\lambda_{LH11} \in [\lambda_{min\text{length}}, \lambda_{max\text{length}}]$.

difference in load per customer (where the average customer at LH11 has a power consumption of about twice the average customer at HD).

Table 10.15. Reliability indices evaluated for the Birka system base case.

<table>
<thead>
<tr>
<th>Load point</th>
<th>$\lambda$ [f/yr]</th>
<th>$U$ [h/yr]</th>
<th>$r$</th>
<th>$L$ [h/f]</th>
<th>$LOE$ [kWh/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH11</td>
<td>0.334494</td>
<td>0.506714</td>
<td>1.51487</td>
<td>768.974</td>
<td>389.65</td>
</tr>
<tr>
<td>HD</td>
<td>0.111307</td>
<td>0.133388</td>
<td>1.19837</td>
<td>22,999.9</td>
<td>3067.9</td>
</tr>
<tr>
<td>SJ</td>
<td>0.110706</td>
<td>0.150543</td>
<td>1.35984</td>
<td>0.8</td>
<td>0.120434</td>
</tr>
</tbody>
</table>

$SAIFI = 0.115491$ [int/yr, cust.] $SAIDI = 0.140386$ [h/yr,cust.]
$CAIDI = 1.21556$ [h/int.] $AENS = 0.144988$ [kWh/yr,cust.]
10.3.8 Identifying the Critical Components

Critical components for the reliability of the system have been identified in similar way as in the analysis of the Flymen system (see Section 10.2). The components are first categorized according to their type, then the failure rates are set to zero for one type at a time, and then the resulting indices are evaluated. The different component cases are:

1. base case,
2. bus-bar,
3. breaker,
4. cable, and
5. transformer.

The results for Load Points LH11, HD and SJ are presented in Figures 10.23 and 10.25. These results strongly indicate that the underground cables have the primary impact on system unreliability at the Load Point LH11. The significant rise in the outage time is because the repair time for the underground cables is much lower than that for the other components. Therefore the average restoration time increases when the number of short interruption times is reduced. However, at the 33 kV load points (see Figures 10.24 and 10.25), other components are deemed to be more critical for this result, namely the breakers. This is an extremely important point because the impact of PM on component behaviour should not be determined by considering the components in isolation (most PM programs do this) but should consider the impact that the component has on the particular system in which it is being used. In this case the conclusion is that cables are the critical components at the 11 kV level.

10.3.9 Impact of Different Cable Voltage Levels

The analysis above indicates that the 11 kV cables have a significant impact. Therefore it is of interest to study the cable components in more detail. A similar sensitivity study has been done to analyse the effect of cables at different voltage levels. The following cases have been considered:
Figure 10.23. Impact of critical components, showing RADPOW output results for Load Point LH11.

Figure 10.24. Impact of critical components, showing RADPOW output results for Load Point HD.
1. base case,
2. 110 kV cables,
3. 33 kV cables, and
4. 11 kV cables.

Figure 10.26 illustrates the results for the three load points in the Birka system. It further confirms that the 11 kV level has a significant impact, and that the 11 kV cables are the critical components in this system at Load Point LH11.

10.3.10 The Benefit of Maintaining the 11 kV Cable

The previous sensitivity studies indicated that the cables have a significant impact on the reliability of the system and are therefore the critical components.
10.3. Birka - an Urban Underground Cable System

![Graphs showing impact of cable operation voltage and unavailability for Load Point LH11.](image)

**Figure 10.26.** Impact of cable operation voltage [kV], showing RADPOW output results for Load Point LH11.

This concludes Step 2 of the procedures defined in Table 6.1. The next step is to analyse the failure modes and causes, in order to identify the improvement that PM could make.

Figure 8.3 presented in Chapter 8 (page 117), summarizes results from a study on the causes of failures for these cables [20]. The cable system in the study included the cable itself, the joints and the terminations. Figure 8.3 puts the results into the framework of an RCM study deducing the following: function, failure modes, failure events and failure causes. Finally, the numerical information gained from the statistical survey has been included. It is at this level that the maintenance activities can be considered and applied. The results show that the causes of failures that have significant impact on the 11 kV cables are: Damage (16%), Personnel (12%) and Material/Method (59%). The causes denoted Damage and Personnel are not likely to be affected by PM but Material/Method could be greatly affected by PM. As this category constitutes 59% of the total, this should be considered in greater depth, as also shown in Figure 8.3. This indicates that the main contributions to this category of causes of failures are: fabric and material (14%), lack of maintenance (5%) and incorrect method or instruction (15%).
10.3. Birka - an Urban Underground Cable System

All of these would benefit by proper maintenance procedures.

Further sensitivity studies have been made to see the effects at the system level if each of these causes of failures could be decreased individually or in combination (in a similar way to what was done in the Flymen system). The different cases have been listed below:

1. the base case,
2. manufacturing or material faults = 14%,
3. lack of maintenance = 5%,
4. incorrect method or instruction = 15%,
5. the total for 2-4 = 34%, and
6. the total for material and method = 59%.

Figure 10.27 shows the benefit of these different cases on system indices. It has been assumed for each case that the causes of failures can be eliminated by the maintenance activities. Thus the corresponding failures would be eliminated and the reliability indices influenced.

The difference between the two last cases (34% and 59%) lies in the reported failure causes material and method but has no further level of classification. This indicates the need for greater focus on completing fault reports with as much detail as possible in order to facilitate the establishment of effective PM programs.

The results establish that there is a benefit in reliability from well-chosen PM actions, however these improvements must be compared with the cost required to achieving it.

10.3.11 Concluding Remarks on the Birka system

The relationship between PM and reliability in an urban distribution system has been studied in order to demonstrate the need for RCM. The results clearly demonstrate the benefits in system reliability obtained by focusing maintenance on the critical components, and on the dominant causes of failures for which maintenance can have an impact. These studies involved 11 kV cables and causes of failures related to “material and methods”.
10.4 Conclusions

This chapter has presented results from reliability analysis of two different power distribution systems. Approach I was used for relating the PM of components to system reliability, based on statistics on the causes of failures and the assumption that maintenance has a percentage impact on reducing the cause of component failures.

In both of these studies, the critical components for system reliability have been evaluated as well as the failure causes dominating the failure of
10.4. Conclusions

Those component types. The results of the Flymen System (a rural system) show overhead lines to be a critical component in that system, and that failure caused by trees and aging contribute significantly to overhead line failure. The results from the Birka case system (an urban system), show that underground cables of 11 kV are a critical component in that system, and that failure caused by material and methods contribute significantly to failure in underground cables. Both these RCM application studies indicate that the effect of PM on system reliability is significant when maintenance measures are focused on the correct method, allowing them to prevent the correct causes of failures and to target the correct and critical components.

The RCM application studies also provided the following general conclusions.

- The crucial need for the appropriate data should be recognized in relation to both system analysis and the lack of detailed information about the components (for example capturing the individual characteristics of a certain type of component).

- For the reliability sensitivities it could be argued that the differences are less than the accuracy of the input data. However, it is important to recognize that these provide information about the different behaviours in the system, which is the aim of the analysis rather than to give a true picture of the system state.

- For the analysis of the Birka case system, it was shown that critical components are different for different load points. This is an important result because the impact of PM on component behaviour should not be determined by considering the components in isolation, but should consider the impact that the component has on the particular system in which it is being used.

The conclusion is that PM can have a major impact on system reliability and that the relationship between failure rate and maintenance should be investigated in more detail. Improvements in reliability indices must be compared with the investment cost required and the benefit in outage cost. Therefore, the relationship between reliability levels and economics should also be investigated. This leads on to the next phase of the analysis that
10.5 Concluding Remarks about the Approach for Relating Reliability and PM

The application studies presented in this chapter were based on Approach I, which constitutes the first attempt to solve the question of relating reliability and PM. A fundamental limitation with this approach is that the time aspect is disregarded. The growth of trees over time for example impacts on the causes of failures, which has been disregarded in this approach. This raises the following questions: "How can this approach be improved?", "Could a theoretical relation between failure rate and maintenance be proposed?", and "Could a generic theoretical approach be formulated?".

The time aspect of maintenance has been included in diagnostic methods, therefore KTH’s research activities in cable diagnosis mentioned in Chapter 9 should be helpful for including this aspect. This leads onto Approach II, which is analysed further in the following two chapters where the underground cable component and the Birka system have been analysed further in the Cable Application Study.
Chapter 11

Modelling the Relationship between Failure Rate and Maintenance: Approach II

This chapter defines a quantitative relationship between reliability and PM for an underground cable component susceptible to faulting due to water treeing. The chapter is based on results from experience, experiments and physical expressions. The resulting model includes the time parameter, and uses the approach referred to as Approach II. The modelling of the cable component is done for the specific purpose of demonstrating how to develop theory for generating generic principles.

11.1 Introduction

11.1.1 Definitions of Parameters for Component Behavior

Chapter 9 summarized results from different research studies and analyses of the cable component behaviour that have specifically looked at both the phenomenon and prevention of water trees. Together with this knowledge about component behaviour and previous studies of the failure rate, the following parameters for the component behaviour can be defined.
11.1. Introduction

- **Water-tree length** denoted by \( l \) [mm or \( \% \)], is a measurement of the longest water tree in a cable sample; the percentage unit refers to the proportion of maximum cable insulation thickness.

- **Normalized breakdown voltage** denoted by \( \frac{U_{bd}}{U_0} \), is a measurement of the cable condition that is its ability to withstand overvoltages, where \( U_{bd} \) is the breakdown voltage and \( U_0 \) is the phase-to-ground voltage and the quotient is consequently a normalized value.

- **Non-linear loss parameter** denoted by \( \Delta \varepsilon'' \) is the increase in \( \varepsilon'' \) (typically from 0.5\( U_0 \) to \( U_0 \)) which is the dielectric loss (the imaginary part of the relative permittivity).

11.1.2 Objective

The objective here is to formulate a relationship between system reliability and the PM of components. It has been found that these factors are connected through causes of failures of components. One of the primary aims of the Cable Application Study and the development of a model for a quantitative definition of this relationship, is to show that it is actually possible to make the model. Furthermore that rather than being based on assessments, this model can be based on knowledge of the following: actual experience, experiments and physical models. Consequently, the modelling of \( \lambda(t, PM) \) that is presented in this chapter is based on real data and theories that connect preventing failures and improving failure rate.

The component focused on in the application study is the underground cable. It has been found that insulation failure is one of the major causes of system failure for cable components. The specific ageing mechanism in insulation material is known as water treeing, which was investigated in Chapter 9.

11.1.3 Process and Logic

The physical process studied can be summarized as follows: water trees grow through the cable insulation which results in a decrease in the breakdown voltage of the cable. The breakdown voltage of a cable gives a measure of the condition of the cable in the form of resisting overvoltages that is the
11.1. Introduction
cable’s ability to fulfill component function. The decrease in cable condition leads to a higher failure rate for the component. The parameters included in this process, expressed as functions of time, are:

1. the water-tree length denoted by \( l(t) \) [mm or \( \% \)],
2. the normalized breakdown voltage denoted by \( U_{bd}/U_0(t) \), and
3. the failure rate denoted by \( \lambda(t) \) [\( t/yr \) and \( km \)].

![Diagram](image_url)

**Figure 11.1.** Illustration of the process relating water-treeed cable-insulation as the cause of failure to application of a PM activity.

The connection between resulting failure rate and cause of failure through water-tree growth is the breakdown voltage:

\[
l(t) \Rightarrow U_{bd}/U_0(t) \Rightarrow \lambda(t).
\]

In this application study, PM efforts should be applied to prevent the growth of water trees. The logic for preventing the process described above can be summarized as follows.

1. PM by rehabilitation methods is applied by injecting silicon to fill the water trees, which results in:
   (a) stopping of the existing water-tree growth, and
   (b) improving the condition of the cable.

2. The effect of the PM efforts is an improvement in the cable condition.
3. The improvement in the cable condition is assumed to stabilize the failure rate.

The functional relationships can therefore be expressed as follows:

\[ PM \Rightarrow l(t) \Rightarrow U_{bd}/U_0(t) \Rightarrow \lambda(t). \]

Another parameter, the non-linear loss parameter \( (\Delta \varepsilon'') \), has been identified to be of great interest. This parameter provides an alternative indicator (measure) of cable condition without itself being destructive as the breakdown voltage tests \( (U_{bd}/U_0) \) [101]. Therefore this parameter would be of great use for defining when to perform the PM task.

### 11.2 Procedures for Modelling \( \lambda(t, PM) \)

It should be emphasized that the main difficulties with modelling the relationship between failure rate and PM lie in finding supporting real data, and understanding the related physical process. The modelling includes using the available knowledge in a suitable way. The result would be both the resultant model itself and proof that it is possible to achieve.

#### 11.2.1 Supporting Data Sources

To relate failure rate with PM, comprehensive knowledge about the component is required. To understand the cable component behaviour, a literature study has been undertaken to identify available and possibly useful knowledge. The list below summarizes the useful sources obtained to support the model development.

1. A survey and analysis of XLPE cable faults exhibiting a high number of water trees, reported by Svel (Association of Swedish Electrical Power Utilities) [104]. This supports the modelling of failure rate \( (\lambda(t)) \).

2. Research results analysing XLPE cable component behaviour in terms of for example breakdown voltage \( (U_{bd}/U_0) \), loss parameter and the relationship between these. This is supported by studies made at KTH [101], [126], [100].
3. The relationship between cable condition and loss parameter ($\Delta \varepsilon''$) as presented in an ELFORSK report [128], and also [101].

4. The effect on breakdown voltage ($U_{bd}/U_0$) of a PM method supported by SINTEF, presented in [130].

These supporting sources of data have been discussed further in the following sections, while presenting the modelling of the different parameters required in greater detail.

### 11.2.2 Modelling Steps

The aim here is to develop a model of failure rate as a function of time and a PM method ($\lambda(t, PM)$), that is based as far as possible on existing data and theories. For the XLPE cable component, this means that the model should be based on the data sources presented in Section 11.2.1. Furthermore, this model attempts to relate the following parameters (all expressed as variables of time) to PM:

- failure rate denoted $\lambda(t)$ [f/yr and km],
- water-tree length denoted $lt$ [% or mm], and
- cable condition defined by the normalized breakdown voltage, denoted $U_{bd}/U_0(t)$, which could be measured by either,
  
  - breakdown voltage tests denoted $U_{bd}/U_0$, or
  
  - non-linear loss parameter denoted by $\Delta \varepsilon''$.

The solution is given by:

$$\lambda(t, PM) = \ldots = f(\ldots , \Delta \varepsilon'') \quad (11.1)$$

where $\lambda(t, PM)$ is used for prediction, and for example $\Delta \varepsilon''$ is measured. In order to obtain this functional relationship, several relationships between the various parameters have had to be deduced. Which parameter to start with is a matter of choice and the choice here has been to start with the failure rate as a function of time, which would be obtained from statistics.
11.3 Modelling Failure Rate

11.3.1 Introduction

The objective here is to model the failure rate as a function of time, and to base this model on real data.

A detailed study of XLPE cable failures has been done by Svel, and presented in [104]. This report has been identified as giving support to a model of failure rate related to failures due to the phenomenon referred to as water treeing.

11.3.2 The Svel Study of XLPE cables

Data for XLPE cables exposed to water treeing has been collected for the period 1965 – 1988 [104]. Two changes in cable production in 1974 – 1975
### 11.3. Modelling Failure Rate

Table 11.1. Summary of steps in the deduction of the model describing failure rate as a function of PM ($\lambda(t, PM)$).

<table>
<thead>
<tr>
<th>Step</th>
<th>Activity</th>
<th>Resulting function</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Modelling failure rate</td>
<td>$\lambda(t)$</td>
<td>Svel [104]</td>
</tr>
<tr>
<td>2</td>
<td>Modelling water-tree length</td>
<td>$l(t)$</td>
<td>KTH [126],[100]</td>
</tr>
<tr>
<td>3</td>
<td>Superposition of results</td>
<td>$\lambda(t, l)$</td>
<td>Step 1 and 2</td>
</tr>
<tr>
<td>4</td>
<td>Modelling break down voltage</td>
<td>$U_{bd}/U_0(l)$</td>
<td>KTH [126]</td>
</tr>
<tr>
<td>5</td>
<td>Superposition of results</td>
<td>$U_{bd}/U_0(t)$</td>
<td>Step 2 and 4</td>
</tr>
<tr>
<td>6</td>
<td>Modelling loss parameter</td>
<td>$\Delta \varepsilon''(U_{bd}/U_0)$</td>
<td>KTH [126]</td>
</tr>
<tr>
<td>7</td>
<td>Superposition of results</td>
<td>$\Delta \varepsilon''(t)$</td>
<td>Step 5 and 6</td>
</tr>
<tr>
<td>8</td>
<td>Summarise results</td>
<td>$\lambda(t, \Delta \varepsilon'', l, U_{bd}/U_0)$</td>
<td>Step 1, 2, 5 and 7</td>
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</table>

Stage A: Water-tree length

<table>
<thead>
<tr>
<th>Step</th>
<th>Activity</th>
<th>Resulting function</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Modelling effect of PM</td>
<td>$U_{bd}/U_0(PM)$</td>
<td>SINTEF [130]</td>
</tr>
<tr>
<td>10</td>
<td>Superposition of results</td>
<td>$U_{bd}/U_0(t, PM)$</td>
<td>Step 9 and 5</td>
</tr>
<tr>
<td>11</td>
<td>Modelling effect of PM</td>
<td>$\lambda(t, PM)$</td>
<td>Step 8 and 9</td>
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</table>

Stage B: Effect of maintenance

<table>
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<th>Activity</th>
<th>Resulting function</th>
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<tr>
<td>12</td>
<td>Repetition of results</td>
<td>$\lambda(t, PM)$</td>
<td>Stage A</td>
</tr>
</tbody>
</table>

Stage C: Water-tree length
11.3 Modelling Failure Rate

have greatly impacted on the water-treeing phenomenon. The first was a change in the outer semiconductor from being painted and taped to being extruded. This decreased water penetration. The second was a change in the binding process from steam-vulcanizing to a dry method. This involved a lowering of the water content in the insulation. Consequently both these changes resulted in a reduction in the initiation of water-tree growth. Based on these changes in the cable component, the statistics can be treated as two different study objects: (i) cables produced up to 1975, and (ii) cables produced after 1975. Causes of cable failures were classified as presented previously, and it has been shown that the significant cause of cable failure is water treeing, averaging 38% of all the causes in the total population of analyzed cables.

In addition to this, cables can be of two different categories, those with and those without the extruded layer. From the statistics presented, it was identified that the inclusion of the extruded layer led to a significant change in failure rate. Of the total 228 cable failures, there were 211 in the 2559 km of cable without an extruded outer semi-conduction layer, and 17 in the 10,500 km of cable with the extruded layer.

The total length of cables was estimated and the results have been presented as an average kilometre of cable in service per year. The results show that the first group of cables (produced before 1975) represents a comparatively small part of the population in kilometres, but a comparatively large number of failures.

11.3.3 Input data for the modelling

The failure rate function ($\lambda(t)$) for an XLPE cable component can be estimated based on the data presented in the previous section. The supporting data selected for the analysis covered:

- the period 1970 – 1988 (19 years),
- failures caused by water treeing, and
- cables without an extruded layer.

Moreover, the cables that were selected to be studied were those that were put into service 1970 – 1975 (as listed above) and had data collected
11.3. Modelling Failure Rate

on them during the period 1970-1988. Cables put into service earlier than this are so small in number and length that the information that would be gained was considered to be non-significant. For the cables included in the study, the data collection period is 19 years, which includes the failure process. However this is not the case for the large population of cables with the extruded layer, which have not yet started to fail given the limits set by the study period and are therefore not included.

Based on the Svel report [104], the age of the cable when the failure occurs (in years after being put into service) was identified. These results show that most failures occur after 9 – 15 years of service. Estimated average length of cable [km] as presented in the report was, based on the average length that was extracted for cables put into service during 1970 – 1975.

These data constitute the input source for providing failure rate changes during this 19 year period. Table 11.2 presents the resulting failure data and calculated failure rates. The cables put into service in 1970 have a total aging of 18 years. However, those put into service in 1975 have only a total aging of 13 years. Consequently, the full samples of data covers the years until year 13. This time is defined as follows:

\[ t_{svel} = 13 \text{ [yr].} \]  \hspace{1cm} (11.2)

11.3.4 Mathematical Model and Analysis

The data chosen for the analysis are cables put into operation 1970-1975, and data collected for these during the period 1970-1988. The cable population (total length) is not constant during the time period, however for a period of 13 years, the data provide results for the complete population. The time parameter in this context could therefore be presented in two different ways, as shown in Figure 11.3; either the real time for the system, or the aging time for the different cables. When using this data in the context of modelling the behaviour of a cable component, the aging time has been used.

Using numerical methods the experience data presented in Table 11.2 can be adjusted to a curve. In this situation the curve would present the failure rate as a function of time \( \lambda(t) \).
### Table 11.2

Failure occurrences (in years after being put into service) caused by water trees, in XLPE cables put into service during the early to mid 1970s.

<table>
<thead>
<tr>
<th></th>
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<th>4.5</th>
<th>1.5</th>
<th>1.5</th>
<th>100 km</th>
</tr>
</thead>
</table>

11.3. Modelling Failure Rate

As mentioned in the previous section, the data set is complete up until year 13 of aging. In the following modelling, results up until 13 years of aging have been used. However graphs are first plotted for the complete data set.

Figure 11.4 presents results for cables put into service over different years. The plots are results from simple linear piecewise interpolations. The graphs show an initial trend of an almost constant failure rate for about the first 4 - 6 years, then it increases to a maximum level at about 10 - 13 years. Figure 11.5 demonstrates the total failure rate over time for the whole cable population. Note that it is only the population of cables put into service 1970 that are included in the system at the 18th year of aging, and consequently the population decreases seen in that year.

Figure 11.5 shows the behaviour of an average cable component from the Svel study. In this analysis here, the objective is to formulate a general function for the failure rate. Therefore the next step in the analysis is to approximate the available data with a function.
Figure 11.4. Failure rate as a function of time for XLPE cables put into service 1970-1975.

Figure 11.5. Failure rate as a function of time for XLPE cables put into service 1970-1975.
11.3.5 Approximation of the Data to a Function

This section introduce two different approaches to solving this task. Firstly, a least square method, and secondly a polynomial curve-fitting method.

The least square method implies that a known function can be approximated with observed data in such a way that the sum of the square of approximation error can be minimized. Figure 11.5 illustrates the behaviour for the complete data set, and shows a trend similar to that of an exponentially distributed function. Based on this observation, the following choice of function for the data has been assumed, where the function $F(t) \approx y$, and $y$ is the set of observed values constituting the collected statistics:

$$F(t) = \{ \ x_1 \cdot e^{x_2 t} \ : \ 0 \leq t \leq t_{\text{set}}. \quad (11.3)$$

The unknown parameters for the function $(x_1$ and $x_2$) can be defined by curve fitting by the least square method. This implies that an abstract model $(Ax)$ is made for the observed data $(b)$. The resulting solutions, that are the normal equations are written $A^T A x = A^T b$. The vector $(x = (A^T A)^{-1} A^T b)$ is the least square solution to $Ax = b$. In this example the model function is not a linear function and it is therefore necessary to rewrite the function for example by use of the $ln$ function. However, the resulting function did not give a good approximation of this data, therefore an alternative method has been analyzed as follows.

The data has been fitted to different degrees of polynomials, using the MATLAB standard functions for polynomial curve fitting. Figure 11.6 demonstrates six of these with functions approximated with the data for the full cable population data sets (for 13 years in operation). The accuracy of the model would increase with a higher degree of polynomial, however at six degrees, too much data are included for capturing the smooth increase in the failure rate. Consequently, the five degree polynomial has been chosen for the following analyses. The error gained using these approximations has been analyzed and no trends have been identified. Table 11.3 summarizes the errors using time steps of one hour (note that for the following analysis the much smaller time step of 0.01 h has been used).

This accuracy table also shows another factor to be considered in the modelling, where the first element shows negative values. This characteristic is obviously not possible for the failure rate function that is being modelled.
Table 11.3. The accuracy of function fitting for $\lambda(t)$ and Time Step 1.

<table>
<thead>
<tr>
<th>$t$ [year]</th>
<th>$\lambda_{\text{observed}}$</th>
<th>$\lambda = f(\text{poly5})$</th>
<th>$\lambda_{\text{observed}} - \lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>$-0.0080$</td>
<td>$0.0080$</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>$0.0030$</td>
<td>$-0.0030$</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>$0.0189$</td>
<td>$-0.0189$</td>
</tr>
<tr>
<td>3</td>
<td>0.0556</td>
<td>0.0453</td>
<td>0.0103</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0.0860</td>
<td>$-0.0860$</td>
</tr>
<tr>
<td>5</td>
<td>0.2778</td>
<td>0.1437</td>
<td>0.1341</td>
</tr>
<tr>
<td>6</td>
<td>0.3333</td>
<td>0.2200</td>
<td>0.1133</td>
</tr>
<tr>
<td>7</td>
<td>0.2222</td>
<td>0.3168</td>
<td>$-0.0946$</td>
</tr>
<tr>
<td>8</td>
<td>0.1667</td>
<td>0.4361</td>
<td>$-0.2694$</td>
</tr>
<tr>
<td>9</td>
<td>0.6667</td>
<td>0.5809</td>
<td>0.0858</td>
</tr>
<tr>
<td>10</td>
<td>1.0000</td>
<td>0.7559</td>
<td>0.2441</td>
</tr>
<tr>
<td>11</td>
<td>0.9444</td>
<td>0.9676</td>
<td>$-0.0232$</td>
</tr>
<tr>
<td>12</td>
<td>1.0556</td>
<td>1.2254</td>
<td>$-0.1699$</td>
</tr>
<tr>
<td>13</td>
<td>1.6111</td>
<td>1.5418</td>
<td>0.0693</td>
</tr>
</tbody>
</table>

To correct this in the model, the resulting approximated function has been adjusted by replacing all the negative elements by zero.

Figure 11.7 shows this polynomial fit in detail. The data set including the total length of cables covers the period of time until $t_{\text{vel}} = 13$ years. For the modelling of the failure rate it this data set of the total population that has been used. The major reason for not including the later time period is because the cable population is smaller and the last point actually only includes one set of cables that were put into operation in 1970. The next section continues a discussion about modelling the failure rate function.

11.3.6 Assumptions about the Failure Rate Characteristics

The approximation of a function of the cable data as presented in the previous section included the period until $t_{\text{vel}} = 13$ years of operation or aging. How the failure rate behaves after this period of time is fairly unknown. The data available for the years up until 18 years of operation are poor as these
11.3. Modelling Failure Rate

Figure 11.6. Polynomial curve-fitting functions.

Figure 11.7. Polynomial fitting with 5 degrees for the failure rate in the full population data.
11.3. Modelling Failure Rate

cover such a small part of the cable population. However it is possible to argue that one characteristic could be better than another.

This failure rate function corresponds to the failure due to water-tree length. Svef data support a model for an average behaviour between aging years $0 - 13$. However data do exist for some cables up to the aging time of 18 years. In the model proposed, a polynomial function has been approximated with the data up to year $t_{svef} = 13$, which correspond to a complete population of cables (total cable length). An assumption has to be made about the characteristic beyond this year.

Figure 11.8 shows two different alternatives.

1. Increasing failure rate function:
   where the assumed function implies a continuation of the polynomial function.

2. Constant function for failure rate:
   where the assumed constant value is based on the polynomial function value at the time $t_{svef}$ (the end of the full data set).

In the Cable Application Study, the latter of these two alternatives has been used, however the true characteristic is likely to be somewhere between these two. This is based on the assumption that the water-trees have penetrated the whole insulation width and therefore, no further decrease in cable condition due to water-trees is expected.

For the first alternative, it is interesting to note that the need and the cost of corrective maintenance would escalate with time. Consequently with this model, a greater benefit would be achieved by using PM. However one argument against the first alternative is that the water trees have a maximum length. Physically then, it is therefore reasonable to assume that the failure rate would reach a maximum value as well. On the other hand, if it is considered that the number of water trees has an impact, it could be argued that the failure rate would continue to increase. Moreover, a second argument against using the first alternative is that the available data based on experience show a decreased rather than an increased behaviour in the failure rate. This could however, depend on that the cables have been replaced.

The following remarks can be made for the second alternative. Firstly that the resulting time period is supported by the SINTEF material [130],
11.3. Modelling Failure Rate

which says that it takes water trees about 12 – 15 years to grow through the insulation. Consequently, the assumption seems reasonable. Secondly, with respect to the transition between the upward curve given by the polynomial assessment and the constant value, there is a discontinuity that is improbably in a practical sense. Instead it is more likely that there is a smooth transition from the upward gradient curve to the constant. Therefore the gradient will gradually decrease from the final polynomial value to zero, although over a small time period. However, this problem with the model is compensated by the fact that the assumed function is based on a very limited use of assumptions. Actually the only assumption made is that the end value of the data defines the continued function. Consequently, the smooth function would be achieved at the expense of introducing unknown data, which is not considered sufficient enough reason for doing so.

![Graph showing data points and polynomial fit](image)

**Figure 11.8.** Assumed characteristics for the failure rate following from the polynomial function.
11.3.7 Resulting Model of the Failure Rate in Time $\lambda(t)$

A failure rate function has been defined based on data from the Svel study and approximations presented in the previous section. Consequently, the first step in the process of modelling $\lambda(t, PM)$ has been completed.

The resulting failure rate function with units of failure occurrences per 100 km and yr is defined as follows in general terms:

$$
\lambda(t) = \begin{cases} 
0 & : 0 \leq t \leq t_{\rho 0} \\
\text{poly}(f(t), 5) & : t_{\rho 0} \leq t \leq t_{\text{svel}} \\
f(13) & : t_{\text{svel}} \leq t \leq T,
\end{cases}
$$

(11.4)

where $f(t)$ refers to a polynomial that approximates to the Svel data of five degrees. One assumption made for the data was that if the initial function values become negative, they are replaced with zero values. The time $t_{\text{svel}}$ refers to the end period of the data from Svel that was identified to provide significant input data.

The resulting failure rate function with the input of data and the use of time steps of 0.01 can therefore be presented as follows:

$$
\lambda(t) = \begin{cases} 
0.0000 & : 0.0000 \leq t \leq 0.7400 \\
-0.0080 + 0.0109t - 0.0014t^2 + & : 0.7400 \leq t \leq 13.0000 \\
+0.0016t^3 - 0.0001t^4 & : 13.0000 \leq t \leq T.
\end{cases}
$$

(11.5)

Figure 11.9 illustrates this function together with water-tree growth over time. This figure shows the resulting failure rate function for the Cable Application Study, that is where the maximum failure rate level is reached after 13 years of operation. Numerical values for the function are presented in the first column noted $\lambda_{old}(t)$ in Tables 11.9 and 11.11. Note that the tabled values represent function values for integer numbers for time.

11.4 Modelling Water Tree Length

11.4.1 Characteristics of Water-tree Length

The concept of water treeing was introduced in Section 9.2. It was also identified that the type of water trees that are most likely to cause cable
Figure 11.9. Relationship between models of water-tree length and failure rate for the XLPE cable component. (The dotted lines show on different possible functions for reaching the maximum level of water-tree length.)
faults are the so-called vented trees. Furthermore, it was recognized that
these have a characteristic growth involving an initial inception stage, fol-
lowed by a rapid growth stage, that in a final stages slows down but still
continues. However, data supporting such a function in real time is not
available. Results have been presented in [126] that show both the length
and rate of water-tree growth linear with laboratory aging time. This state-
ment confirms the previous concern about the transitions in the failure rate
characteristics.

Evaluation of a method for the rehabilitation of water-treed XLPE cables
has been made by the SINTEF in Norway as introduced in Section 9.4.2.
In that study, attempts were made to model water-tree length after fault
rehabilitation. The time parameter used was however the aging time in the
laboratory. The water-tree length was modelled based on the assumption of
constant linear growth of water trees.

The conclusion is that it is a very difficult task to model the water-tree
length in real time. Even though much research has been conducted within
this specific area the problem has still not been solved. However that does
not necessary present a reason for not making an initial assumption to see
where it would lead. A reasonable assumption seems to be that once the
trees start to grow they grow uniformly and with a linear increase until the
maximum length is reached. The upper plot in Figure 11.9 presents a set of
possible functions based around this assumption.

Data found to support the slope of this function can be found in the
SINTEF report [130], which states that maximal water-tree length is reached
after about 12-15 years. The report shows results from an application where
maximal water-tree length is 5.5 mm (the entire width of the insulation).

Based on this result as well as on the previously-developed model of the
failure rate (see Section 11.3.7), the time limit of 13 years ($t_{\text{max}} = 13$)
has been chosen for the Cable Application Study. It is however important
to recognize that the model being developed does not require such an as-
sumption, and more complex functional relations could also be incorporated.
Consequently, the second step in the process of modelling $\Lambda(t, PM)$ has been
completed. The following is the resulting function for water-tree length over
time:
11.5. Modelling Breakdown Voltage Function

\[
l(t) = \begin{cases} \frac{l_{max}}{t_{max}} \cdot t & : 0 \leq t \leq t_{max} \\ l_{max} & : t_{max} \leq t \leq T \end{cases}
\]  

Figure 11.9 includes an illustration of this function. The figure shows both the different possible functions for reaching the maximum level of water-tree length, as well as the specific function for the application study that is with \( l_{max} = 5.5 \text{ mm} \) and \( t_{max} = 13 \text{ years} \).

11.4.2 Relationship between Failure Rate and Water-tree Length

It has been established in [126], [101], [130] and [104] that water-tree length relates to increasing failure rate. Furthermore, failure rate reaches its maximum when water trees cross the whole insulation layer. However a relationship between these has not yet been defined.

Section 11.3.7 defined the function for \( \lambda(t) \) for a cable exposed to water treeing, and Section 11.4.1 modelled the length of water trees \( (l(t)) \). Assuming that there is a proportionality between these, and by superposition of these two results would therefore give a relation for the failure rate as a function of water-tree length. Figure 11.9 illustrates the resulting relationship between failure rate and water-tree length. Of critical importance in this context, is defining the time period over which the water-tree length has a significant impact on the increase in failure rate. For this example, it seems to be around 6-13 years.

11.5 Modelling Breakdown Voltage Function

The condition of a cable can be defined by measuring its breakdown voltage (its capacity to resist overvoltages). These could be due to for example faults in the AC system, switching operations in the network, or lightning.

Results from studies of breakdown-strength testing of water-treeed XLPE cables have been presented in [126], and report the results of two of breakdown test investigations: the first with lightning impulses, and the second with AC impulses. The dielectric loss \( (\epsilon'' \text{)} \) at \( U_0 \) and 0.1Hz, and normalized breakdown voltage was plotted for these two investigations. From the
11.5. Modelling Breakdown Voltage Function

First investigation, results show a normalized breakdown voltage varying between 5 - 35 times the service voltage. The second investigation showed corresponding results of about 2 - 10 times. Consequently, it is of great importance to know what kind of faults are being considered in the analysis of the component behaviour. In this present study, the faults of the AC loads are considered. Therefore the normalized breakdown voltage is expected to lie within the interval of 2 - 10 times the service voltage.

11.5.1 Breakdown Voltage as a Function of Water Trees

A correlation between electrical breakdown voltage and water-tree length has been shown and discussed in Section 9.3.1. Breakdown voltage and the water-tree content have been investigated in work done to develop the dielectric spectroscopy measurement system for diagnosis of XLPE cables. Based on these results [100], assumptions have been made about the relationship between breakdown voltage and water-tree length. Further refinements would be possible with access to source data.

Figure 11.10 (after [100]) defines a relationship between breakdown voltage ($U_{bd}/U_0$) and the longest observed water tree ($l_{max}$). This figure shows that the breakdown voltage decreases from a maximum value of around 10 to a minimum value of about 2. The water-tree length on the other hand increases from 0 to maximum of 100%.

A simple assumption in the modelling is therefore to assume a linear relationship between breakdown voltage and water-tree length within the boundaries: $U_{bd}/U_0 : 10 \rightarrow 2$ and $l : 0 \rightarrow 100$. The resulting model shown in Figure 11.11 can consequently be formulated as follows:

$$U_{bd}/U_0(l) = U_{bd}/U_0(l = 0) - \frac{(U_{bd}/U_0(l = 0) - U_{bd}/U_0(l = 100))}{l_{max}} \cdot l \quad 0 \leq l \leq l_{max}$$

where $l : 0 \rightarrow 100\%$.

(11.7)

In the Cable Application Study, the input data used for this equation are:
11.5. Modelling Breakdown Voltage Function

\[ l_{\text{max}} = 5.5 \text{ mm, and } U_{\text{bd}}/U_0(l = 0) = 10, \quad U_{\text{bd}}/U_0(l = 100\% \equiv 5.5\text{mm}) = 2, \] (11.8)

which are based on results from research results at KTH and SINTEF (as introduced in Section 11.2.1).

Figure 11.12 shows results for the breakdown voltage as a function of water-tree length.

![Graph showing relationship between normalized breakdown voltage and longest water-tree observed in investigated cables [100].](image)

**Figure 11.10.** Relationship between normalized breakdown voltage and the longest water-tree observed in investigated cables [100].

11.5.2 Breakdown Voltage as a Function of Time

The function for the water-tree length \((l(t))\) was defined in Section 11.4.1, and Section 11.5.1 presented a definition of a relationship between breakdown voltage and water-tree length. Superposition of these two results would therefore give a relation for the breakdown voltage as a function of time.
Figure 11.11. Functional relationship between breakdown voltage and water-tree length in XLPE cable components, based on results from KTH and SINTEF.
The resulting function for the normalized breakdown voltage varying in time is defined by

\[
U_{bd}/U_0(t) = \begin{cases} 
bd_{\text{max}} - k_{bd} \cdot t & : t_0 \leq t \leq t_{\text{max}} \\
bd_{\text{min}} & : t_{\text{max}} \leq t \leq T 
\end{cases}
\]

(11.9)

where:

- \( \bd_{\text{max}} \) is the maximum level for the normalized breakdown voltage,
- \( \bd_{\text{min}} \) is the minimum level for the normalized breakdown voltage,
- \( t_{\text{max}} \) is the year when the water trees reach their maximum length and the breakdown voltage is assumed to reach a constant level,
- \( k_{bd} \) defines the slope for the decrease as

\[
k_{bd} = (\bd_{\text{max}} - \bd_{\text{min}})/t_{\text{max}},
\]

(11.10)

- \( t_0 \) is the starting point for time in the model, and
- \( T \) is the end point for time in the model.

In the Cable Application Study, the input data for the model of the breakdown voltage consist of the following two values:

\[
\bd_{\text{max}} = 10 \quad \text{and} \quad \bd_{\text{min}} = 2,
\]

(11.11)

which are based on the results from KTH [126] discussed in Section 9.3.1.

The resulting graph of the breakdown voltage as a function of time for the cable is presented in Figure 11.12.

### 11.6 Modelling Loss Parameter Function

This section includes the non-linear loss parameter \((\Delta \varepsilon')\) in the modelling procedure. This parameter can be measured by a non-destructive method and is therefore very valuable to use and preferable to the breakdown-voltage test method which is a destructive method (destroying the measured object).
Figure 11.12. Model for normalized breakdown voltage as a function of time.

Diagnosis methods for measurements of cable behaviour were introduced in Section 9.4.1.

It is important to note that since this parameter can be measured without destroying the cable, it could for example be used as an indicator of when PM should be undertaken. Consequently it is of great interest to include the loss parameter in this procedure for modelling the relationship between failure rate and PM in real time.

It is also relevant to comment that no previous results have been found that relate these parameters, and specifically for this purpose. This is not only because it is difficult to accomplish but also because the benefits of doing it are unproven; which the work done here aims to rectify. Consequently it has been shown that data from earlier investigations of the loss parameter and the breakdown voltage (as presented in [126]), can be used to obtain the relations necessary to establish the required functional relationship for the model being developed.
11.6. Modelling Loss Parameter Function

Table 11.4. Non-linear loss parameter and normalized breakdown voltage input data.

<table>
<thead>
<tr>
<th>Loss parameter $\Delta \varepsilon''$</th>
<th>Breakdown voltage $U_{bd}/U_0$</th>
<th>Equivalent time [yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>2.5</td>
<td>12.1875</td>
</tr>
<tr>
<td>0.001</td>
<td>3</td>
<td>11.3750</td>
</tr>
<tr>
<td>0.0001</td>
<td>4</td>
<td>9.7500</td>
</tr>
<tr>
<td>0.00005</td>
<td>5</td>
<td>8.1250</td>
</tr>
<tr>
<td>0.00003</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

11.6.1 Relationship between the Loss Parameter and Breakdown Voltage

Results from XLPE cable studies of more than 200 field measurements combined with laboratory investigations have been presented in [126]. These include an analysis of the relationship between the non-linear loss parameter ($\Delta \varepsilon''$) and the breakdown voltage ($U_{bd}/U_0$). Figure 11.13 from [126], presents the resulting measurements.

The data in the above show a trend where the breakdown voltage decreases from about 10 asymptotically towards 2.5. $\Delta \varepsilon''$ varies from about $10^{-5}$ to 0.1 (note that the values for the non-linear loss parameter are presented in log scale). An exponential trend can be seen for the relation. Based on such an assumption, an exponential function has been estimated to fit the measurement data. Figure 11.14 shows the resulting function, which is based on data presented in Table 11.4. Similarities between the two figures can be seen, with a significant increase in the loss parameter function when the breakdown voltage decreases towards 2.

11.6.2 Loss Parameter as a Function of Time

The model for breakdown voltage over time presented in Section 11.5.2 shows an initial decrease from 10 and then a constant value at 2. The loss parameter on the other hand (seen in Figure 11.14) shows a relationship with breakdown voltage decreasing from the value of 10 to 2.5. Consequently, these two results together show the relations for these parameters as functions of time.
11.6. **Modelling Loss Parameter Function**

![Graph](image)

**Figure 11.13.** The non-linear loss parameter as a function of normalized breakdown voltage \([126]\).
Figure 11.14. The non-linear loss parameter as a function of normalized breakdown voltage.

Figure 11.15 shows the results when superposing the relationships defined earlier on. Compared with the previously modelled parameter functions, the loss parameter exhibits behaviour with high sensitivity.

11.7 Resulting Model of Cable Component Behavior over Time

The preceding sections have treated the modelling of cable component behaviour. For the Cable Application Study, this has meant modelling the characteristics of an XLPE cable that is effected by water-tree growth through its cable insulation. Furthermore, the cable component behaviour has been defined by the following three parameter functions:

1. failure rate \( \lambda(t) \),
2. water-tree length \( l(t) \), and
3. normalized breakdown voltage \( U_{bd}/U_0(t) \),
where the last parameter can be measured by either breakdown voltage tests or measurements of the non-linear loss parameter ($\Delta e''$).

Figures 11.16 and 11.17 illustrate these functions for the Cable Application Study. The results demonstrate a model for the effect of water treeing in an XLPE-insulated cable component.

Table 11.5 summarizes the resulting functions, the approximations used to obtain these, the assumptions made, and the supporting data sources. Some clarifications are required here in relation to the table. On the one hand, the *approximation* implies assumptions about the function characteristics. For example, in regard to the failure rate, the function is approximated to the data from Sveb by a polynomial function. On the other hand, the *assumptions* refer to the specific adjustments for a realistic model of the parameter where: (i) the failure rate cannot drop below zero, or (ii) the specific assumptions for providing a single result for the cable, being the maximum length of water trees after 13 years, which was shown to lie within the real time period. Finally, it should be recognized from the results presented in the table, that this in some regards heuristic approach for defining a quanti-
tative model for the component behaviour, is firstly supported by real data, and secondly is based on a limited set of assumptions that could easily be adjusted.

This completes the first task in the modelling of component behaviour, being to deduce a functional relationship for the component over time that is, with aging.

Figure 11.16. Resulting model for XLPE cable component behavior.
Table 11.5. Summary of the model for cable component behavior.

<table>
<thead>
<tr>
<th>Failure rate ( \lambda(t) )</th>
<th>Water-tree length ( l(t) )</th>
<th>Cable condition ( \frac{U_{bd}}{U_0(t)} ), ( \Delta^\prime \epsilon(t) )</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
<td><img src="image3.png" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>Approximation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>poly((f, 5)t : 0 -&gt; t_{svel} = 13)</td>
<td>Linear to max. value Constant at max.</td>
<td>Linear from max. to min. Constant at min.</td>
</tr>
<tr>
<td><strong>Assumptions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( f(t) &lt; 0 \rightarrow f(t) \equiv 0 )</td>
<td>( t_{\text{max}} = 13 )</td>
<td>( bd_{\text{max}} = 10 ), ( bd_{\text{min}} = 2 )</td>
</tr>
<tr>
<td>( t &gt; t_{svel} \rightarrow f(t) \equiv f(t_{svel}) )</td>
<td></td>
<td>( \Delta^\prime \epsilon(U_{bd}/U_0) )</td>
</tr>
<tr>
<td><strong>Data source</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Svel [104]</td>
<td>SINTEF [130]</td>
<td>KTH [126], [101],[100]</td>
</tr>
</tbody>
</table>
Figure 11.17. Resulting model for XLPE cable component condition.
11.8 Modelling the Impact of Rehabilitation Preventive Maintenance

11.8.1 Introduction

Preceding sections of this chapter have defined component behaviour by modelling the two functions failure rate ($\lambda(t)$) and water-tree length ($l(t)$), and indicated the condition of the cable using the functions normalized breakdown voltage ($U_{bd}/U_0(t)$) and the linear loss parameter ($\Delta e^l(t)$). As the main objective of the work presented in this thesis is to achieve a model that provides a quantitative relationship between PM and reliability, the next step in the modelling procedure is to resolve how these defined functions can be extended to include the effect of PM.

It has proven quite difficult to find literature or research results to support such a model, and no similar attempts to relate the information in this way have been found.

However, for this application study of an XLPE cable affected by water treeing, results have been found that can support such a model. SINTEF in Norway have analysed the effect of applying a rehabilitation method for XLPE cables with the aim of preventing failures due to water-tree growth [130]. Experiences and results from this study have been identified to support the objective here of modelling the cable component behaviour, which can be used in this study to translate the benefit of PM on breakdown voltage ($U_{bd}/U_0$) into a benefit in the failure rate ($\lambda(t)$).

11.8.2 SINTEF Study of XLPE Cables

The effect of PM on an XLPE cable exposed to water treeing has been studied at SINTEF (see [130] and in Section 9.4.2).

The condition of the cable was defined by measuring the breakdown voltage in different cable samples. Furthermore, a statistical analysis was made of the measurement test results. This analysis resulted in a probability of breakdown voltage occurring of 0.63 based on Weibull distribution with a 95% confidence interval. These measurements were made at four different times: (i) just before rehabilitation, (ii) four months after, (iii) one year after, and (iv) two year after rehabilitation treatment. The total measuring period was consequently two years and four months. Table 11.6 and Figure
Table 11.6. Results from breakdown AC testing for water-tree affected cables (after SINTEF).

<table>
<thead>
<tr>
<th>$U_{0.63}$</th>
<th>95% conf.interval</th>
<th>$t$ [mth]</th>
</tr>
</thead>
<tbody>
<tr>
<td>52.2 kV</td>
<td>46.2 – 57.3 kV</td>
<td>0</td>
</tr>
<tr>
<td>64.3 kV</td>
<td>58.2 – 69.4 kV</td>
<td>4</td>
</tr>
<tr>
<td>78.5 kV</td>
<td>71.8 – 84.2 kV</td>
<td>16</td>
</tr>
<tr>
<td>73.7 kV</td>
<td>64.7 – 81.3 kV</td>
<td>28</td>
</tr>
</tbody>
</table>

11.18 present the results from the study. The change in breakdown voltage as a function of time has been shown and it can be seen that the last drop in breakdown voltage is not numerically significant. Therefore, only the first three points have been used in the modelling.

![Figure 11.18](image)

**Figure 11.18.** Change in the breakdown voltage of XLPE cables due to preventive maintenance through rehabilitation (results from the SINTEF).
Table 11.7. Breakdown voltage input data for the application study.

<table>
<thead>
<tr>
<th>Time t [yr]</th>
<th>$U_{bd}(t)$ [kV]</th>
<th>$U_{bd}/U_0(t)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>52.2</td>
<td>3.7672</td>
</tr>
<tr>
<td>$\frac{1}{3}$</td>
<td>64.3</td>
<td>4.6405</td>
</tr>
<tr>
<td>$\frac{1}{2}$</td>
<td>78.5</td>
<td>5.6652</td>
</tr>
</tbody>
</table>

11.8.3 Input data for Modelling the Effect of Rehabilitation

Results from investigations of XLPE cable conditions done at KTH, [126] are presented in terms of normalized breakdown voltage. Normalization implies that the breakdown strength is divided by the RMS value of the phase-to-ground voltage ($U_0$). In the SINTEF study, the rehabilitation was applied to a 24 kV cable that is with phase-to-phase voltage of 24 kV. For a symmetric three phase voltage system, (that is three sinusoidal voltages with a phase angle of 120° between the voltages and with the same peak value compared with ground), the phase-to-phase voltage equals the root square of three times the phase-to-ground voltage. Consequently the resulting normalized breakdown voltage for this study is defined by:

$$U_{bd}/U_0 = \{U_0 = 24/\sqrt{3} kV\} = U_{bd} \cdot \frac{\sqrt{3}}{24} \approx U_{bd}/14. \quad (11.12)$$

The results of the benefit in breakdown voltage shown in the SINTEF study were presented as measurements of the breakdown voltage. Therefore, these results have been evaluated as normalized values for further use in this study. Consequently, data for the defined significant data points (presented in Table 11.6) have been normalized for this application study (see Table 11.7). These data have been used as input data for the benefit of PM in this application study.

The Benefit in breakdown voltage

The benefit in breakdown voltage can be defined by the percentage increase in breakdown voltage, and evaluated as follows:
\[
\Delta U_1 = \left( \frac{100}{U_{bd}/U_0(t = 0)} \right) U_{bd}/U_0(t = 1/3) - 100, \quad (11.13)
\]

and in similar way for the next level of increase (\(\Delta U_2\)). The resulting numerical values for the Cable Application Study are:

\[
\Delta U_1 \approx 23\% \text{ and } \Delta U_2 \approx 22\%. \quad (11.14)
\]

Figure 11.19 shows the resulting benefit in normalized breakdown voltage due to the rehabilitation of XLPE cable.

\[\text{Figure 11.19. Input data for the analysis of the benefit in breakdown voltage due to PM through rehabilitation, using input data based on results from SINTEF.}\]

**Discussion and Validation of Results**

Section 11.8.2 presented a definition of a model for the effect of PM on the breakdown voltage, based on results from a SINTEF study. However, this model included only the time period after about one year following
rehabilitation. These results show that this rehabilitation led to an initial rapid increase in breakdown voltage, which after about a year degraded somewhat.

This information should be related to the previously identified relationships for the cable component over time. Therefore it is of interest to investigate whether or not any knowledge is available about at the time the rehabilitation activity was applied, or the condition of the cable at that time.

The breakdown voltage at the first measuring point could be used for this purpose. This is the point where $U_{50\%} = 52.2$ kV, which equals the normalized breakdown voltage of 3.767. Equation 11.7 gives a point that would agree with a degraded breakdown voltage after about 10 years of operation ($t = (10 - 3.767) \cdot 13/8 \approx 10$ yr).

The corresponding water-tree length could be calculated from previous results as follows: $l = (100/13) \cdot 10 \approx 77\%$ or 4.2 mm. This value could be compared with the statement in the SINTEF report, that the cables put through a test would have water trees of about 95–99\% of the maximum water-three length, which would imply about 12 years of operation in the model developed here. Consequently, there is a difference of about 20\% or 2 years. However given the quite poor availability of data suitable for comparing these results with other sources, and the need to use several heuristic assumptions, differences are not so unexpected. However, the results show that the input data sources are comparative, which indicates that the resulting model could be fairly realistic.

### 11.8.4 Effect of Rehabilitation on Water-tree Length

In the rehabilitation method, the injected silicon penetrates gradually through the insulation with the effect of stopping water-tree growth. However new trees are not prevented from growing. The new water-trees are assumed to start to grow with the same initial behaviour as the previous trees as presented in Section 11.4.1.

Figure 11.20 shows the resulting behaviour of water-tree length before and after cable rehabilitation. The parameter of water-tree length ($l(t)$) is consequently included in the failure rate model in the first and last stages, and with similar characteristics in both of these.
11.8. Modelling the Impact of Rehabilitation Preventive Maintenance

Figure 11.20. Model of water-tree length before and after the rehabilitation at time $t_{PM}$.

11.8.5 Modelling the Effect on the Breakdown Voltage

The rehabilitation process leads to both a stop in water-tree growth as the silicon penetrates through the insulation, as well as an improvement in breakdown voltage.

It could be asked why the breakdown voltage does not reach the values of new cables. Is the rehabilitation process inadequate for this? There seems to be no firm answer to this, and the SINTEF report supports this modelling, showing a certain but limited benefit. Although finding valid or certain answers may not be possible, some indications would still be useful anyway; for example, water trees still exist but are now filled with silicon and so may behave better than water trees otherwise, but not as well as pristine XPLE. However the silicon trees are then prevented from growing further, which causes the failure rate to remain constant until more water trees grow to a substantial size.

After the rehabilitation, new water-trees will start to grow and the breakdown voltage will degrade again because of these. By using some previously
deduced relations between water-tree length and breakdown voltage, a point can be identified where the water trees would contribute to a further reduction in the breakdown voltage.

Based on the previous relationships between breakdown voltage and the effect of the PM through rehabilitation, a resulting function can be defined, built up of six different intervals. The characteristic for the first interval depends on the time that the PM activity is applied. For a useful effect, the PM activity should be applied before the cable reaches the constant low level of breakdown voltage that is during the period with a constant decrease of the function that identifies the first interval. The following two intervals relate to the effect of increased breakdown voltage due to the PM activity within intervals $\Delta t_1$ and $\Delta t_2$ based on SINTEF data. The third interval represents the new level of improved breakdown voltage that becomes constant when the water trees have been filled with silicon. However due to the growth of new water-trees, the breakdown voltage for the cable will continue to decrease when these new water-trees have reached a significant level. Finally, the water tree reaches a maximum level which would result in maximal impact on the breakdown voltage which has then reached its low constant value.

The breakdown voltage is consequently affected by both a benefit from the rehabilitation as well as a decrease due to water trees before and after the maintenance activity. Figure 11.21 shows in detail the different time points and functional relationships required to obtain the resulting function for the breakdown voltage. This includes the time when PM is applied ($t_{PM}$), as well as the measured effect of the PM ($t_1$ and $t_2$). It also includes the equivalent times for obtaining the corresponding voltages of the breakdown voltage ($t_{c1}$ and $t_{c2}$) that are based on the assumption that the cable behaves the same as a new cable with respect to the growth of new water-trees after the PM activity. Finally, Figure 11.22 presents the resulting function for the normalized breakdown voltage in relation to the length of water trees.
11.8. Modelling the Impact of Rehabilitation Preventive Maintenance

Equation 11.15 summarizes the resulting function for the breakdown voltage as follows:

\[
F_{U_{bd/u0}}(t, PM) =
\begin{align*}
&= bd_{\text{max}} - k_{bd} \cdot t \\
&= (bd_{\text{max}} - k_{bd} \cdot t_{PM})(1 + \frac{\Delta U_1}{\Delta t^2} \cdot (t - t_{PM})) \\
&= (bd_{\text{max}} - k_{bd} \cdot t_1)(1 + \frac{\Delta U_2}{\Delta t_2^2} \cdot (t - t_1)) \\
&= bd_{\text{max}} - k_{bd} \cdot t_{c2} \\
&= bd_{\text{max}} - k_{bd} \cdot (t - t_{PM}) \\
&= bd_{\text{min}}
\end{align*}
\]

: \quad t_0 \leq t \leq t_{\text{max}}

: \quad t_{PM} \leq t \leq t_1

: \quad t_1 \leq t \leq t_2

: \quad t_2 \leq t \leq t_3

: \quad t_3 \leq t \leq t_{\text{max}} + t_{PM}

: \quad t_{\text{max}} + t_{PM} \leq t \leq T.

(11.15)

Additional parameters included in the modelling of the impact of the PM have been presented in the following list:

- \( t_{PM} \) is the time when PM is applied,
- \( \Delta U_1 \) and \( \Delta U_2 \) are the benefits gained in normalized breakdown voltage due to the rehabilitation, where 0.23 implies an increase of 23%,
- \( \Delta t_1 \) and \( \Delta t_2 \) are the measuring points for the change in breakdown voltage,
- \( t_1 = t_{PM} + \Delta t_1 \),
- \( t_2 = t_1 + \Delta t_2 \), and
- \( t_3 = b_{\text{max}} - k_{bd} \cdot t_{PM} \), which is the intersection point when the decrease in the breakdown voltage caused by new water-trees reaches the same level as the constant level gained after the rehabilitation.

The input data for this specific study are summarized in Table 11.8, which also defines the values for \( k_{bd}, t_1, t_2, \text{and} t_3 \).

11.8.6 Modelling the Effect on the Failure Rate

New water-trees start to grow just after rehabilitation. However these do not initially lead to cable faults, since the normalized breakdown voltage
Table 11.8. Summary of the input data for the breakdown function for the Cable Application Study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_{max}$</td>
<td>10</td>
<td>KTH</td>
</tr>
<tr>
<td>$b_{min}$</td>
<td>2</td>
<td>KTH</td>
</tr>
<tr>
<td>$t_{max}$</td>
<td>13</td>
<td>KTH and SINTEF</td>
</tr>
<tr>
<td>$\Delta U_1$</td>
<td>23%</td>
<td>SINTEF</td>
</tr>
<tr>
<td>$\Delta U_2$</td>
<td>22%</td>
<td>SINTEF</td>
</tr>
<tr>
<td>$\Delta t_1$</td>
<td>0.33</td>
<td>SINTEF</td>
</tr>
<tr>
<td>$\Delta t_2$</td>
<td>1</td>
<td>SINTEF</td>
</tr>
</tbody>
</table>

Figure 11.21. Time parameters for deducing the effect on breakdown characteristics due to PM through rehabilitation.
(in this example about 10) gives the cable much better characteristics than required to withstand overvoltages (in this example about 5). Therefore the cable faults start to occur first after a time when the water trees have grown a certain length, and the breakdown consequently decreases.

After rehabilitation, the failure rate function over time is assumed to exhibit an equivalent effect as does the breakdown voltage. This is based on the relationships between the parameters illustrated in Figures 11.23 and 11.24.

This means that before the PM activity is applied, the failure function follows the original function, referred to further on as $\lambda_{org}(t)$. This function was presented earlier on in Section 11.3.7, and Equations 11.4 and 11.5. A characteristic for this function is an increased failure rate function due to water-tree length that reaches a maximum value which defines a continued constant rate. Further on when the PM activity is applied, the effect from the rehabilitation is treated in similar way as for the breakdown voltage, which implies that the failure rate is decreasing within the period of $t_1$ and $t_2$, due to the benefits $\Delta U_1$ and $\Delta U_2$. The effect on failure rate due to the

**Figure 11.22.** Model for the normalized breakdown voltage affected by PM through rehabilitation, showing results for $t_{PM} = 11$. 

[Graph showing normalized breakdown voltage vs. time]
11.8. Modelling the Impact of Rehabilitation Preventive Maintenance 264

PM activity is defined based on relationships between breakdown voltage and failure rate over time deduced earlier.

The corresponding time for the function to reach the same value before PM was decided for the new breakdown voltage values. This time is referred to as an equivalent time. Based on the SINTEF data there are two such times: $t_{e1}$ and $t_{e2}$. The corresponding failure rates at these times have been defined. A linear relationship has been assumed between the time period $\Delta t_1$ and $\Delta t_2$ as for the breakdown voltage. However it should be noted that as previously described, the failure rate function defined follows a polynomial function rather than a linear one. Therefore, the function defined includes the assumption that the change in the failure rate within these points can be assumed to be linear. The difference in numerical values by using either of these functions interpolated between the equivalent times would be very small. Therefore the conclusion is that the simplified function can be justifiably used for convenience.

Due to the growth of new water-trees, the failure rate will increase again. This effect begins at the point $t_3$ when the effect of the new water-trees on the failure rate becomes predominant on the overall failure rate for the cable. Consequently, this function ($\lambda(t, PM)$) can be formulated for five different periods as presented below.

The resulting failure rate function in response to rehabilitation is consequently affected by both an increase in breakdown voltage (due to the PM which stop the growth of the existing water-trees), and (ii) an increase in water trees before and after the maintenance activity. The following formula summarizes the function:

$$
\lambda(t, PM) = \begin{cases} 
\lambda(t) & : t_0 \leq t \leq t_{PM} \\
\frac{\lambda(t_{PM}) - \lambda(t_{e1})}{\Delta t_1} (t - t_{PM}) & : t_{PM} \leq t \leq t_{1} \\
\frac{\lambda(t_{e1}) - \lambda(t_{e2})}{\Delta t_2} (t - t_{e1}) & : t_{1} \leq t \leq t_{2} \\
\lambda(t_{e2}) & : t_{2} \leq t \leq t_{3} \\
\lambda(t_{e2} + t) & : t_{3} \leq t \leq T.
\end{cases}
$$

(11.16)

Figures 11.23 shows in detail the approach used for defining the failure rate with the benefit due to the rehabilitation. It specifically illustrates the different time points and corresponding function values.
Finally, Figure 11.24 presents the resulting failure rate function in an XLPE cable affected by and rehabilitated from water-tree growth.

![Graph showing failure rate function](image)

**Figure 11.23.** Time parameters for deducing the effect on the failure rate function of PM through rehabilitation, using the results for $t_{PM} = 11$.

The Effect of Rehabilitation on the Loss Parameter

The last parameter to define here is the non-linear loss parameter. Section 11.6.2 defined a relationship for the non-linear loss parameter as a function of time ($\Delta e''(t)$). Furthermore, this function was defined based on results relating the loss parameter to the breakdown voltage.

If the same relationship between the non-linear loss parameter and the breakdown voltage is assumed to hold before as well as after the PM rehabilitation, then the resulting relationship for the non-linear loss parameter including the effect of rehabilitation could be obtained. However, there are no available data to support this assumption, and it does not seem reasonable to make this assumption either, since the cable condition changes as a result of the rehabilitation, and a new characteristic would be expected for the loss parameter.
11.8. Modelling the Impact of Rehabilitation Preventive Maintenance

![Graph showing failure rate function affected by PM through rehabilitation, using the results for $t_{PM} = 11$.](image)

**Figure 11.24.** Model of the failure rate function affected by PM through rehabilitation, using the results for $t_{PM} = 11$.

Nevertheless, it is appropriate to note the following. Firstly, the loss parameter could be used primarily to define the point in time to apply the PM action, and secondly it should be possible to measure the effect of PM on the loss parameter to define a relationship if needed. In this model, it is suggested that the non-linear loss parameter can be used for defining when to apply the activity. It would therefore support in defining maintenance strategies.

### 11.8.7 Resulting Model of the Rehabilitated Cable Component Affected by Water Treeing

Figure 11.25 presents the resulting functions for the three variables, $\lambda(t)$, $l(t)$ and $U_{bd}/U_0$, that characterize the behaviour of the XLPE cable component. The resulting model relates the failure rate to the effect of the PM activity applied to prevent water-tree growth in an average XLPE cable.
Figure 11.25. The resulting relationships for an XLPE cable component defining a model of $\lambda(t, PM)$.

11.9 Modelling the Impact of Preventive Maintenance by Replacement

11.9.1 Introduction

In this section, an alternative PM method to rehabilitation has been studied that involves replacement of the cable component. This situation is used for example if a population of cables is to be replaced, but due to limits in expenses and the impact on system function, they must be replaced at various times during an investment period. Consequently, this step in the modelling procedure is an extension of the previously defined functions for component behaviour including the effect of PM by replacement.

11.9.2 Assumption and Validation

It is assumed that the PM activity of replacement implies that the cable component behaves the same way as a new component after
11.9. Modelling the Impact of Preventive Maintenance by Replacement

the replacement.

This assumption implies that the component behavior including the effect of PM by replacement results in function characteristics like those for cable-aging summarized in Section 11.12. Consequently, this assumption has produced a simple and straightforward solution for this step of the modelling. However in model validation it should be asked whether or not this assumption is reasonable.

The practical implication of the assumption is that the replaced cable (the new cable) has the same behaviour as the old cable originally did. However this would not be the case in reality for an XLPE cable, as the problem with water treeing occurred primarily in the cables produced in the mid 1970s. If those cables are replaced with a cable produced today, the same water-tree development phenomenon would not appear. On the other hand, for other types of components such as overhead lines or transformers, the new component would be expected to closely resemble the old component. Consequently the assumption is justified keeping in mind that the application study is being done with the primary objective of showing how the modelling can be realized rather than defining the true model for this specific case.

Another aspect that justifies the assumption is that it allows for the so-called worst case, since the new XPLE cables are less prone to failure caused by the water-tree phenomenon than the old cables. Therefore with this assumption, the failure rate function is expected to have worse component characteristics and consequently the benefit of replacement would represent a worst case situation.

The conclusion is consequently that the assumption made for the effect on component behaviour by replacement is valid, and should produce results with a pessimistic view of the benefit from the PM activity.

Figures 11.26 and 11.27 show the results for the XLPE cable component using this model in the cable application example.

11.9.3 Modelling the Effect of Preventive Maintenance

The effect of PM by replacement of a cable system component has been analyzed with the same procedure as for PM by rehabilitation. Figures 11.28 and 11.29 show the results of the functions for the breakdown voltage
Figure 11.26. Effect of the replacement of a cable system component on the breakdown voltage.

Figure 11.27. Effect of the replacement of a cable system component on the failure rate.
and the failure rate. As expected, the water-tree length determines these characteristics.

Figure 11.28. The effect of the replacement of a cable system component on breakdown voltage and water-tree length.

Figure 11.30 shows the resulting model for failure rate when the XLPE cable component undergoes PM by replacement.

11.10 The Effect of Different Preventive Maintenance Plans

In the previous sections, the impact of PM by either rehabilitation or replacement has been modelled. However, one effect that has not yet been introduced is when to apply the PM activity.

The point in time when PM is applied is crucial to the maintenance planning and strategy definitions. These issues are considered in detail in the next Chapter 12. However, in this section the various effects of PM have been analyzed in respect to when the PM effort is applied. The results have
Figure 11.29. Effect of the replacement of a cable system component on failure rate and water-tree length.

Figure 11.30. Resulting failure rate model with the effect of preventive maintenance by replacement.
been shown for the Cable Application Study. A specific maintenance plan has also been defined and used for the analysis in the next chapter.

### 11.10.1 The Effect of Applying Rehabilitation at Different Times

Figure 11.31 demonstrates the impact of PM on the breakdown voltage and the failure rate function depending on when the PM activity is applied. The results are shown for PM applied within the period 6-13 years.

It can be seen that the resulting benefit on failure rate that is gained by the PM action varies according to when the PM measure is applied. If it is applied too early or too late, then the benefit gained can be limited. This has been highlighted by looking at the functions when PM is applied after 9, 11 and 12 years. These three PM occasions are spread within the period where PM has a relatively significant effect on the failure rate.

In the Cable Application Study a maintenance plan where PM is applied on three occasions at years 9, 11, and 12 has been considered in the following analysis of PM times.

**Figure 11.31.** Impact on the breakdown voltage and failure rate of applying PM at different times.
Further analysis focuses on these three PM occasions. Figures 11.32 and 11.33 illustrate the results for the breakdown voltage and failure rate when PM is applied in these three different years. The figures show the different effects of the PM activity.

![Figure 11.32. Effect of rehabilitation of a cable system component on the breakdown voltage.](image)

### 11.10.2 The Effect of Applying Replacement at Different Times

In the same way as for the rehabilitation, the effect of applying replacement at different times has also been analyzed. Figure 11.34 shows the results for the cable system component. Furthermore, the plan for applying PM at years 9, 11 and 12 has been analyzed. The results from this analysis are presented in Figure 11.35 for the breakdown voltage and in Figure 11.36 for the failure rate.
11.10. The Effect of Different Preventive Maintenance Plans

![Graph of failure rate over time]

**Figure 11.33.** Effect of rehabilitation of a cable system component on the failure rate.

![Graph of failure rate over time]

**Figure 11.34.** Effect on failure rate caused by cable system component replacement at different years.
Figure 11.35. Effect on the breakdown voltage function caused by cable system component replacement at three different points in time.

Figure 11.36. Effect on the failure rate function caused by cable system component replacement at three different points in time.
11.10.3 Modelling Corrective Maintenance

The work presented in this thesis focuses on the modelling of PM. However to capture the effect of PM and to enable the defining of a PM strategy, the alternative to PM (which is to correct failures by corrective maintenance or CM) should be addressed in the model.

One of the fundamental differences between PM and CM is that CM is an activity undertaken as a result of a random process the occurrences of failures. This is contrary to PM, which is performed at certain defined points in time. Traditionally, these time points were at predefined intervals. This work suggests however that CM measures should be related to the actual condition and reliability of the components.

As the main focus of this work is not on developing theory for modelling CM, the following simple assumptions have been made. It has been assumed that CM restores the component after failure, and that the component behaviour after the CM activity is the same as the time just before the failure occurred.

CM will be included in the model based on this assumption without introducing any more complications into the model. However the different effects of CM should be discussed along with the basis for making the assumption above.

The alternative effects of CM are that it either improves the cable behaviour, reduces it, or it restores it to what it was before. Consequently, the assumption made follows the last of these three.

It could be argued that one or another assumption is more possible, however investigating this falls outside the scope of this work. Briefly, it could be said that if the cable is assumed to be improved by CM, then one possible model would be to assume, in the same way as for replacement, that the cable would then become as good as new. Instead of assuming there would be no effect on the component behaviour, this would give an optimistic model showing that CM is as good as replacement, which seems unreasonable. On the other hand, if it is assumed that the CM worsens the component behaviour after the restoration, then a very pessimistic view of the effect of CM is captured. For some circumstances, it is arguable that the best effect is not to do any PM at all, such as shown in Chapter 8, where it can be argued that an un-maintained cable has the longest lifetime. However
generally, maintenance has been demonstrated to have a positive effect on component lifetime, and therefore there is no reason not to incorporate such an aspect into the limited scope for modelling CM.

The conclusion is consequently that the assumption made is valid for a simple model of CM that would produce results with a pessimistic rather than optimist outcome (compared with if the behaviour was improved by the CM activity).

There is one further aspect of importance to consider, that the different component types in the distribution system can be as either, (i) discrete components like transformers, breakers and so on, or (ii) lines and cables which are considered in units of length. This difference in component types could impact on the above statement about the effect of CM. For CM of feeders (lines or cables) it is most probable that just a part of the length is effected by the CM measure. Therefore, it would be reasonable not to assume that the component is as good as new after the CM. However, considering for example a breaker, it is more reasonable to assume that the component would behave like new after a CM measure. The conclusion is consequently that the treatment by CM should be evaluated depending on the type of component that is considered.

11.11 Comparison Between Preventive Maintenance Methods

This chapter deduces relationships to support functions for failure rate due to failures caused by water-tree growth in a cable system component. For the Cable Application Study these functions include the effect of applying PM either by rehabilitation (injection of silicon $PM_{si}$) or replacement ($PM_{rp}$) of cable. CM has also been considered leading to a restoration result where there is no effect on the failure rate.

Tables 11.9 - 11.11 present results for the three following resultant functions.

1. Water-tree growth in the cable is left as it is, as an aging process denoted by $\lambda_{d,t}(t)$.

2. PM is applied by rehabilitation and denoted by $\lambda_{PM_{si}}(t)$.
3. PM is applied by replacement, and denoted by $\lambda_{PM_P}(t)$.

Note that the values in the tables are presented for integer values of time (selected function values for complete years).

The first function refers to the aging process in the cable resulting from water-tree effects impacting on the failure rate with no impact of maintenance. The two following functions represent the results of applying PM either by rehabilitation or replacement. The CM as described above would follow the first of the three functions, that is have no impact on the failure rate.

Figure 11.37 compares the two different PM activities that have been studied. Three different characteristics for the failure rate function have been shown: (i) without maintenance, (ii) with maintenance by rehabilitation, and (iii) maintenance by replacement. The results are shown for PM applied after 11 years. The three functions have similar initial and final behaviours. When PM is applied, the failure rate either drops down to an initial growth rate for the replacement case, or shows a decreased drop in the rehabilitation case.

It is understood that benefit by rehabilitation would change with the time of maintenance application, and furthermore that there is a period after Year 6 and before Year 13, within which a benefit would be gained. Figure 11.38 shows the results when the time for the maintenance activity is changed between Years 8-13. On the one hand, it can be seen that the benefit for the rehabilitation is not significant if applied too early or too late. On the other hand, it can be seen that the benefit for the replacement is proportional to when the measure is undertaken, since the effect is always that the failure rate is set to zero. This issue of comparing the effect of different maintenance methods is further analyzed in Chapter 12, the system and cost benefit analysis.

This summary presents the final results of this chapter, which serve as input data for the proceeding analysis. In the next chapter the model developed ($\lambda(t, PM)$) has been used to predict the behaviour of an average cable as one component in a distribution system.

In the validation of the model implemented here, some calculations had to be made by hand. Tables 11.9 to 11.11 present time parameters which determine the deduction of the failure rate functions due to rehabilitation. For correctness of the results the following should be valid:
11.11. Comparison Between Preventive Maintenance Methods

**Figure 11.37.** Benefit to failure rate of preventive maintenance by either replacement or rehabilitation of the cable component.

**Figure 11.38.** Comparison of the benefit to failure rate of preventive maintenance by either replacement or rehabilitation of the cable component.
### Table 11.9. Result for the $\lambda(t, PM)$ model of a cable system component with PM applied at Year 9.

<table>
<thead>
<tr>
<th>Time [yr]</th>
<th>$\lambda_{old}(t)$ [$/100$ km and yr]</th>
<th>$\lambda_{PMa}(t, t_{PM} = 9)$ [$/100$ km and yr]</th>
<th>$\lambda_{PMa}(t, t_{PM} = 9)$ [$/100$ km and yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>1</td>
<td>0.0030</td>
<td>0.0188</td>
<td>0.0188</td>
</tr>
<tr>
<td>2</td>
<td>0.0188</td>
<td>0.0453</td>
<td>0.0453</td>
</tr>
<tr>
<td>3</td>
<td>0.0860</td>
<td>0.1437</td>
<td>0.1437</td>
</tr>
<tr>
<td>5</td>
<td>0.2200</td>
<td>0.2200</td>
<td>0.2200</td>
</tr>
<tr>
<td>7</td>
<td>0.3168</td>
<td>0.4361</td>
<td>0.4361</td>
</tr>
<tr>
<td>9*</td>
<td>0.5809</td>
<td>0.7558</td>
<td>0.0030</td>
</tr>
<tr>
<td>10</td>
<td>0.5809</td>
<td>0.9676</td>
<td>0.1631</td>
</tr>
<tr>
<td>12</td>
<td>1.2254</td>
<td>1.5418</td>
<td>0.1437</td>
</tr>
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<td>15</td>
<td>1.5418</td>
<td>1.5418</td>
<td>0.2200</td>
</tr>
<tr>
<td>16</td>
<td>1.5418</td>
<td>0.3168</td>
<td>0.3168</td>
</tr>
<tr>
<td>17</td>
<td>1.5418</td>
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<td>0.4361</td>
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<tr>
<td>18</td>
<td>1.5418</td>
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<tr>
<td>19</td>
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<td>0.7558</td>
</tr>
<tr>
<td>20</td>
<td>1.5418</td>
<td>0.9676</td>
<td>0.9676</td>
</tr>
<tr>
<td>21</td>
<td>1.5418</td>
<td>1.2254</td>
<td>1.2254</td>
</tr>
<tr>
<td>22*</td>
<td>1.5418</td>
<td>1.5418</td>
<td>1.5418</td>
</tr>
<tr>
<td>23</td>
<td>1.5418</td>
<td>1.5418</td>
<td>1.5418</td>
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<tr>
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<td>1.5418</td>
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</tr>
<tr>
<td>30</td>
<td>1.5418</td>
<td>1.5418</td>
<td>1.5418</td>
</tr>
</tbody>
</table>

Special time points:

- $t_{c2} = 5.28$ 0.1631 0.1631 0.1631
- $t_{c1} = 7.33$ 0.3535 0.3535 0.3535
- $t_1 = 9.33$ 0.6350 0.3535 0.0000
- $t_2 = 10.33$ 0.8213 0.1631 0.0073
- $t_3 = 14.28$ 1.5418 0.1631 0.1631
Table 11.10. Result for the $\lambda(t, PM)$ model for a cable system component with PM applied at Year 11.

<table>
<thead>
<tr>
<th>Time [yr]</th>
<th>$\lambda_{dd}(t)$ [f/100 km and yr]</th>
<th>$\lambda_{PM_s}(t, t_{PM} = 11)$ [f/100 km and yr]</th>
<th>$\lambda_{PM_p}(t, t_{PM} = 11)$ [f/100 km and yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>1</td>
<td>0.0030</td>
<td>0.0030</td>
<td>0.0030</td>
</tr>
<tr>
<td>2</td>
<td>0.0188</td>
<td>0.0188</td>
<td>0.0188</td>
</tr>
<tr>
<td>3</td>
<td>0.0453</td>
<td>0.0453</td>
<td>0.0453</td>
</tr>
<tr>
<td>4</td>
<td>0.0860</td>
<td>0.0860</td>
<td>0.0860</td>
</tr>
<tr>
<td>5</td>
<td>0.1437</td>
<td>0.1437</td>
<td>0.1437</td>
</tr>
<tr>
<td>6</td>
<td>0.2200</td>
<td>0.2200</td>
<td>0.2200</td>
</tr>
<tr>
<td>7</td>
<td>0.3168</td>
<td>0.3168</td>
<td>0.3168</td>
</tr>
<tr>
<td>8</td>
<td>0.4361</td>
<td>0.4361</td>
<td>0.4361</td>
</tr>
<tr>
<td>9</td>
<td>0.5809</td>
<td>0.5809</td>
<td>0.5809</td>
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<tr>
<td>10</td>
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<td>0.7558</td>
<td>0.7558</td>
</tr>
<tr>
<td>11*</td>
<td>0.9676</td>
<td>0.9676</td>
<td>0.0000</td>
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<tr>
<td>12</td>
<td>1.2254</td>
<td>0.5568</td>
<td>0.0030</td>
</tr>
<tr>
<td>13</td>
<td>1.5418</td>
<td>0.4780</td>
<td>0.0189</td>
</tr>
<tr>
<td>14</td>
<td>1.5418</td>
<td>0.4780</td>
<td>0.0453</td>
</tr>
<tr>
<td>15</td>
<td>1.5418</td>
<td>0.4780</td>
<td>0.0860</td>
</tr>
<tr>
<td>16</td>
<td>1.5418</td>
<td>0.4780</td>
<td>0.1437</td>
</tr>
<tr>
<td>17</td>
<td>1.5418</td>
<td>0.4780</td>
<td>0.2200</td>
</tr>
<tr>
<td>18</td>
<td>1.5418</td>
<td>0.4780</td>
<td>0.3168</td>
</tr>
<tr>
<td>19</td>
<td>1.5418</td>
<td>0.4780</td>
<td>0.4361</td>
</tr>
<tr>
<td>20</td>
<td>1.5418</td>
<td>0.5809</td>
<td>0.5809</td>
</tr>
<tr>
<td>21</td>
<td>1.5418</td>
<td>0.7558</td>
<td>0.7558</td>
</tr>
<tr>
<td>22</td>
<td>1.5418</td>
<td>0.9676</td>
<td>0.9676</td>
</tr>
<tr>
<td>23</td>
<td>1.5418</td>
<td>1.2254</td>
<td>1.2254</td>
</tr>
<tr>
<td>24*</td>
<td>1.5418</td>
<td>1.5418</td>
<td>1.5418</td>
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<tr>
<td>25</td>
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</tr>
<tr>
<td>30</td>
<td>1.5418</td>
<td>1.5418</td>
<td>1.5418</td>
</tr>
</tbody>
</table>

Special time points:
- $t_{c2} = 8.31$
- $t_{e1} = 9.79$
- $t_1 = 11.33$
- $t_2 = 12.33$
- $t_3 = 19.31$
### Table 11.11. Result for the $\lambda(t, PM)$ model of a cable system component with PM applied at Year 12.

<table>
<thead>
<tr>
<th>Time [yr]</th>
<th>$\lambda_{old}(t)$ [$/100$ km and yr]</th>
<th>$\lambda_{PM,t}(t, t_{PM} = 12)$ [$/100$ km and yr]</th>
<th>$\lambda_{PM,(t,t_{PM} = 12)}$ [$/100$ km and yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>1</td>
<td>0.0030</td>
<td>0.0030</td>
<td>0.0030</td>
</tr>
<tr>
<td>2</td>
<td>0.0188</td>
<td>0.0188</td>
<td>0.0188</td>
</tr>
<tr>
<td>3</td>
<td>0.0453</td>
<td>0.0453</td>
<td>0.0453</td>
</tr>
<tr>
<td>4</td>
<td>0.0860</td>
<td>0.0860</td>
<td>0.0860</td>
</tr>
<tr>
<td>5</td>
<td>0.1437</td>
<td>0.1437</td>
<td>0.1437</td>
</tr>
<tr>
<td>6</td>
<td>0.2200</td>
<td>0.2200</td>
<td>0.2200</td>
</tr>
<tr>
<td>7</td>
<td>0.3168</td>
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<td>0.3168</td>
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<tr>
<td>8</td>
<td>0.4361</td>
<td>0.4361</td>
<td>0.4361</td>
</tr>
<tr>
<td>9</td>
<td>0.5809</td>
<td>0.5809</td>
<td>0.5809</td>
</tr>
<tr>
<td>10</td>
<td>0.7558</td>
<td>0.7558</td>
<td>0.7558</td>
</tr>
<tr>
<td>11</td>
<td>0.9676</td>
<td>0.9676</td>
<td>0.9676</td>
</tr>
<tr>
<td>12*</td>
<td>1.2254</td>
<td>1.2254</td>
<td>0.0000</td>
</tr>
<tr>
<td>13</td>
<td>1.5418</td>
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<td>0.0030</td>
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<td>14</td>
<td>1.5418</td>
<td>0.7219</td>
<td>0.0188</td>
</tr>
<tr>
<td>15</td>
<td>1.5418</td>
<td>0.7219</td>
<td>0.0453</td>
</tr>
<tr>
<td>16</td>
<td>1.5418</td>
<td>0.7219</td>
<td>0.0860</td>
</tr>
<tr>
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<td>1.5418</td>
<td>0.7219</td>
<td>0.1437</td>
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<td>0.7219</td>
<td>0.2200</td>
</tr>
<tr>
<td>19</td>
<td>1.5418</td>
<td>0.7219</td>
<td>0.3168</td>
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<tr>
<td>20</td>
<td>1.5418</td>
<td>0.7219</td>
<td>0.4361</td>
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<tr>
<td>21</td>
<td>1.5418</td>
<td>0.7219</td>
<td>0.5809</td>
</tr>
<tr>
<td>22</td>
<td>1.5418</td>
<td>0.7558</td>
<td>0.7558</td>
</tr>
<tr>
<td>23</td>
<td>1.5418</td>
<td>0.9676</td>
<td>0.9676</td>
</tr>
<tr>
<td>24</td>
<td>1.5418</td>
<td>1.2254</td>
<td>1.2254</td>
</tr>
<tr>
<td>25*</td>
<td>1.5418</td>
<td>1.5418</td>
<td>1.5418</td>
</tr>
<tr>
<td>26</td>
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<tr>
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<td>1.5418</td>
<td>1.5418</td>
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<tr>
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<td>1.5418</td>
<td>1.5418</td>
<td>1.5418</td>
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<tr>
<td>30</td>
<td>1.5418</td>
<td>1.5418</td>
<td>1.5418</td>
</tr>
</tbody>
</table>

Special time points:

- $t_{e2} = 9.82$  
- $t_{e1} = 11.02$  
- $t_1 = 12.33$  
- $t_2 = 13.33$  
- $t_3 = 21.82$
\[ \lambda_{PM_i}(t_1) \leftrightarrow \lambda_{old}(t_{c1}) \]
\[ \lambda_{PM_i}(t_2) \leftrightarrow \lambda_{old}(t_{c2}) \]
\[ \lambda_{PM_i}(t_3) \leftrightarrow \lambda_{old}(t_{c2}) \leftrightarrow \lambda_{PM_{r_{3}}(t_3)}. \]

It is interesting to note that the last of these relations (Equation 11.17) states that the failure rate function due to rehabilitation intersects the failure rate function due to replacement at a specific point \( t_3 \). This time parameter varies depending on when the PM action is applied.

The following assumption was made in the model: \( \max(\lambda_{old}(t)) = \lambda_{old}(t = 13.00) \). This leads to: \( \max(\lambda_{PM_{r_{3}}(t)}) = \lambda_{PM_{r_{3}}(t = 13 + t_{PM})} \). Since the rehabilitation process results in a failure rate that terminates into the same function as for the replacement situation, then the maximum value is equal and: \( \max(\lambda_{PM_i}(t)) = \lambda_{PM_i}(t = 13 + t_{PM}) \). The maximum values for the failure rate function should therefore for the cases with \( t_{PM} = 9, 11 \) and 12, be \( t = 22, 24 \) and 25 respectively, which is supported by the results presented in Tables 11.9 to 11.11.

### 11.12 Remarks about the Implementation of the Model

The model developed for the failure rate effected by PM has been implemented in the Cable Application Study. This has been done using the programming tool MATLAB, which was introduced in Section 6.3. A summary of the input data files and used is provided in Appendix C.
Chapter 12

System Analyses for Various Maintenance Strategies

This chapter relates to the RCM procedures of estimation of composite failure rate, sensitivity analysis and cost and benefit analysis as presented in Table 6.1. The objective of the work relates to defining effective maintenance strategies focusing on preventive maintenance (PM) and reliability. Therefore, the scope of the financial analysis is the comparison of PM methods including the possibility of performing no PM, that is only corrective maintenance (CM).

12.1 Introduction

The previous chapter presented procedures developed for modelling component behaviour that define a qualitative relationship between PM and reliability performance. Furthermore this was illustrated by studying a specific component the XLPE cable component affected by water treeing. However, this model relates to one failure cause only for the cable component. Consequently, the result from Chapter 11 provides a model of the failure rate behaviour of one component (XLPE cable) and one cause of failure (water treeing).

In this chapter the model developed for the failure rate has been extended to include a system perspective. The purpose here is to achieve a model...
12.1. Introduction

that can be used to analyse the effect of preventing failures in the included components at the system level. Furthermore, the aim has been to define effective maintenance strategies, which means that system analysis should also consider when it is the best time for performing the PM activities, and on which components. Due to limitations in cost and system requirements, PM is applied to certain components at a time, and within a given time period it is not automatic that all components will be exposed to PM.

The above discussion has introduced several complications to the analysis of the effect of PM on the system. Consequently, before a system effect analysis can be performed, there are several issues that must be solved, and two of these can be summarized as follows. Firstly, the component has to be modelled as part of a system which can be done by introducing the concept of an average component. Secondly, the composite failure rate has to be modelled for an average component, which is the failure rate due to all causes of failures.

Similar to as in the previous chapter, the theory developed is presented by using an application study. To enable the system effect analysis to be performed, input data is required for both a system as well as its included components.

In earlier chapters, a detailed analysis of the Birka system was presented by both analysis of the causes of failures for the 11 kV cable component (Chapter 8), and by reliability analysis (Chapter 10). Consequently, the analysis of the Birka system performed together with the model for the cable component behaviour developed in Chapter 11 constitute the required input data for the analysis of the system effects and maintenance strategies in this chapter.

The following sections present all these issues in greater detail by, on the one hand introducing the concepts of maintenance strategies, average cables and composite failure rate, and on the other hand by illustrating the application to the cable component as part of the Birka system and with results for reliability indices from RADPOW. Finally, a cost and benefit analysis is performed to achieve the solution that is the cost effective maintenance strategy.
12.2 Input Data for the System Effect Analysis

12.2.1 Birka Liljeholmen System

Both the Birka and the Liljeholmen 11 kV stations have been presented and analysed earlier, firstly by a study of the statistics and practices (in Chapter 8), and secondly by a system effect analysis with Approach I (in Chapter 10). The focus for the Birka system analysis in this chapter is on the effect of PM applied to the 11 kV cable component. Furthermore, these 11 kV cables were represented in the reliability network as being of the one average cable type and laid in parallel.

The RADPOW input data for the Birka system analysis are the same as those used for the system analysis presented earlier. The component reliability input data for analysing the system with RADPOW are presented in Section 10.3.5 and Tables 10.13 and 10.14. These data represent the base case for the Birka system, which is the data set that is being varied for different cases in the sensitivity analysis. The input reliability data that are effected in the system analysis for the Cable Application Study are the failure rate for the average 11 kV cable. The cable used here (LH11) is defined by the average failure rate and average length as follows:

\[
\begin{align*}
\lambda_{LH11} & = 0.10069 \ [f/yr] \quad \text{with} \\
l_{av} & = 8.10584 \ [km]
\end{align*}
\] (12.1)

Furthermore, Table 12.1 presents the resulting output data from the RADPOW analysis for the base case. This provides reliability load point indices as well as different system performance indices. In the Cable Application Study, the impact of PM on the 11 kV cable has been analysed. However, for the Birka system, there is only one load point at this voltage level, called Load Point 1, Lp1 or LH11, since it is this load point that is connected to the Liljeholmen Station (LH).

12.2.2 Failure Rate Functions for XLPE Cable Component

Failure rate functions for an XLPE cable component were modelled in Chapter 11. Furthermore, functions for the PM regime applied after 9, 11 and 12 years were defined. Function values for the beginning of each year are
presented in Tables 11.9 and 11.11. These tables present results for three different failure rate functions, firstly due to aging \( \lambda_{dd}(t) \), secondly and thirdly due to the impact of PM using either the rehabilitation method \( \lambda_{PMi}(t, t_{PM}) \) or the replacement method \( \lambda_{PMr}(t, t_{PM}) \).

Figure 12.1 illustrates these failure rate functions with the three PM measures: \( t_{PM1} = 9 \), \( t_{PM2} = 11 \) and \( t_{PM3} = 12 \). For all these functions the failure rate lies in the interval \([0, 1.5418] \, f/100 \, km \) and \( yr = [0, 0.015418] \, f/yr \) and km.

Note that these failure rate functions refer to failures due only to water treeing. Therefore, a general description of the failure rate functions of \( \lambda_{wt}(t) \) [f/yr] has been defined as follows. The input data for the Birka system analysis presented in Section 12.2.1 used the unit for failure rate of failures per year. Moreover, the average cable length for the 11 kV cable shown in Equation 12.1 is 8.10584 km. If the failure rate functions discussed above are transformed into an equivalent unit, the following corresponding interval is achieved:

\[
\lambda_{wt}(t) \subseteq [0, 0.12579] \quad [f/yr]
\]

(12.2)

where 0.12579 \( \approx (1.5418 \times 8.1584)/100 \). This failure rate represents an XLPE cable that is affected by water treeing and has a length of about 8.106 km.

**Table 12.1.** Evaluated reliability indices for the Birka system base case.

<table>
<thead>
<tr>
<th>Load point</th>
<th>( \lambda ) [f/yr]</th>
<th>( U ) [h/yr]</th>
<th>( r ) [h/f]</th>
<th>( L ) [kW]</th>
<th>( LOE ) [kWh/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH11</td>
<td>0.334494</td>
<td>0.506714</td>
<td>1.51487</td>
<td>768.974</td>
<td>389.65</td>
</tr>
<tr>
<td>HD</td>
<td>0.111307</td>
<td>0.133388</td>
<td>1.19837</td>
<td>22999.9</td>
<td>3067.9</td>
</tr>
<tr>
<td>SJ</td>
<td>0.110706</td>
<td>0.150543</td>
<td>1.35984</td>
<td>0.8</td>
<td>0.120434</td>
</tr>
<tr>
<td>SAIFI</td>
<td>0.115491</td>
<td>[int/yr,cust.]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAIDI</td>
<td>1.21556</td>
<td>[h/int.]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAI = 0.114036 [h/yr,cust.]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AENS = 0.144988 [kWh/yr,cust.]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 12.1. Resulting failure rate functions for the cable component for three maintenance plans: $t_{PM1} = 9$, $t_{PM2} = 11$, and $t_{PM3} = 12$. 
12.2.3 Validation of the Combination of Input Data

Two different sources of data and relationships have been deduced which both relate to the cable component behaviour. First of all a model of the failure rate characteristics due to a specific failure cause and a model of PM for the same have been modelled. Secondly, a system cable component (the average 11 kV cable) has been analysed in great detail for the Birka System. The combination of these two modelling efforts results in realizing a complete RCM study. However before realizing this, it must be clear that the data are compatible, which is discussed in this section. The purpose of this is to justify that the output result not only provides an illustration but also a relevant analysis.

The input data for the system-effect analysis comes from the following.

1. The failure rate model for a component affected by water treeing, based on Svel data:
   \[ \lambda_{wt} \subseteq [0, 0.015418] \text{ [f/yr.km]} \] (from Chapter 11).

2. Birka system 11kV cable based on Birka data:
   \[ \lambda_{LH11} \approx 0.0124 \text{ [f/yr.km]} \] (from Equation 12.1).

Consequently, the contribution of water-treeing failures to total failures corresponds to a failure rate increase of more than about 100%. To verify whether this is reasonable or not, the two different data sources should be studied in greater depth.

1. Svel report data analysis
   This data refers to XLPE cables for 12kV and higher. Most quantities refer to 12kV and 24 kV, and further details are not provided in the report.
   The data used from the Svel report are data for the population of cables without an extruded layer put into operation 1970-1975, and have a total length 1800 km. Within the years 1975-1988 these cables fail 175 times = \( 175/(14 \cdot 1800) \approx 0.00694 \text{ f/yr and km} \); or for the total population of cables with an aging time of 13 years (cable put into operation 1970, which includes failures occurring between 1970-1983), \( 114/(13 \cdot 1800) \approx 0.0045 \text{ f/yr and km} \).
Furthermore the Svel report indicates that an XLPE cable with an
extruded layer should have about 0.0003 f/yr and km, and that the
average failure rate for XLPE cables in Sweden (mixture of XLPE
types) is about 0.003 f/yr and km.

2. 11kV data
The Birka 11 kV data includes a mixture of cable types and ages with
the failure rate 0.01242 f/yr and km.

Other sources of cable statistics (this is discussed the report Causes
of failures) show values of 0.05 f/yr and km in Norway (1967-1983 1-
380 kV) Svel 0.03 f/yr and km (11 kV 1995-1997) 0.02 f/yr and km
mass-impregnated cable (Norway).

From the above comparison of data it can be concluded that the failure
rate data for the 11 kV cable are higher than the data for the general XLPE
cable not exposed to water trees. This result is expected since more failures
tend to occur at lower voltage levels. However, the question was whether
the relationship between $\lambda_{w}(t)$ and $\lambda_{L11}$ was reasonable. It is difficult
to answer this, but the observations made indicate that the relationship is
reasonable, and that the difference was expected to be larger.

Conclusion

The conclusion is therefore that it is reasonable to assume that the two
data sources agree for time zero, which is before the water trees have any
impact on the failure rate. This model is supported by the interviews and
discussions with maintenance personnel about the 11 kV Birka cables where
it is not identified that water-tree growth is an actual problem at this point.

Remarks

A further comment about the input data relates to the detailed knowledge
gained about failure causes for the Birka 11 kV cables. The statistical data
analysis of Birka data shows the result that the maximal contribution from
water trees (failures due to material and method) is 14%.
12.2. Input Data for the System Effect Analysis

This figure (14% of 0.1007 f/yr) equals 0.01410 f/yr which implies 0.00174 f/yr and km. It is interesting to compare this number with the failure rate model. It can be seen that it would correspond to the time between zero and one year of water-tree growth. Consequently, the assumption to superpose the two data sources at time zero is validated.

12.2.4 Loss Parameter for Supporting Maintenance Strategy

The linear loss parameter ($\Delta'' \epsilon$) was introduced in Chapter 9. Furthermore, in Chapter 11 it was identified to be useful for defining the condition of the cable that in turn was transformed into a relation for the failure rate of the cable. The benefit with using this parameter is that it can be measured without destroying the sample material, which is not the case for the alternative method of breakdown strength.

The cable condition can therefore be measured by using the loss parameter. Results from such measurements enable distinguishing between those cables that have a better or a worse condition than an average cable. Moreover, this would support obtaining:

- a ranking of cables based on cable condition, which would define which cables to apply the PM activity to, and

- a criteria for when a PM activity should be applied, for example $\Delta'' \epsilon < 0.1$, and if it is reasonable at any one time to delay the PM activity.

The conclusion is that measurements of the loss parameter can be used as input data for a maintenance strategy. This can be done by using historical information about the component up to the decision time. These data can support the two decisions, firstly whether PM should be applied based on a criteria, and secondly the order in which to maintain the components.
12.3 Concepts for the System Effect of Maintenance Strategies

12.3.1 Composite Failure Rate

As discussed earlier, component failures occur due to different causes of failures, which in turn could be effected by PM. The causes of failures in the cable component have been analysed in detail, and a result from these studies is the development of a model that defines the variation of the failure rate function over time and with the PM method. This model refers to a cable type that is prone to fail due to water treeing and the PM methods analysed to prevent this specific cause of failure. However, the cable is affected by other types of failures, for example due to corrosion, which also contributes to the failure rate of the component. Consequently, a component failure rate is made up of the contribution from several causes of failures, and the total failure rate means a composite rate of those contributions.

A next step in the Cable Application Study is therefore to extend the model developed for failure rate in order to represent the composite failure rate. The input data required to obtain such a model for failure rate were presented and analysed in Section 12.2. Furthermore, it was identified that these data originate from two data sources: firstly from the Birka system and specifically data for the 11 kV cable component, and secondly from the failure rate function developed for the water-tree contribution to the XLPE cable.

The corresponding failure rate data are: 0.10069 f/yr, as defined in Equation 12.1, and the interval of [0.012579] f/yr as defined in Equation 12.2. The first refers to the Birka cable data for the average failure rate of an 11 kV cable (failures due to all failure causes). The second refers to the XLPE cable data for a failure rate function due to the failure caused by water treeing.

To enable a system effect analysis of the impact of PM to be performed, the following assumptions have been made:

- the average 11 kV cable in the Birka system is affected by water treeing,
- at time zero the failure rate due to all failure causes equals the input data for the Birka base system (0.10069 f/yr),
• from time zero until the end of the interval the composite failure rate is made up of the sum of the contribution from the water-tree failure rate effect and the nominal value which represents the effects from other causes of failures.

These assumptions mean that the failure rate model developed is superposed on the Birka system data. A discussion about the justification of such an approximation was made in Section 12.2.3.

The resulting composite failure rate function for the Cable Application Study (for the average 11 kV cable in the Birka system) is therefore given by:

$$\lambda_{tot}(t) = \lambda_{LH11} + \lambda_{wt}(t) \quad [f/yr] \quad t_0 \leq t \leq T$$

where $$\lambda_{wt}(t) \subseteq \begin{cases} \lambda_{old}(t) & \text{if no PM} \\ \lambda_{PMi}(t) & \text{if } PM_{si} \\ \lambda_{PMp}(t) & \text{if } PM_{rp}. \end{cases}$$

(12.3)

The corresponding interval for the function is given by:

$$\lambda_{tot}(t) \subseteq [0.10069, 0.22650] \quad [f/yr].$$

(12.4)

This interval suggests that the composite failure rate for $$\lambda_{tot}(t)$$ increases with somewhat more than 100% due to the impact of water-tree failures. This characteristic is illustrated in Figure 12.2. This figure shows three failure rate functions for the Cable Application Study. The first is the composite failure rate function ($$\lambda_{tot}(t)$$), the second is the failure rate function due to water treeing ($$\lambda_{wt}(t)$$), and the third is the nominal value for the Birka system average 11 kV cable ($$\lambda_{LH11}$$). The conclusion is that in the model of the composite failure rate for the 1 kV cable in the Birka system, that the failure cause water treeing makes a significant contribution to failure.

12.3.2 Maintenance Strategy

In previous analysis, the system has been reduced by: (i) focusing the analysis on those included components that have a significant impact on the system reliability and could be improved by PM, and (ii) the failure causes that could be affected by PM for those components have been identified.
Figure 12.2. Illustration of the composite failure rate for the 11 kV average cable in the Birka system affected by water treeing.
12.3. Concepts for the System Effect of Maintenance Strategies

The maintenance strategy for the system aims to find suitable and effective PM activities to reduce those failure causes which would in turn result in finding the best solution for system reliability.

To create this strategy for a certain time period (for example \( T \subseteq [0, 30] \)), the following questions have to be answered for each failure cause that is related to a specific component or component type such as XLPE cable affected by treeing):

1. What type of PM method should be applied?
2. With what frequency should it be applied?
3. At what points in time should it be applied?
4. What proportion of the component type will undergo PM each time?

The last of these questions is very much related to the second. Obviously, if it is possible to maintain all system components at one time, it is probably only necessary to apply one PM activity during the period. However for a power delivery system in operation, this would not be possible, since the system reliability for the supply has to fulfill certain levels, and it would also be very costly to undertake all the investments at any one point in time instead of spreading them over a period of years. Consequently, a sound maintenance strategy would divide the PM activities over several points in time for different components.

For the Cable Application Study as presented in Chapter 11, a plan of PM activities was suggested with three application occasion times 9, 11 and 12 years after coming into operation. To complete the maintenance strategy for the Cable Application Study, there is one further issue to decide, and that is, the proportion of the XLPE cable components that should be treated to prevent water-tree failures at each maintenance activity.

The Cable Application Study results are presented for two different strategies which are presented in Table 12.2. These have been chosen to capture a reasonable spread, that is with a total of either 30% or 90% of cables undergoing PM. Furthermore, equal time points have been chosen to provide results for comparisons between the two PM methods. It should however be recognized that the methodology as well as the implementation supports analysis of the whole range of possible strategies. In practice, a
range of sensitivity studies would be conducted to assess all possible and practical alternatives.

Finally some general remarks about the choice of maintenance strategy have been presented. An effective maintenance strategy requires that the benefit gained must justify the expenditure made to achieve it. Furthermore, a limited capital expenditure per year means that the investments must be spread over a number of years. Consequently, the PM will be spread over a number of years, with the proportion of components maintained being less than 100%. Broadly, the choice of strategy depends on how much money there is to spend.

**Table 12.2.** Two maintenance strategies for the Cable Component Application Study with either rehabilitation $PM_{i,j}$ or replacement $PM_{r,j}$.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Year</th>
<th>Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>$PM_{i,1}$</td>
<td>$t_{PM1} = 9$</td>
<td>$s_1 = 0.1$</td>
</tr>
<tr>
<td>$PM_{i,2}$</td>
<td>$t_{PM2} = 11$</td>
<td>$s_2 = 0.1$</td>
</tr>
<tr>
<td>$PM_{i,3}$</td>
<td>$t_{PM3} = 12$</td>
<td>$s_3 = 0.1$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measure</th>
<th>Year</th>
<th>Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>$PM_{i,1}$</td>
<td>$t_{PM1} = 9$</td>
<td>$s_1 = 0.3$</td>
</tr>
<tr>
<td>$PM_{i,2}$</td>
<td>$t_{PM2} = 11$</td>
<td>$s_2 = 0.3$</td>
</tr>
<tr>
<td>$PM_{i,3}$</td>
<td>$t_{PM3} = 12$</td>
<td>$s_3 = 0.3$</td>
</tr>
</tbody>
</table>

The first strategy implies that a total of 30% of the component type undergoes PM. This situation could correspond to where a maintenance strategy for a certain time period is constricted by a limit or a maximum number of components to be affected by PM. Such a limit would primarily be based on restrictions on reliability performance rather than on cost, since the latter would imply restrictions on when to make the PM. It is assumed that the maintenance is applied on three occasions. Consequently the maintenance strategy should distribute the 30% of cables over three PM times. Table 12.3 demonstrates the eight different maintenance strategies that fulfill those requirements.
12.3.3 Average Component Composite Failure Rate

Previous sections have identified the need for, and showed the definitions of: (i) composite failure rates for the components (presented in Section 12.3.1), and (ii) a maintenance strategy for the system (presented in Section 12.3.2). Both these are required to support a system analysis of the effect by PM. However one further concept has to be introduced before the system reliability analysis can be performed; and that is the focus of this section.

As discussed earlier, a general maintenance strategy will result in less than all the components of a certain type undergoing PM at the same time, or by the same method. Moreover, some components might not undergo PM at all during the time period for which the strategy corresponds. This situation creates different component behaviour over time for components that have the same original conditions. In other words, the failure rate functions for components with similar failure rate characteristics may differ with time since they are subject to differing PM methods. Consider for example, three XLPE cables that are exposed to water treeing. Assume that one of these undergoes PM year 9 by rehabilitation of the cable, the next cable at year 11 by replacement, and the third cable has no PM at all, then the maintenance strategy would result in three different failure rate functions for this one component type. Furthermore, the situation could be that 10% of

<table>
<thead>
<tr>
<th>Strategy</th>
<th>$s_1$</th>
<th>$s_2$</th>
<th>$s_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1*</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>0.2</td>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>4</td>
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</tr>
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<td>0</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0</td>
<td>0.3</td>
</tr>
</tbody>
</table>

*Corresponds to Strategy $S_1$. 

Table 12.3. Different maintenance strategies with preventive maintenance applied on three occasions to a total of 30% of the components.
the XLPE cables follow the first pattern, and so on. Consequently, it can be acknowledged that the complexity of the maintenance issue has become even greater. To capture this complication with a mixture of different failure rate functions for components with similar component behaviour, the concept of average component has been introduced.

An average component is one that represents all the components of that type and their different behaviours due to a specific maintenance strategy. For the above example with the three components, the average component failure rate would be the resulting failure rate function when these different failure functions have been combined in a way that takes into account the type of PM method, the time for the activity, the number of components and so on.

To demonstrate the different failure rate functions, the following example has been used. Consider a system with cable components that are exposed to PM by rehabilitation at three different points in time, being 9, 11 and 12 years after coming into service. Furthermore, assume that 10% of the cables undergo PM by rehabilitation at each time. This maintenance strategy corresponds to $S_1$ as defined in Table 12.2. This situation results in four different failure rate functions which represent the component behaviour for the four different classes of cables, being those rehabilitated at years 9, 11, or 12, or not exposed to PM by rehabilitation. The first three of these correspond to a failure rate function that is valid for 10% of the cables each. The last cable class is represented by 70% of the cables. Figure 12.3 illustrates the concept of the average cable for this example, that is, where 10% of the components are replaced each time. The resulting model for the average component then implies a 70% "old component". Furthermore, Figure 12.4 illustrates the resulting four different failure rate functions.

However, the aim here is to define one failure rate function that represents the average behaviour of the component type. An average failure rate function ($\lambda_{av}(t)$) for this example and with time $t : 0 \to 30$ is made stepwise of the following different functions:
\[
\begin{align*}
\lambda_{av}(0) &= \lambda_{old}(t) \\
\lambda_{av}(1) &= \lambda_{old}(t) \\
\cdots &= \lambda_{old}(t) \\
\lambda_{av}(9) &= 0.9 \cdot \lambda_{dd}(t) + 0.1 \cdot \lambda_{PM1}(t), \\
\cdots &= 0.9 \cdot \lambda_{dd}(t) + 0.1 \cdot \lambda_{PM1}(t), \\
\lambda_{av}(11) &= 0.8 \cdot \lambda_{dd}(t) + 0.1 \cdot \lambda_{PM1}(t) + 0.1 \cdot \lambda_{PM2}(t), \\
\lambda_{av}(12) &= 0.7 \cdot \lambda_{dd}(t) + 0.1 \cdot \lambda_{PM1}(t) + 0.1 \cdot \lambda_{PM2}(t) + 0.1 \cdot \lambda_{PM3}(t), \\
\cdots &= 0.7 \cdot \lambda_{dd}(t) + 0.1 \cdot \lambda_{PM1}(t) + 0.1 \cdot \lambda_{PM2}(t) + 0.1 \cdot \lambda_{PM3}(t), \text{ and} \\
\lambda_{av}(30) &= 0.7 \cdot \lambda_{dd}(t) + 0.1 \cdot \lambda_{PM1}(t) + 0.1 \cdot \lambda_{PM2}(t) + 0.1 \cdot \lambda_{PM3}(t),
\end{align*}
\]

(12.5)

where \( \lambda_{dd}(t) \) refers to the components that do not undergo PM, and \( \lambda_{PMi}(t) \) refers to the components undergoing PM at times \( i = 1, 2, 3 \).

This equation can be re-written in a more compact form as follows:

\[
\begin{align*}
\lambda_{av}(t) &= \\
&= \begin{cases} \\
\lambda_{dd}(t) & : \quad 0 \leq t \leq 9 \\
0.9 \cdot \lambda_{dd}(t) + 0.1 \cdot \lambda_{PM1}(t) & : \quad 9 \leq t \leq 11 \\
0.8 \cdot \lambda_{dd}(t) + 0.1 \cdot \lambda_{PM1}(t) + 0.1 \cdot \lambda_{PM2}(t) & : \quad 11 \leq t \leq 12 \\
0.7 \cdot \lambda_{dd}(t) + 0.1 \cdot \lambda_{PM1}(t) + 0.1 \cdot \lambda_{PM2}(t) + 0.1 \cdot \lambda_{PM3}(t) & : \quad 12 \leq t \leq 30 \\
\end{cases}
\end{align*}
\]

(12.6)

### 12.4 Modelling Composite Failure Rate for the Average Cable Component

#### 12.4.1 Resulting Composite Failure Rate Model

A composite failure rate function for an average 11 kV cable component can be formulated based on those concepts and results that were presented in Section 12.3. This model for the component failure rate constitutes an extension of the Cable Application Study that enables the system reliability analysis for analysing the effect of different maintenance strategies.

The composite failure rate for an average 11 kV cable component has been defined in Equation 12.3 as follows:
12.4. Modelling Composite Failure Rate for the Average Cable Component

**Figure 12.3.** Representation of the average component.

**Figure 12.4.** Illustration of different failure rate functions due to a maintenance strategy.
12.4. Modelling Composite Failure Rate for the Average Cable Component

\[ \lambda_{\text{tot}}(t) = \lambda_{LH11} + \lambda_{\text{wt}}(t) \quad [\text{f/yr}] : \quad t_0 \leq t \leq T \]

where \( \lambda_{\text{wt}}(t) \subseteq \begin{cases} 
\lambda_{\text{old}}(t) & \text{if no PM} \\
\lambda_{PM_{s1}}(t) & \text{if } PM_{s1} \\
\lambda_{PM_{r2}}(t) & \text{if } PM_{r2}.
\end{cases} \) (12.7)

Two maintenance strategies denoted \( S_1 \) and \( S_2 \) were defined in Table 12.2. For both of these, PM is applied at three points in time: 9, 11 and 12 years after coming into service. The proportion of cables undergoing PM at each time is 10% for \( S_1 \), and 30% for \( S_2 \).

Finally, the average component failure rate was introduced and Equation 12.6 illustrated how it can be evaluated.

The composite failure rate for the average 11 kV cable can be evaluated based on these three concepts with corresponding results. The following is a general presentation of the resulting equation:

\[ \lambda_{\text{atot}}(t) = \lambda_{LH11} + \lambda_{\text{wt}}(t) \quad : \quad t_0 \leq t \leq T \quad [\text{f/yr}] \] (12.8)

\[ \lambda_{\text{atot}}(t, \text{no PM}) = \lambda_{LH11} + \lambda_{\text{old}}(t) \cdot (l_{av}/100) \quad : \quad t_0 \leq t \leq T[f/yr] \] (12.9)

\[ \lambda_{\text{atot}}(t, PM_{s3}, S) = \lambda_{LH11} + (l_{av} / 100) \cdot \begin{cases} 
\lambda_{\text{old}}(t) & \text{if no PM} \\
(1 - s_1) \cdot \lambda_{\text{old}}(t) + s_1 \cdot \lambda_{PM_{s1}}(t) & : t_{PM1} \leq t \leq t_{PM2} \\
(1 - (s_1 + s_2)) \cdot \lambda_{\text{dd}}(t) + s_1 \cdot \lambda_{PM_{s1}}(t) + s_2 \cdot \lambda_{PM_{s2}}(t) & : t_{PM2} \leq t \leq t_{PM3} \\
(1 - (s_1 + s_2 + s_3)) \cdot \lambda_{\text{dd}}(t) + s_1 \cdot \lambda_{PM_{s1}}(t) + s_2 \cdot \lambda_{PM_{s2}}(t) + s_3 \cdot \lambda_{PM_{s3}}(t) & : t_{PM3} \leq t \leq T
\end{cases} \] (12.10)

This model includes the assumption that, for the same component, PM is applied either once or not at all during the time period being analysed.
12.4.2 Analysis of the Effect of Different Strategies

Maintenance strategies have been discussed earlier, and in Section 12.3.2 there were two strategies defined for demonstrating purposes, presented in Table 12.2.

These two different strategies have been studied in detail for the Cable Application Study. Furthermore, this includes analyses of PM featuring both rehabilitation and replacement methods. Consequently, there are three different maintenance methods being represented, each with a failure rate function as follows.

- No PM, where the components are only affected by CM,
  \[ \lambda_{atot}(t) : t_0 \leq t \leq T \ [f/yr]. \]

- PM by rehabilitation,
  \[ \lambda_{atot}(t, PM_{si}) \text{ for a specific strategy } S : t_0 \leq t \leq T \ [f/yr]. \]

- PM by replacement,
  \[ \lambda_{atot}(t, PM_{rp}) \text{ for a specific strategy } S : t_0 \leq t \leq T \ [f/yr]. \]

12.4.3 Comparison of Maintenance Methods

A comparison of these different maintenance methods has been done. Figure 12.5 demonstrates the results for the Cable Application Study. This figure illustrates the characteristics of the three failure rate functions presented above. Furthermore, this figure shows results for the situation where the 11 kV average cable in the Birka system is exposed to strategy \( S_2 \) (with 30\% of the cables rehabilitated at years 9, 11 and 12). A significant result is that PM for reducing failures is the most effective method. Moreover, the result indicates that the lowest failure rate function is obtained for the situation where PM is performed by replacement.

12.4.4 Comparing the Two Maintenance Strategies

In the next step of the analysis, the effect of different strategies for maintenance have been analysed. For the Cable Application Study, the previously defined strategies \( S_1 \) and \( S_2 \) have been studied in detail.
12.4. Modelling Composite Failure Rate for the Average Cable Component

![Graph showing composite failure rate](image)

**Figure 12.5.** Comparison of failure rate functions for different maintenance methods, showing results for the situation with the 11 kV average cable component in the Birka system which is affected by water treeing and exposed to the maintenance strategy $S_2$. 
12.4. Modelling Composite Failure Rate for the Average Cable Component

Figure 12.6 shows the effect of two different strategies for PM on the composite failure rate. With $S_1$, 10% of the cables are rehabilitated on the three maintenance occasions, and with $S_2$, 30% of the cables are rehabilitated on the three maintenance occasions. This means that with the first strategy a total of 30% of the total population of cables are changed within the period compared with 90% for the second. Consequently, the figure shows a span for the probable effect of the maintenance strategy that is the benefit in the composite component failure rate.

Figure 12.7 shows the results for the same analysis when PM is applied by replacement instead. A similar behaviour can be seen in cable rehabilitation, however the difference in benefit for the different strategies is even more significant.

\[ \lambda_{\text{tot}}(t) \]

\[ \lambda_{\text{tot}}(t,\text{PM}_{S_1},S) \]

\[ \lambda_{\text{tot}}(t,\text{PM}_{S_2},S) \]

\[ \lambda_{\text{tot}}(t,\text{PM}_{S_3},S) \]

**Figure 12.6.** Effect of $PM_{S_i}$ using different strategies for the 11 kV average cable in the Birka system.
Figure 12.7. Effect of $PM_{rp}$ using different strategies for the 11 kV average cable in the Birka system.
12.4.5 The Effect of Different Strategies

Detailed analyses have been made for the different strategies. In strategy $S_2$, a total of 90% of cables are maintained with equal amounts at three points in time (30% at years 9, 11 and 12). If it is assumed instead that the constraint for the maintenance strategy is that the amount of cables maintained constitute 90% of the total, then numerous different possible strategies are obtained. This aspect of constraint for maintenance plans was previously discussed in Section 12.3.2. Figure 12.8 illustrates the effect of different strategies when rehabilitation is applied that sum up to a total of 90% of cables maintained. Results from a similar analysis when replacement is applied is displayed in Figure 12.9. This figure suggests that an optimal solution exists; for example where the composite failure rate is limited by a criteria for the upper level, and the optimal solution is the maintenance strategy for which the failure rate reaches that level last in time.

A similar analysis has been made for the first PM strategy ($S_1$). This strategy implies that a total of 30% of cables are maintained at three points in time. As presented earlier in Table 12.3, this constraint results in eight different cases for dividing the PM measures. Figure 12.10 displays these possible maintenance strategies. It can be seen that the effect of applying the PM method by rehabilitation is different depending on when it is applied. For example the extremes that is either performing all PM at the first or last point in time for maintenance shows that the benefit in reliability would increase in the earlier one. In other words the greatest benefit to failure rate is gained if the rehabilitation effort is concentrated to the first maintenance occasion. However it is important to note that the cost is dependent on when the investment in maintenance is made, which is further analysed in Section 12.6. Similar analysis of when PM involves replacement is presented in Figure 12.11. Both these results indicate that the time aspect is important when determining an effective maintenance plan.

12.4.6 Resulting Failure Rate Functions as Input Data for the System Analysis

Tables 12.4 and 12.5 present selected values for each year for the resulting composite failure rate functions for an average 11 kV cable component in the Birka System. Furthermore, these correspond to strategy $S_1$ and $S_2$. 

Figure 12.8. Effect of different strategies for rehabilitating 30% of cables on three occasions (variations of $S_3$).
Figure 12.9. Effect of different strategies for replacing 30% of cables on three occasions (variations of $S_2$).
Figure 12.10. Effect of different strategies for rehabilitating 10% of cables on three occasions (variations of $S_1$).
Figure 12.11. Effect of different strategies for replacing 10% of cables on three occasions (variations of $S_1$).
respectively. These data demonstrate reliability input data for the system effect analysis with RADPOW.

The results have been validated by comparisons with corresponding manually calculated values using Equation 12.10. The selected values have been presented below. The conclusion is that the results for the implemented equations are correct.

\[
t = 9 \Leftrightarrow t_{PM1} \Rightarrow \\
\lambda_{atot}(9, \text{no PM}) = \lambda_{LH11} + \lambda_{old}(9) \cdot (l_{av}/100) = \\
0.10069 + 0.5809 \cdot (8.10584/100) = 0.14778,
\]

\[
\lambda_{atot}(9, PM_{s13}, S) = \lambda_{LH11} + (l_{av}/100) \cdot (0.9 \cdot \lambda_{old}(9) + 0.1 \cdot \lambda_{PM_{s1}}(9)) = \\
= 0.10069 + (8.10584/100) \cdot (0.5809) = 0.14778,
\]

\[
\lambda_{atot}(9, PM_{r3}, S) = \lambda_{LH11} + (l_{av}/100) \cdot (0.9 \cdot \lambda_{old}(9) + 0.1 \cdot \lambda_{PM_{r1}}(9)) = \\
= 0.10069 + (8.10584/100) \cdot (0.9 \cdot 0.5809) = 0.14307,
\]

\[
t = 22 \Leftrightarrow t_{PM2} \Rightarrow \\
\lambda_{atot}(22, \text{no PM}) = \lambda_{LH11} + \lambda_{old}(22) \cdot (l_{av}/100) = \\
0.10069 + 1.5418 \cdot (8.10584/100) = 0.22567,
\]

\[
\lambda_{atot}(22, PM_{s13}, S) = \lambda_{LH11} + (l_{av}/100) \cdot (0.7 \cdot \lambda_{old}(22) + 0.1 \cdot \lambda_{PM_{s1}}(22)) + \\
0.1 \cdot \lambda_{PM_{s2}}(22) + 0.1 \cdot \lambda_{PM_{s13}}(22)) = 0.10069 + (8.10584/100) \cdot \\
(0.7 \cdot 1.5418 + 0.1 \cdot 1.5418 + 0.1 \cdot 0.9676 + 0.1 \cdot 0.7558) = 0.21464, \text{ and}
\]

\[
\lambda_{atot}(22, PM_{r3}, S) = \lambda_{LH11} + (l_{av}/100) \cdot (0.7 \cdot \lambda_{old}(22) + 0.1 \cdot \lambda_{PM_{r1}}(22)) + \\
0.1 \cdot \lambda_{PM_{r2}}(22) + 0.1 \cdot \lambda_{PM_{r3}}(22)) = 0.10069 + (8.10584/100) \cdot \\
(0.7 \cdot 1.5418 + 0.1 \cdot 1.5418 + 0.1 \cdot 0.9676 + 0.1 \cdot 0.7558) = 0.21464.
\]

### 12.5 System Reliability Analysis Comparing PM Strategies

This section shifts the analysis from the component to the system level and focuses on the evaluation of reliability for which the tool RADPOW has
Table 12.4. Results for the composite failure rate function ($\lambda_{tot}(t)$) for the 11 kV average cable in the Birka system affected by water treeing and subject to preventive maintenance strategy $S_1$. Integer values are listed that provide input data for reliability system analysis (RADPOW) and cost benefit analysis.

<table>
<thead>
<tr>
<th>Time [yr]</th>
<th>$\lambda_{tot}(t, \text{no PM})$ [f/yr]</th>
<th>$\lambda_{tot}(t, PM_{si}, S_1)$ [f/yr]</th>
<th>$\lambda_{tot}(t, PM_{rp}, S_1)$ [f/yr]</th>
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</thead>
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Special time point:

$t_3 = 21.82$  $0.22567$  $0.21353$  $0.21353$
### 12.5. System Reliability Analysis Comparing PM Strategies

Table 12.5. Results for the composite failure rate function ($\lambda_{att}(t)$) for the 11 kV average cable in the Birka system affected by water treeing and subject to preventive maintenance strategy $S_2$. Integer values are listed to provide input data for reliability system analysis (RADPOW) and cost benefit analysis.

<table>
<thead>
<tr>
<th>Time [yr]</th>
<th>$\lambda_{att}(t, \text{no PM})$ [f/yr]</th>
<th>$\lambda_{att}(t, PM_{si}, S_2)$ [f/yr]</th>
<th>$\lambda_{att}(t, PM_{rp}, S_2)$ [f/yr]</th>
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<tr>
<td>30</td>
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<td>0.22567</td>
</tr>
</tbody>
</table>

Special time point:

$t_3 = 21.82$ 0.22567 0.18926 0.18926
been used. RADPOW provides reliability indices for load points and system reliability indices. The tool was introduced in Chapter 4.

The objective here is to define the effect on system reliability by PM on selected components in the system. Furthermore, this should be made in quantitative terms. This implies that the Cable Application Study should be extended by performing a reliability analysis where the defined model for failure rate that is the composite failure rate for an average component as defined in Equations 12.9 and 12.10 that is the component input data.

RADPOW has been run repeated times to simulate the failure rate change over time. The previously defined two maintenance strategies ($S_1$ and $S_2$) have been analysed. Input data for the corresponding failure rate functions for these two maintenance strategies were presented in Tables 12.4 and 12.5. This section presents the resulting output, which are the load point reliability indices and system performance indices. MATLAB has been used as a tool for the analysis of the data.

The output are reliability indices varying in time depending on the changed characteristics of the failure rate, and specifically the contribution of the failure causes due to water trees.

### 12.5.1 Effect on Reliability Indices due to Water-tree Growth

Figure 12.12 presents the resulting functions for the Birka system reliability indices when the 11 kV cable components have an increased failure rate function due to water-tree growth. The system includes three load points where the first is on the 11 kV level but the other two are on the 33 kV voltage level. However, the model for failure rate change over time only relates to the failures for the 11 kV cable, and failures for other components are assumed constant in time. Consequently, load points 2 and 3 (that is SJ and HD) have reliability functions that are constant in time and are therefore not considered in the following analysis of the effect of PM.

The first graph shows the failure rate function. The effect on the failure rate due to water-tree growth has been discussed in earlier sections, however then the focus was on either the effect on the individual cable component, or as a model for the average 11 kV cable in the Birka system. In this analysis, the 11 kV component has been put into a system context, and the effect on
the system reliability analysed. The failure rate functions refer to different load points in the system, and as earlier stated, it is for Load Point 1 that the impact of the included failure rate function can be seen. It can also be seen that the failure rate for Load Point 1 varies from about 0.3345 to 0.5844 failures per year, which implies an increase of about 75%.

However, the customer (load point) is not only affected by the failures occurring but also of the duration that these appear (the outage time) as well as the amount of energy that is not supplied. Indices to capture the these parameters are illustrated in the following plottings. It can be seen that the characteristic of the failure rate function (increasing due to water-tree growth), dominates in the functions for unavailability and loss of energy, compared with the contribution from the outage time \( U = \lambda \cdot r \), \( LOE = L \cdot U \). This is explained by the restoration time being equal for both lengths of water trees, and consequently is constant in time in this context; and this should be compared with the failure rate with a significant increase in time. Furthermore, it can be seen that the outage time is the only one of the functions that is decreasing due to the water-tree effect, meaning that the average restoration time when a failure occurs is shorter. This is because the contribution to restoration time from the 11 kV cables is comparatively small compared with the other components in the system; for example repair time is 6 h for an 11 kV cable compared with 48 h for a 33 kV cable. For the energy not-supplied, it can be seen that the load points represent different types of customers with a wide range of energy requirements. The third load point (the subway), has such a low consumption per customer so it is not seen in the figure.

Table 12.6 summarizes some results for the load point reliability indices shown in Figure 12.12. This presents the boundary values for the load point indices at Load Point 1, being the values at time zero \( t_0 \) and at the end of the period \( T \). These numbers correspond to the reliability indices: maximum and minimum values. As stated earlier, for all of the indices except for the outage time, the maximum value is reached as a result of the maximum contribution to failure rate due to the water trees. Moreover, the last column in the same table presents the individual percentage increases for the different indices. For the maximum value of the failure rate function, the increase from the initial value at time zero is about 75%. For the unavailability, the corresponding increase is 49%, which is the same increase that appears for
the loss of supplied energy. On the other hand, the restoration time decreases (−17%). These results show a significant impact on the load point reliability indices due to the failures caused by water trees. Consequently it is of great interest to analyse how these percentages could be reduced by PM. Methods to solve this are analysed further in the following section.

Figure 12.12. Load point indices for the Birka system with 11 kV cables affected by water-tree growth; note that Load Point Lp1 refers to the only customer using 11 kV level (LH11).

12.5.2 Impact of PM on Reliability Indices

Resulting reliability indices for Load Point 1 have been analysed for different choices of maintenance strategies where PM has been applied to reduce failures due to water trees. Moreover, the PM is performed using either one of the methods of rehabilitation or replacement of 11 kV cables.
Figures 12.13 and 12.14 demonstrate the result for the two strategies $S_1$ and $S_2$. These results demonstrate the impact of a maintenance strategy where maintenance is applied on three occasions, years 9, 11 and 12, and at each time with the proportion of either 10% of the cables maintained ($S_1$) or 30% ($S_2$). Consequently, 30% (or 90%) of the 11 kV cables are maintained during the time period by either replacement or rehabilitation. The results show a significant effect of PM in reducing the failure rate. Furthermore, this leads to reductions in the unavailability and the energy not-supplied.

Energy not supplied is a useful load point index that relates the unavailability with the energy supply demand. Table 12.7 presents results for Load Point 1 subject to either one of the maintenance strategies $S_1$ or $S_2$. These data show that the total energy not-supplied during the studied period of 30 years, is 16.14 MWh when no PM is applied. Furthermore, for strategy $S_1$, this number is reduced to 15.75 MWh when subject to the silicon injection method (rehabilitation), and to 15.61 MWh for the replacement method. For strategy $S_2$, the equivalent numbers are 14.97 MWh and 14.57 MWh respectively, that is with a total of 90% of 11 cables applied to PM. Consequently, the PM methods analysed can reduce the energy not-supplied at Load Point 1 by up to around 2 MWh. This benefit can be valued and depends on the cost of the customer interruption. This aspect is analysed further in Section 12.6.

Furthermore, the impact on the system performance indices has been analysed. Figures 12.15 and 12.16 present the results for four different system indices. As can be seen from the figures, the characteristics follow the behaviour of the load point indices for Load Point 1. This is an expected result, since the load point failure for this system is dominated by failures

<table>
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<th>Indices</th>
<th>$t = t_0$ yr</th>
<th>$t = T$ yr</th>
<th>Increase</th>
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<td>$\lambda_{Lp1}$</td>
<td>0.33449 f/yr</td>
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<td>+75%</td>
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<td>$U_{Lp1}$</td>
<td>0.50671 h/yr</td>
<td>0.75667 h/yr</td>
<td>+49%</td>
</tr>
<tr>
<td>$r_{Lp1}$</td>
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</tr>
<tr>
<td>$LOE_{Lp1}$</td>
<td>389.650 kWh/yr</td>
<td>581.739 kWh/yr</td>
<td>+49%</td>
</tr>
</tbody>
</table>
at the 11 kV level and especially by the significant contribution from the failures due to water-tree growth.

The reduction in the reliability functions leads to improved system behaviour. However, the figures demonstrate that this benefit is reducing with time, and after a certain time the functions reach the same function values as for the system not-affected by maintenance. Both for the rehabilitation, the failure rate reaches the maximum value at year 25. However, the replacement method provides better reliability after PM until about year 22 ($t_3 = 21.82$ years) for both of the strategies.

![Figure 12.13. Effect on reliability indices for Load Point 1 (LH11) due to different preventive maintenance (PM) methods. PM applied with strategy S1, at years 9, 11 and 12 with 10% of the cables subject to PM on each occasion.](image-url)
### Table 12.7
Results for energy not-supplied for the Cable Application Study with different maintenance methods and two PM strategies $S_1$ and $S_2$.

<table>
<thead>
<tr>
<th>Time [yr]</th>
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<th>$LOE_{L,pt}(t, PM_{rp}, S)$ [kWh/yr]</th>
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<td>581.86</td>
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</table>

**Total:**

| MWh | 16.14 | 15.75 | 14.97 | 15.61 | 14.57 |
Figure 12.14. Effect on reliability indices for Load Point 1 (LH11) due to different preventive maintenance methods (PM). PM applied with strategy S2, at years 9, 11 and 12 with 30% of the cables subject to PM on each occasion.
Figure 12.15. Effect on system performance indices due to preventive (PM) maintenance methods to reduce water-tree failures. PM applied with strategy $S_1$ at years 9, 11 and 12 with 10% of cables subject to PM on each occasion.
Figure 12.16. Effect on system performance indices due to preventive maintenance (PM) methods to reduce water-tree failures. PM applied with strategy $S_2$ at years 9, 11 and 12 with 30% of cables subject to PM on each occasion.
12.5.3 Which PM Method is the Best?

A fundamental question for an RCM plan and the actual question raised at this point in the Cable Application Study is the following:

Which PM method is the best?

For the Cable Application Study, this question relates to the choice between no PM, or PM by either rehabilitation or replacement of the 11 kV cables in the Birka system.

The system reliability effect analysis, which takes into account the impact of maintenance methods, should provide results that support the decision. However, there is not an obvious answer to the question. The optimal choice of method would depend on the specific requirements. However, one solution is to evaluate expected reliability indices over the time period that is an average value for a load point as follows:

\[
\lambda_{av,LP} = \frac{\sum_{t=t_0}^{T} \lambda_{LP}(t,PM)}{(T-t_0)},
\]

\[
U_{av,LP} = \frac{\sum_{t=t_0}^{T} U_{LP}(t,PM)}{(T-t_0)},
\]

\[
r_{av,LP} = \frac{\sum_{t=t_0}^{T} r_{LP}(t,PM)}{(T-t_0)}, \quad \text{and}
\]

\[
LOE_{av,LP} = \sum_{t=t_0}^{T} \text{LOE}_{LP}(t,PM)
\]

(12.11)

The first three average values relate to the basic reliability performance indices, and the last to a reliability index that includes the effect on customer supply.

These indices have been evaluated for the Cable Application Study. Table 12.8 summarizes the result. The results show consistently that the best reliability is gained with PM by replacement and with as much as possible of the component subject to PM (strategy S2). For example, energy not-supplied is reduced by about 1 MWh with this solution. Furthermore, this
is a consequence of the "gain" in the lowest unavailability, which in this example is from 0.69 to 0.63 h/yr.

Table 12.8. Comparing maintenance methods based on reliability indices with results for the Cable Application Study.

<table>
<thead>
<tr>
<th>Reliability factor</th>
<th>Unit</th>
<th>Average values for different maintenance methods</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CM</td>
</tr>
<tr>
<td>$\lambda_{av,Lp1}$</td>
<td>[f/yr]</td>
<td>0.52154</td>
</tr>
<tr>
<td>$U_{av,Lp1}$</td>
<td>[h/yr]</td>
<td>0.69950</td>
</tr>
<tr>
<td>$r_{av,Lp1}$</td>
<td>[h/f]</td>
<td>1.40374</td>
</tr>
<tr>
<td>$LOLE_{av,Lp1}$</td>
<td>[MWh/yr]</td>
<td>16.14</td>
</tr>
</tbody>
</table>

12.6 Cost and Benefit Analysis Comparing Maintenance Strategies

This section introduces some fundamentals of economic analysis, defines cost factors of special interest for this RCM methodology development, develops models for evaluation of cost functions for the same, and finally performs a total cost analysis. Moreover, all these theories are exemplified for the previous application study that is the Cable Application Study. The section therefore also includes a treatment of required input data to support the methods defined for the cost evaluation.

The nomenclature used for the cost analysis has been chosen to where possible, agree with those defined in the reference books [2] and [3].

12.6.1 Introduction to Cost Analysis

This section introduces the aspect of cost into the methodology development. Thereby the RCM analysis reaches its final step which relates the benefit in cost due to reliability and PM. The motivation for any PM strategy must include financial considerations. These should justify that the cost for applying the PM measure should be less than not taking any action, that is
12.6. *Cost and Benefit Analysis Comparing Maintenance Strategies*  

CM. Therefore, a very important issue is to compare the costs associated with different PM methods as well as only CM, which is the focus for the financial analysis presented in this section. The problem being investigated is how to relate reliability with PM. Furthermore, it has been identified that this can be made by analysing component failures and how to prevent them. The introductory general question is therefore:

*What kind of costs are associated with failures?*

There are several costs that can be related to the effect of interruption of supply. One way of grouping these is by distinguishing between *cost due to failure* and *cost due to preventing failure*. The first of these two categories is related to the cost of restoring failure; for example repairs, penalty costs to the affected customers, or losses in revenue due to reductions for non-delivered energy. The second category relates to the costs of the PM actions such as for example replacement of the cable. Another way of grouping the same costs is by distinguishing between the parties *utility costs* or *customer costs*. On the one hand here the cost for the restoration of failure *cost of failure*, and the cost for the preventive action to combat the failure *cost of PM* are both related to the utility. On the other hand, the cost for a supply interruption affects the customer, who will suffer from unavailability and for example then be compensated for via a penalty cost for the *cost of interruption*. Finally, with the focus on the reliability, the costs can be grouped into either *reliability costs* (those costs for investment needed to achieve a certain level of reliability, for example PM actions), or *reliability value* (the benefit derived by the customers and society). The first would include the balance between no PM (which is CM) and PM actions. The concepts of reliability cost and reliability worth (value) are discussed further in [1].

The cost analysis that follows relates to the modelling and the evaluation of the following.

1. The cost of failure ($C_f$).
2. The cost of PM ($C_{PM}$).
3. The cost of interruption ($C_{int}$).
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The optimal maintenance method and PM strategy is the solution that minimizes the total cost, which is the sum of these three costs that relates to both the utility and the customer cost.

It is interesting to note that some of these above introduced costs are related to the component failure itself, and some to the system effect of the failure. Therefore the reliability input data for the cost and benefit analysis are both from the component and the system level. The input data required for the Cable Application Study are presented in the next section.

12.6.2 Input Data for the Cost Benefit Analysis

The input data required for the cost and benefit analysis can be grouped into three types: (i) the cost specific data (for example the cost of repair), (ii) the reliability data for the system being analysed both for the component level (failure rate for average component) and for the system level (loss of energy for the affected load point), and (iii) the economic factors (for example interest rates). In the following paragraphs these data are presented as input data for the Cable Application Study that is the Birka system.

The costs of different maintenance activities for the Birka system have been analysed, and specifically costs related to faults in the 11 kV underground cables analysed as presented in report [20]. A result from this analysis is the average cost for the repair of cable, which is SEK 20,000-40,000 depending on cable length, laying conditions and related factors. Another interesting figure to keep in mind is MSEK 5 that Birka Service receive per month for handling the maintenance of Birka Näts network (not only the Stockholm network). Moreover, the cost of cable replacement (for two parallel cables) costs about SEK 2000/m, where the cost for the cable itself is a small part of the whole cost. The largest contribution to the cost relates to the laying.

The SINTEF study presents cost data for the two PM methods of rehabilitation and replacement as shown in Table 9.2. From the values in the table, the following average costs per metre cable are obtained: NKR 294/m and 261/m for the rehabilitation, and NKR 452/m and 569/m respectively for the replacement. One Norwegian crown (NKR) is about 1.5 Swedish crowns (SEK) and the resulting average values in SEK are 416 and
12.6. Cost and Benefit Analysis Comparing Maintenance Strategies

766. Consequently the cost for rehabilitation is about 54% of the cost for replacement.

It can be seen that the data from the SINTEF study shows much lower costs than the Birka study. This is probably due to the Birka system being analysed to represent an urban network which implies many complications for the cable laying, resulting in high costs. Based on this observation and the data above, the following assumptions are made for the input cost data for the analysis: \( c_{PM_n} = \text{SEK} \, 1000/\text{m} \) for silicon rehabilitation, and \( c_{PM_r} = \text{SEK} \, 2000/\text{m} \) for replacement. Consequently, it is assumed that the rehabilitation method costs half as much as the replacement method.

In the Cable Application Study, two different types of PM methods have been analysed (rehabilitation and replacement of cable), along with the situation without any PM. Therefore there are three different sets of input data for the system being analysed, referred to as: no PM, \( PM_{rp} \) and \( PM_{si} \). Furthermore, these maintenance methods have been analysed for two different strategies \( (S_1 \) and \( S_2) \) as defined in Table 12.2. Moreover, the component being effected by the PM measure is an average cable of the 11 kV underground cable referred to LH11. As defined by Equation 12.1, the length of this cable is 8,10584 km.

The component input data used for the cost analysis are represented by the composite failure rate function which is \( \lambda_{atot}(t, \text{no PM}), \lambda_{atot}(t, PM_{si}, S) \) and \( \lambda_{atot}(t, PM_{rp}, S) \) [1/yr]. Tables 12.4 and 12.5 present annual values for these failure rate functions for the different maintenance methods and strategies analysed.

The system input data used for the cost analysis are represented by the energy not-supplied function, that is \( LOE_{lp1}(t, \text{no PM}), LOE_{lp1}(t, PM_{si}, S) \) and \( LOE_{lp1}(t, PM_{rp}, S) \) [kWh/yr]. Table 12.7 presents annual values for these functions, which are output values from the reliability analysis using RADPOW.

Finally to complete the input data required for the cost analysis, the economic evaluation factors need to be defined. These include for example, the rates on capital and the cost of interruption, plus related costs. These kinds of data are somewhat more subjective than those discussed earlier, and also sensitive to changes on the financial market. Therefore it has been decided to use the same numerical values for these factors as those used in a recent economic analysis at a Swedish utility, Vattenfall and presented in
The interruption cost is discussed further when modelling the cost of interruption.

Table 12.9 summarizes the specifically introduced input data for cost and benefit analysis of the Cable Application Study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Repair cost</td>
<td>( c_f )</td>
<td>30,000 SEK/f</td>
<td>[120], [20]</td>
</tr>
<tr>
<td>Replacement cost</td>
<td>( c_{PM_{rp}} )</td>
<td>( 2 \cdot 10^6 ) [SEK/km]</td>
<td>[120], [20]</td>
</tr>
<tr>
<td>Rehabilitation cost</td>
<td>( c_{PM_{si}} )</td>
<td>( 1 \cdot 10^6 ) [SEK/km]</td>
<td>[120], [20], [130]</td>
</tr>
<tr>
<td>Cost for interruption</td>
<td>( c_{int} )</td>
<td>43 [SEK/kWh]</td>
<td>[139],[138]</td>
</tr>
<tr>
<td>Inflation</td>
<td>( d_1 )</td>
<td>0.02 i.e. 2%</td>
<td>[140], [138]</td>
</tr>
<tr>
<td>Interest rate</td>
<td>( d_2 )</td>
<td>0.07 i.e. 7%</td>
<td>[140], [138]</td>
</tr>
</tbody>
</table>

### 12.6.3 Fundamental Concepts and Methods used for the Economic Analysis

The aim of this cost and benefit analysis was to provide decision support for the maintenance planning; in other words for choosing maintenance method and strategy. However to achieve this, it is necessary to transform the technical issues (reliability indices) into economic quantities (like the cost of interruption), which in turn requires a basic knowledge of economic concepts and methods. In this section, some fundamental techniques for cost analysis are introduced that will be used in the modelling of cost functions for solving of the maintenance question.

An economic analysis is crucial for evaluating the effect of different maintenance strategies and maintenance methods. These analyses relate to long-term profitable assessment, that is investment calculations. Moreover, PM could be considered as an investment with the purpose of reducing the number of failures or improving component condition.

In general terms, an investment refers to the use of capital, which results in long-term payment consequences [141]. For an electric power system, long-term would typically refer to an expected lifetime of about 30 years.
Investments are taken up as assets in the balance sheet, and commonly as building and construction assets. The cost of the investment is then divided by depreciations over the economic lifetime of the investment.

Investment decisions are often times difficult. This is mainly due to their characteristic uncertainty. For example, it is difficult to decide the future payments and the economic lifetime of the investments. Investment calculations aim to simplify and support investments decisions. The most fundamental concepts are the in-and-out payments. The investment calculation is primarily about deciding whether or not a resource requirement (in the form of a base investment) is justifiable with respect to size and distribution over the period of payment surplus (of in-and-out payments). However, payments at different points in time are not comparable. The money that is available today is of greater value than the same amount of money after a period of time (for instance a year). This is due to the fact that the amount of money that is available today could be increased by a favourable interest rate. Put simply, a one-hundred Swedish Crown note today has a current value of SEK 100, however SEK 100 after 20 years will have a value that is appreciably lower than 100 SEK today. Therefore, to make different payments comparable it is necessary to re-evaluate them to the same point in time.

Another fundamental concept is the, interest rate, or the owners earning requirement on income from capital. There is no simple way to decide on this, however it should be defined in respect to the following: the rate on which loans are made, the alternative uses of the investment resources, or the risk that is associated with the investment.

Economic calculations are for reasons of simplicity, normally made on a yearly basis. This implies the assumption that all payments are considered as transferred at the same time each year.

Three commonly used methods for investment calculations are presented below.

1. Pay Back Method
   The pay back method defines how long it will take for the investment to recover initial outlay. This is the pay back period. In this simple form of the method, this time is defined as the time when the invested capital without the rate, equals the sum of the yearly surplus expressed by a simple ratio. This method is suitable for comparing investments
with short lifetimes. This is for example because it does not consider when the payments are made and therefore would ignore the benefits from early payments.

2. Present Value Method
The present value method means that all the payments are compared at one point in time, being the present time. The present value (PV) means the amount of money that should be put into the bank now at a certain rate ($d$) to pay for an outlay ($C$) after $n$ years. This means that all future payments are re-calculated to the equivalent value for the present time. This is made by discounting the payment surplus for each year by the use of a capital rate, for example an interest rate.

The present value of one outlay ($C$) to be payed after $n$ years is gained by multiplying this with the present value factor ($PV_f(n, d)$) as follows:

$$PV = C \cdot PV_f(n, d) \Leftrightarrow C \cdot (1 + d)^{-n} \quad [\text{SEK}] \quad (12.12)$$

where $C$ is the outlay in [SEK], $n$ is the number of years from the present to the date of outlay, and $d$ is the discount rate where for example an interest rate of 7% ⇒ $d = 0.07$.

A common situation is where there are equal annual payments. In this case the total present value is the sum of present values for these yearly payments. For this case, a specific formula for the present value can be evaluated by using the present value sum factor ($PV_{sf}(n, d)$), which is defined as follows:

$$PV = C \cdot PV_{sf}(n, r) \Leftrightarrow C \cdot \frac{(1 + d)^n - 1}{d(1 + d)^n} \quad [\text{SEK}] \quad (12.13)$$

This method is a powerful tool and is widely used. However, the main disadvantage with it is that the discount rate, which to a great extent decides the result, is somewhat subjective. One way of getting around this is by using the internal rate of return. The internal rate of return is defined by the discount rate that results in a zero net present value, which is when the present value of the costs equals the revenues.
However, in this analysis here, only the costs are being analysed and this alternative method will therefore not be investigated further.

3. Annual Cost Method

In this method the costs are evaluated as annual payments. This method is useful when comparing alternative investments with different lifetimes. The present value is then spread over the lifetime, for example with a yearly equal sum of the depreciation and the interest rate over an asset lifetime. This constant annual payment is usually referred to as the annuitized value \( a \). The annuity that defines equal yearly payments of a present value can be evaluated by using the previously defined present value sum factor as follows:

\[
a = \frac{PV}{PV_{s,f}(0, r)} \Leftrightarrow PV \cdot \frac{d(1+d)^n}{(1+d)^n-1} \quad \text{[SEK]} \quad (12.14)
\]

The following simple calculations have been used to provide examples of the above methods.

*Example 12.1.* Evaluate the present value of an investment in PM performed on cables after 9 years of service, for a cost of MSEK 2/km. Assume that 30% of the cables with average length of 8.016 km are effected by the PM measure. Furthermore, assume that this amount of money could be put into the bank with a rate of 2%. (Solution) The cost of PM is a one time cost of: \( 2 \cdot 0.3 \cdot 8.016 \approx \text{MSEK} 4.864 \), using Equation 12.12 \( PV = C \cdot (1 + d)^{-n} = 4.864 \cdot (1.02)^{-9} \approx \text{MSEK} 4.07 \).

*Example 12.2.* Assume the same situation as in Example 12.1, but with PM applied at years 11 and 12 respectively. Now, evaluate the total present value for the three investment costs. (Solution) Equation 12.12 \( PV = C \cdot (1 + d)^{-n} + C \cdot (1 + d/100)^{-11} + C \cdot (1 + d)^{-12} = 4.864 \cdot (0.837 + 0.804 + 0.788) \approx \text{MSEK} 11.82 \). If there was no rate, the cost would instead be \( 4.864 \cdot 3 \approx \text{MSEK} 14.59 \).

These two examples illustrate the benefit of for example a utility having a contract with a fixed price for future PM activities. However, if the future investments were payed with loans instead, the economic evaluation should take into account the rate of the loan that would increase the required cost of the investment.
Example 12.3. Based on Example 12.2, use present value analysis to show which of the three alternative time points for PM (9, 11 or 12) is the most cost effective. (Solution) Evaluate the present values for the three investment alternatives and choose the solution with the lowest present value. Equation 12.12 \( PV = C \cdot (1 + d)^{-n} \)
Alternative 1: \( PV = 4.864 \cdot (1.07/100)^{-9} \approx MSEK4.07 \),
Alternative 2: \( PV = 4.864 \cdot (1.07/100)^{-11} \approx MSEK3.91 \), and
Alternative 3: \( PV = 4.864 \cdot (1.07/100)^{-12} \approx MSEK3.835 \),
\( \Rightarrow \) Alternative 3.

This example demonstrates that the lowest present value is gained with the investment as late as possible. Consequently, it has been shown that it is most cost-effective to perform the PM measure as late as possible.

Example 12.4. Evaluate the annual constant payment of the depreciation and the interest rate. Assume the investment cost for PM by replacement of cables is MSEK 4.864. Furthermore, assume a remaining lifetime of 21 years and an interest rate of 7\%. (Solution) Equation 12.14 \( a = PV \cdot \frac{d \cdot (1 + d)^n}{(1 + d)^n - 1} = PV \cdot \left(0.07 \cdot \frac{(1.07)^{21}}{1 - (1.07)^{21}} \right) \approx 0.092 \Rightarrow \) Annual payment is \( 4.864 \cdot 0.092 \approx MSEK0.449 \).

Example 12.5. Evaluate the present value for a yearly payment of MSEK 0.449 for 21 years, and with an interest rate of 7\%. (Solution) Equation 12.13 \( PV = C \cdot PV_{sf}(21, 7) = C \cdot \frac{(1.07)^{21} - 1}{0.07(1.07)^{21}} = 0.449 \cdot 10.8335 \approx MSEK4.865 \).

It can be seen from these simple examples that an economic analysis could be very extensive and complicated. However making a comprehensive cost analysis lies outside the scope of this thesis, and the cost functions that are being modelling require quite simple cost considerations, though these are by no means trivial.

12.6.4 Modelling the Cost of Failure

The cost for restoration of supply after failure from a utility perspective, can be expressed as the product of the failure rate and the cost for restoration. A general formula for the annual cost of restoration, referred to here as cost of failure, can consequently be defined with the simple relation:
\[ C_f(t) = \lambda(t) \cdot c_f(t) \quad t_0 \leq t \leq T \quad \text{[SEK/yr]} \quad (12.15) \]

where \( \lambda(t) \) is the failure rate [f/yr], and \( c_f(t) \) is the cost of failure [SEK/f].

The failure rate function which depends on the choice of maintenance method and strategy has been analysed previously in great detail. The input data functions for the Cable Application Study are as introduced in Section 12.6.2: \( \lambda_{at\alpha}(t, \text{no PM}) \), \( \lambda_{at\alpha}(t, PM_{st}, S) \) and \( \lambda_{at\alpha}(t, PM_{rp}, S) \).

For defining the cost function, it is desirable to predict how the cost of failure could change in the future. From the input data (Section 12.6.2), a fixed cost for repair is known. Assume that this cost of a failure changes with time \( (c_f(t) \) during the period \( t = 0, \ldots n \), and increases with a rate of \( d_1 \) (for example due to inflation) each year, then the resulting cost per failure for each year is then defined by a geometric series [61]. Consequently, the cost of failure function can be defined by the following equation:

\[ c_f(t) = c_f(t = 0) \cdot (1 + d_1)^t \quad t_0 \leq t \leq T \quad \text{[SEK/f]} \quad (12.16) \]

where \( c_f(t = 0) \) is the cost of failure (for example the repair cost provided by present data in [SEK/f], and \( d_1 \) is the inflation rate, for example 2\% \( \Rightarrow \) \( d_1 = 0.02 \).

Figure 12.17 illustrates a function for the cost per failure, when the cost is increased with the inflation rate of 2\% over a 30 year period. For this situation, the cost is increased by the factor \((1.02)^{30} \approx 1.81\), that is by 80\%, and the cost of failure increases from SEK 30,000 to 54,000.

The cost of failure with CM means simply that the maintenance activity is applied when failure occurs. As a result from the earlier analysis and assumptions, the CM results in no-effect on the failure rate function. Therefore, the failure rate function corresponding to the CM case is \( \lambda_{tot}(t, \text{noPM}) \). Based on Equations 12.15 and 12.16, the resulting function for cost of failure with the CM method can therefore be expressed as follows:
12.6. Cost and Benefit Analysis Comparing Maintenance Strategies

\[ CCM_f(t) = \lambda_{ata}(t, \text{no PM}) \cdot c_f \cdot (1 + d_1)^t \]  \[ \text{[SEK/yr]} \]  \hspace{1cm} (12.17)

The cost of failure functions when PM is applied can be defined in a similar way as for the CM method. However, the characteristic of the failure rate functions depend on the choice of PM strategy \( S \). In the Cable Application Study with the two different PM methods of rehabilitation \( PM_{si} \) and replacement \( PM_{rp} \), the resulting cost of failure functions are expressed as follows:

\[ CPM_{f,si}(t, S) = \lambda_{ata}(t, PM_{si}) \cdot c_f \cdot (1 + d_1)^t \]  \[ \text{[SEK/yr]}, \]  \hspace{1cm} (12.18)

and

\[ CPM_{f,rp}(t, S) = \lambda_{ata}(t, PM_{rp}) \cdot c_f \cdot (1 + d_1)^t \]  \[ \text{[SEK/yr]}. \]  \hspace{1cm} (12.19)

The functions for cost of failure defined above represent three different maintenance methods. The effect of these different methods has been analysed for the Cable Application Study.

Figure 12.18 shows yearly cost results for the three different cost functions of \( CCM_f(t) \), \( CPM_{f,si}(t, S) \) and \( CPM_{f,rp}(t, S) \). Furthermore, the results are shown for two PM strategies, where PM is applied at years 9, 11 and 12, and with 10% \( (S_1) \) or 30% \( (S_2) \) of the cables subject to PM on each occasion. The trend in the increase of cost due to the interest rate can be seen as well as the rise due to PM activities. Furthermore, it can be seen that the costs for PM methods are consistently higher than for the CM method. Table 12.10 presents the resulting values for the cost of failure function. These values demonstrate the reduction in the cost of failure due to PM. This decrease depends on the strategy, where in \( S_1 \) a total of 30% of the 11 kV cables are maintained, and in \( S_2 \) a total of 90% are. These strategies, for the replacement method regime, give a benefit within the interval SEK 20,000 – 50,000. The overall conclusion from these results is that the lowest cost of failure is gained with PM by replacement. This is due to both the lowest total cost over the whole period, as well as for each year during the period.
Another way of presenting the cost is by cumulative values. This involves a cost function that adds the cost for each year to that year. Figure 12.19 shows the cumulative cost functions for a similar situation to what was presented above. These results illustrate what the maximum and the minimum costs in respect to failure are each year for the CM method and the $PM_{rp}$ method respectively. This implies that in this application study comparing the combinations of two maintenance strategies, that the most cost effective solution is to perform PM using the replacement method.

The results for the Cable Application Study have been validated by comparisons with corresponding manually calculated values using Equations 12.17 to 12.19. The conclusion is that the results presented from the equations implemented are correct. The values selected have been presented below.

\[
\text{Input data } \quad c_f = 30000 \quad \text{SEK/f, } d_1 = 0.02
\]

Strategy $S_1$ applies:
\[
s_1 = s_2 = s_3 = 0.1, t_{PM1} = 9, t_{PM1} = 11, t_{PM1} = 12
\]
\[
\implies CCM_f(t = 0) = \lambda_{atot}(t = 0, \text{no PM}) \cdot 30000 \cdot 1 = 0.10069 \cdot 30000 \approx 3021 \quad \text{SEK/yr}
\]
\[
\implies CPM_{f,si}(t = 9, S) = \lambda_{atot}(t = 9, PM_{si}, S_1) \cdot 30000 \cdot (1.02)^9 = 0.14778 \cdot 30000 \cdot 1.19509 \approx 5298 \quad \text{SEK/yr}
\]
\[
\implies CPM_{f,rp}(t = 9, S) = \lambda_{atot}(t = 9, PM_{rp}, S_1) \cdot 30000 \cdot (1.02)^9 = 0.14307 \cdot 30000 \cdot 1.19509 \approx 5129 \quad \text{SEK/yr}
\]

Strategy $S_2$ applies:
\[
s_1 = s_2 = s_3 = 0.3, t_{PM1} = 9, t_{PM1} = 11, t_{PM1} = 12
\]
\[
\implies CPM_{f,si}(t = 12, S) = \lambda_{atot}(t = 12, PM_{si}, S_2) \cdot 30000 \cdot (1.02)^{12} = 0.15793 \cdot 30000 \cdot 1.26824 \approx 6009 \quad \text{SEK/yr}
\]
\[
\implies CPM_{f,rp}(t = 12, S) = \lambda_{atot}(t = 12, PM_{rp}, S_2) \cdot 30000 \cdot (1.02)^{12} = 0.11180 \cdot 30000 \cdot 1.26824 \approx 4254 \quad \text{SEK/yr}
\]

### 12.6.5 Modelling the Cost of Preventive Maintenance

The cost for a PM activity is a one time cost that in economic values would be spread by depreciation. One common way to consider the cost of depreciation economically is to assume a constant amount for each year, being the sum
### Table 12.10. Results for the cost of failure per year from the Cable Application Study, by different maintenance methods and two preventive maintenance strategies.

<table>
<thead>
<tr>
<th>Time [yr]</th>
<th>$CCM_f(t)$ [SEK/yr]</th>
<th>$CPM_{f,si}(t, S)$ $S_1$</th>
<th>$CPM_{f,si}(t, S)$ $S_2$</th>
<th>$CPM_{f,rp}(t, S)$ $S_1$</th>
<th>$CPM_{f,rp}(t, S)$ $S_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>3021</td>
<td>3021</td>
<td>3021</td>
<td>3021</td>
<td>3021</td>
</tr>
<tr>
<td>1</td>
<td>3089</td>
<td>3089</td>
<td>3089</td>
<td>3089</td>
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<tr>
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<td>3191</td>
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<td>4004</td>
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Total: [MSEK] 0.24602 0.23546 0.21435 0.23202 0.20400
of the cost of the interest rate and the depreciation [141]. This method is
called an annualized method, and was presented in Section 12.6.3. It would
however be very difficult to show the benefit in a PM activity if not only the
cost for the activity itself but also an interest on the capital investment would
be required. Furthermore, in today’s electricity market, it is common that
the utility draws up a contract with a fixed cost for a future PM measure.
Both these observations indicate that a good model for the cost of PM is
annual depreciation based on the fixed cost of the PM, which has been used
in the rest of the analysis.

Two strategies for the PM have been analysed for the Cable Application
Study, being $S_1$ and $S_2$. Both these mean that PM is applied three times
within the study period $t : 0 \rightarrow 30$ years. Consequently, these strategies
result in three different depreciation times for the spread of the investment
costs required for PM. This depreciation time would be the time until the
end of the study period and begin at the maintenance point, expressed as
\[ n = T - t_{PMj} + 1 \text{ for } j = 1, 2, 3. \]

However, the cost of PM for a cable component depends on the length
of cable being measured. In the Cable Application Study, the 11 kV cable
being analysed had an average length ($l_{av}$) of about 8.106 km. Furthermore,
the total PM cost depends on the percentage of the components that are
Figure 12.18. Cost of failure function for three different maintenance methods and two preventive maintenance strategies, using results from the Cable Application Study.
**12.6. Cost and Benefit Analysis Comparing Maintenance Strategies**

![Graph of Cumulative Cost of Failure](image)

**Figure 12.19.** Cumulative cost of failure function for three different maintenance methods and two preventive maintenance strategies, using results from the Cable Application Study.
exposed to the PM routines. This was earlier defined in the maintenance strategy, for example in Strategy S2, with \( s_1 = s_2 = s_3 = 30\% \) of components subject to PM each occasion.

Assuming that the investment costs for PM are either \( c_{PMi} \) for the rehabilitation method, or \( c_{PMr} \) for the replacement method, then the resulting characteristic for the PM cost functions can then be defined by the following equations:

\[
C_{PM_{si,j}} = c_{PM_{si}} \cdot s_j \cdot l_{av} \quad j = 1, 2, 3, \ldots \quad [\text{SEK}] \quad \text{and} \quad C_{PM_{ri,j}} = c_{PM_{ri}} \cdot s_j \cdot l_{av} \quad j = 1, 2, 3, \ldots \quad [\text{SEK}].
\]  

(12.20)

where

- \( c_{PM_{si}} \) is the cost for PM by rehabilitation [SEK/km],
- \( c_{PM_{ri}} \) is the cost for PM by replacement [SEK/km],
- \( s_j \) is the proportion of cables effected by PM at time \( t_{PM_j} \), and
- \( l_{av} \) is the average length of a cable being effected by PM.

The annual cost (in SEK/yr) for the Cable Application Study with PM applied three times with either rehabilitation \( (PM_{si}) \) or replacement \( (PM_{ri}) \) can then be formulated as follows:

\[
CP_{PM_{si}}(t, S) \quad [\text{SEK/yr}] \quad = \quad \begin{cases} 
0 & : t_0 \leq t \leq t_{PM1} \\
\frac{C_{PM_{si,1}}}{(T-t_{PM1}+1)} & : t_{PM1} \leq t \leq t_{PM2} \\
\frac{C_{PM_{si,1}}}{(T-t_{PM1}+1)} + \frac{C_{PM_{si,2}}}{(T-t_{PM2}+1)} & : t_{PM2} \leq t \leq t_{PM3} \\
\frac{C_{PM_{si,1}}}{(T-t_{PM1}+1)} + \frac{C_{PM_{si,2}}}{(T-t_{PM2}+1)} + \frac{C_{PM_{si,3}}}{(T-t_{PM3}+1)} & : t_{PM3} \leq t \leq T
\end{cases}
\]  

(12.21)
and

\[
CPM_{PM_p}(t, S) \quad \text{[SEK/yr]} = \begin{cases} 
0 & : t_0 \leq t \leq t_{PM1} \\
\frac{CPM_{PM1}}{(T-t_{PM1}+1)} & : t_{PM1} \leq t \leq t_{PM2} \\
\frac{CPM_{PM1}}{(T-t_{PM1}+1)} + \frac{CPM_{PM2}}{(T-t_{PM2}+1)} & : t_{PM2} \leq t \leq t_{PM3} \\
\frac{CPM_{PM1}}{(T-t_{PM1}+1)} + \frac{CPM_{PM2}}{(T-t_{PM2}+1)} + \frac{CPM_{PM3}}{(T-t_{PM3}+1)} & : t_{PM2} \leq t \leq T
\end{cases}
\]

(12.22)

Figure 12.20 illustrates the cost functions due to PM, being \( CPM_{PM_{S_1}}(t, S) \) and \( CPM_{PM_{S_2}}(t, S) \). The results are shown for the Cable Application Study and for the two PM strategies \( S_1 \) and \( S_2 \). The three different cost levels due to the depreciation of the PM investment costs can be seen. As expected, these differ by a factor of three (the difference in components affected by PM). Furthermore, Table 12.11 presents annual values for the Cable Application Study with the cost of the three PM measures distributed yearly. The results are presented for the application of the two strategies \( S_1 \) and \( S_2 \). It can be seen that the cost of PM significantly increases with more components being effected by the maintenance action, which is expected for the underground cable component.

The corresponding cumulative cost functions are illustrated in Figure 12.21.

Results for the Cable Application Study have been validated by comparisons with corresponding manually calculated values using Equations 12.20 or 12.22. The conclusion is that the results for the implemented equations are correct. The values selected have been presented below.
12.6. Cost and Benefit Analysis Comparing Maintenance Strategies

Input data: \( T = 30 \) years, \( l_{av} = 8.10584 \) km, \( c_{si} = \) SEK\( 1,000,000 \)

Strategy \( S_1 \) applies:

\( s_1 = s_2 = s_3 = 0.1, t_{PM1} = 9, t_{PM1} = 11, t_{PM1} = 12 \)

\( C_{PM_{s1}} = C_{PM_{s1}} \cdot l_{av} \cdot s_1 \approx 1,000,000 \cdot 8.106 \cdot 0.1 \approx $810,584 \)

\( s_3 = s_2 = s_1 \Rightarrow C_{PM_{s2}} = C_{PM_{s3}} = \) SEK\( 810,600 \)

\( C_{PM_{s1}}(t = 9, S) = \frac{C_{PM_{s1}}}{(T - t_{PM1} + 1)} = \frac{810,584}{22} \approx 36,845 \) SEK/yr

\( C_{PM_{s1}}(t = 11, S) = C_{PM_{s1}}(t = 9, S) + \frac{C_{PM_{s2}}}{(T - t_{PM2} + 1)} = 36,845 + \frac{810,584}{20} \approx 36,845 + 40,529 \approx 77,374 \) SEK/yr

\( T_{C_{PM_{s1}}}(t = 12, S) = C_{PM_{s1}}(t = 11, S) + \frac{C_{PM_{s3}}}{(T - t_{PM3} + 1)} = 81,060 + \frac{810,584}{20} \approx 77,374 + 42,662 \approx 120,036 \) SEK/yr

\( T_{P_{PM_{s1}}} = 2 \cdot C_{PM_{s1}}(t = 9, S) + C_{PM_{s1}}(t = 11, S) + 19\cdot C_{PM_{s1}}(t = 12, S) \approx \) SEK\( 2,431,800 \) \( \Rightarrow 3 \cdot \) SEK\( 810,600 \).

12.6.6 Modelling the Cost of Interruption

As previously discussed, the cost of interruption is related to the customer effect of the availability of supply. This cost is related to the reliability value. It is a difficult matter to define this cost since it is based on subjective judgment, for example how many interruptions that a specific customer determines is acceptable during a certain period of time. Investigations have been made to define this cost, based on questionnaires sent to customers who are divided into different customer categories. Different methods to consider customer interruption costs are evaluated in [142]. Results from a comprehensive study made in Sweden are presented in [139]. This same study was based on a questionnaire sent to 4000 customers with a reply frequency of 57%. The Swedish utilities (including for example Vattenfall and Birka Nät), use the results from this report when evaluating the cost of interruptions.

As input data for this analysis, the cost of interruption \( (c_{int}) \) in [SEK/kWh] as defined in Table 12.9, is the value currently used by Vattenfall.

One reliability index for measuring the customer effect is the energy not-supplied \( (LOE) \). A change in this index can be used to define the benefit in reliability value. In the Cable Application Study, this function has been evaluated as part of the previously presented reliability analysis of the Birka
Table 12.11. Results for the cost of preventive maintenance per year in the Cable Application Study with different maintenance methods and two Strategies ($S_1$ and $S_2$). The results are shown with the cost of PM activity distributed by depreciation without any rate.

<table>
<thead>
<tr>
<th>Time [yr]</th>
<th>$CPM_{PM_1}(t, S)$ $CPM_{PM_2}(t, S)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[SEK/yr] [SEK/yr] [SEK/yr] [SEK/yr]</td>
</tr>
<tr>
<td>0</td>
<td>0 0 0 0</td>
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<td>8</td>
<td>0 0 0 0</td>
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<tr>
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</tr>
<tr>
<td>11*</td>
<td>77374 232121 154748 464244</td>
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<tr>
<td>Total:</td>
<td>2.43175 7.29526 4.86350 14.59052</td>
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</table>
Figure 12.20. Cost of the preventive maintenance (PM) function for three different maintenance methods and two PM strategies, showing results for the Cable Application Study.
Figure 12.21. Cumulative cost of the preventive maintenance (PM) function for three different maintenance methods and two PM strategies, showing results for the Cable Application Study.
12.6. Cost and Benefit Analysis Comparing Maintenance Strategies 347

system. Note that this index is evaluated for each load point, where for the Birka system $Lp_1$ is where the 11 kV cable components are connected.

These reliability functions together with the cost of interruption, constitute the input data for the model defined below for the cost of interruption function. By assuming that the cost for interruptions change in time in similar ways to the cost of failures, and increase with the inflation rate of 2\% over a 30 year period, then the cost of interruption with CM can then be formulated as follows:

$$CCM_{Lp_1, \text{int}}(t) = LOE_{Lp_1}(t, \text{no PM}) \cdot c_{\text{int}} \cdot (1 + d_1)^t \quad t_0 \leq t \leq T \quad [\text{SEK/yr}]$$

(12.23)

where $LOE_{Lp_1}(t)$ is the energy not-supplied function at load point $Lp_1$ in $[\text{kWh/yr}]$, $c_{\text{int}}$ is the customer cost of interruption $[\text{SEK/kWh}]$, and $d_1$ is the inflation rate $2\% \Rightarrow d_1 = 0.02$.

The cost of interruption functions when PM is applied is defined in similar way as the CM as follows:

$$CPM_{\text{int, } PM_{si}}(t, S) = LOE_{Lp_1}(t, PM_{si}, S) \cdot c_{\text{int}} \cdot (1 + d_1)^t \quad [\text{SEK/yr}]$$

(12.24)

and

$$CPM_{\text{int, } PM_{rp}}(t, S) = LOE_{Lp_1}(t, PM_{rp}, S) \cdot c_{\text{int}} \cdot (1 + d_1)^t \quad [\text{SEK/yr}]$$

(12.25)

The resulting cost functions for interruption are shown in Figures 12.22 and 12.23. The results show that the lowest cost of interruption is gained with PM by replacement. Table 12.12 presents the results for the Cable Application Study with the cost of the interruption distributed yearly.

Results for the Cable Application Study have been validated by comparison with corresponding manually-calculated values using Equations 12.23 to 12.25. The conclusion is that the results from the implemented equations are correct. The values selected have been presented below.
\[ T = 30 \text{ year}, c_{int} = 43 \text{ SEK/kWh} \]

Strategy \( S_1 \) applies:

\[ s_1 = s_2 = s_3 = 0.1, t_{PM1} = 9, t_{PM1} = 11, t_{PM1} = 12 \]

\[ \Rightarrow CCM_{int}(t = 0) = LOE_{Lp1}(t = 0, \text{no PM}) \cdot 43 \cdot 1 = 389.65 \cdot 43 \approx 16,755 \text{ SEK/yr} \]

\[ \Rightarrow CPM_{int, PM_1}(t = 9, S) = LOE_{Lp1}(t = 9, PM_{si}, S_1) \cdot 43 \cdot (1.02)^9 \approx 462.07 \cdot 43 \cdot 1.19509 \approx 23,745 \text{ SEK/yr} \]

\[ \Rightarrow CPM_{int, PM_2}(t = 9, S) = LOE_{Lp1}(t = 9, PM_{si}, S_1) \cdot 43 \cdot (1.02)^9 \approx 454.83 \cdot 43 \cdot 1.19509 \approx 23,373 \text{ SEK/yr} \]

**Figure 12.22.** Cost of the interruption function for three different maintenance methods and two preventive maintenance strategies, using results for the Cable Application Study.
Table 12.12. Results for the cost of interruption per year for the Cable Application Study with different maintenance methods and two strategies ($S_1$ and $S_2$)

<table>
<thead>
<tr>
<th>Time [yr]</th>
<th>$CCM_{int}(t)$ [SEK/yr]</th>
<th>$CPM_{int,sl}(t, S)$ [SEK/yr]</th>
<th>$CPM_{int,rl}(t, S)$ [SEK/yr]</th>
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Total: [MSEK] 0.97017 0.94691 0.900037 0.93930 0.87755
Figure 12.23. Cumulative cost of the interruption function for three different maintenance methods and two preventive maintenance strategies, showing results for the Cable Application Study.
12.6.7 Evaluation and Comparison of Total Annualized Costs

Previous sections have defined cost functions for the various situations with different types of PM methods as well as with CM. Furthermore, the impact of different PM strategies has been modelled and analysed. The three different cost functions that have been analysed are: cost of failure, cost of PM, and cost of interruption.

The aim was to compare these maintenance methods and strategies and to define which of the same that would give the most cost-effective solution, that is, result in a cost-effective maintenance plan. Consequently this completes the RCM plan.

One way for comparing these maintenance methods and different strategies is by analysing the annual costs. It is interesting to compare these annual costs both for each year (for example if there is an upper limit for yearly expenses) and as a total cost for the period. The latter is possibly an assessment of the total required resources. However, as identified in Section 12.6, payments made at different points in time are not comparable, since money today has a greater value than the same amount of money in the future. It was also identified that it is cost effective to postpone a PM activity if possible. Consequently, annual cost values are of interest but should be evaluated as present values.

In the Cable Application Study, the total annual costs can be formulated for the three different maintenance methods (CM and PM by either rehabilitation or replacement). Furthermore, the PM methods have been analysed for two different strategies: $S_1$ and $S_2$. Moreover, cost functions have been analysed for three different costs defined as: failure, PM, and interruption. This results in eight different cost functions that can be summarized into the three maintenance methods as follows.

Total annual cost of CM:

$$TCCM(t) = CCM_f(t) + CCM_{int}(t) \quad : \quad t_0 \leq t \leq T \quad [SEK/yr]$$  

(12.26)

Total annual cost of PM by rehabilitation:

$$TCPM_{si}(t, S) =$$

$$CPM_{f,si}(t, S) + CPM_{PM,si}(t, S) + CPM_{int,si}(t, S) \quad [SEK/yr]$$  

(12.27)
Total annual cost of PM by replacement:

\[ TCM_{rp}(t, S) = CPM_{f, rp}(t, S) + CPM_{PM, rp}(t, S) + CPM_{int, rp}(t, S) \quad [SEK/yr] \]

(12.28)

Figures 12.24 and 12.25 show these total annual cost functions for the Cable Application Study, and for the two different analysed strategies. It can be seen clearly that the dominant cost values are those for PM. However, the figures also stress the important factor of the distribution of the costs over time, where for example the significant rise in annual cost due to PM measures occurs after about 11 years. Table 12.13 presents the total annual values for this study. This table shows that for both of the strategies PM implies a reduction in the cost of failures, and the cost of interruption. However, the cost of the PM activity itself (rehabilitation or replacement of underground 11 kV cable) is extensive. The cost analysis therefore indicates that the cost-effective solution found by comparing the total effect on these cost factors is "not to perform PM". However, this analysis does not take into account the effect of the point in time when the PM is made, which is analysed in detail in the next section.

The results could also be analysed regarding the sensitivity of the parameters. When comparing the resulting cost functions it is understood that the cost of failure and the cost of interruption include an economic factor (the rate \( d_1 \)), which is not included in the cost of PM. This means that one way of changing the balance between total costs of the CM and PM methods is to adjust this factor. The rate \( d_1 = 2\% \) is used as input data for the Cable Application Study. Figure 12.26 illustrates the effect of using a rate of 10\% instead. These results indicate a significant change in the balance between the cost of CM and PM. Consequently, the conclusion is that it is possible to obtain an equilibrium level between CM and PM. Whether this would be expected economically is however another matter.

Nonetheless, it is important to recognize that the maintenance of the cable component will be expensive since it involves extensive changes, for example by injection or replacement. For other types of components this situation would be different, for example a circuit breaker could be maintained by less complicated and less expensive methods, and would not be
replaced as a whole entity. Therefore it is understood that the PM benefit for other types of components could be more easily seen than for the cable component. This observation is important for not drawing incorrect conclusions from these results.

![Total annualized costs for maintenance strategy $S_1$](image)

**Figure 12.24.** Annual total costs for Strategy $S_1$, showing results for the Cable Application Study.

### 12.6.8 Present Value Analysis

Total annual cost values for the different maintenance methods were evaluated in the previous section. However, it was also identified that for an accurate comparison it is necessary to evaluate present values. The next step in the analysis is therefore to evaluate present values for these annual costs. The cost functions have been evaluated as present values according to the technique presented earlier in Section 12.6.3.
Figure 12.25. Annual total costs for Strategy $S_2$, showing results for the Cable Application Study.

Table 12.13. Sum of the total annual cost for different maintenance methods for the Cable Application Study and preventive maintenance strategies $S_1$ and $S_2$.

<table>
<thead>
<tr>
<th>Cost factors</th>
<th>Cost of Different maintenance methods [MSEK]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$TCCM$</td>
</tr>
<tr>
<td></td>
<td>$S_1$</td>
</tr>
<tr>
<td>$C_f$</td>
<td>0.24602</td>
</tr>
<tr>
<td>$C_{PM}$</td>
<td></td>
</tr>
<tr>
<td>$C_{int}$</td>
<td>0.97017</td>
</tr>
<tr>
<td>Total</td>
<td>1.21620</td>
</tr>
</tbody>
</table>
12.6. Cost and Benefit Analysis Comparing Maintenance Strategies

![Graph](image)

**Figure 12.26.** Effect of change in economic variables. Annual total costs for Strategy $S_1$, showing results for the Cable Application Study.
Present values can be formulated as the sum of discounted values for payments at different points in time as follows:

\[ TCPV = \sum_{n=t_0}^{T} C(n) \cdot PV_f(n, d_2) \quad : \quad t_0 \leq n \leq T \quad [SEK] \tag{12.29} \]

where \( n \) is the time in numbers of years after the present time for the payment \( C(n) \), \( d \) is the discount rate, \( PV_f(n, d_2) \) is the present value factor as defined in Equation 12.12.

For the Cable Application Study, the following present values can then be defined in a similar way.

**Present value for the total annual cost of CM:**

\[ TCCMPV = \sum_{t=t_0}^{T} TCCM(t) \cdot PV_f(t, d_2) \quad : \quad t_0 \leq t \leq T \quad [SEK] \tag{12.30} \]

**Present value for the total annual cost of PM by rehabilitation:**

\[ TCPM_{s1}PV = \sum_{t=t_0}^{T} TCPM_{s1}(t, S) \cdot PV_f(t, d_2) \quad : \quad t_0 \leq t \leq T \quad [SEK] \tag{12.31} \]

**Present value for the total annual cost of PM by replacement:**

\[ TCPM_{r1}PV = \sum_{t=t_0}^{T} TCPM_{r1}(t, S) \cdot PV_f(t, d_2) \quad : \quad t_0 \leq t \leq T \quad [SEK] \tag{12.32} \]

Figures 12.27 and 12.28 illustrate the procedure for present value analysis, and show the results for the Cable Application Study. These figures present the present value as the sum of the total annual costs which are each individually discounted with a certain rate. For the results presented, the rate is 7\%, which equals the interest rate presented in Table 12.9. Furthermore, the figures illustrate the impact of different maintenance strategies, where \( S_2 \) implies a significantly higher present value than \( S_1 \), which is due to the greater required investment in PM.

Figure 12.29 displays the total present values for the three alternative maintenance methods and the two different Strategies. The results for all
cases show that the PM methods result in the highest present values. This indicates that the cost-effective solution is to ”not-perform PM”, in other words apply CM only, as is shown by the first method. However, it should be emphasized that the outcome is totally dependent on the conditions created by the input data. If for example the discount rate were changed, then different results would be obtained. This effect can also be seen from the figure comparing the results for Strategy $S_1$ with two different discount rates of: (i) zero, which implies that the present value equals the direct sum of the annualized values, and (ii) 7% as previously shown. Two interesting results can be observed here. The first is that the discount rate has a significant impact on the total present value, and secondly that the difference between the payments required for CM and PM can be reduced. This latter observation leads to the conclusion that there would exist an optimal point when it is equally beneficial to apply PM as CM, and moreover that there would be a solution where PM would be preferable to CM. Analysis of the impact of different rates has been made and the point for which it is equally beneficial to use either CM or PM has been identified. Table 12.14 summarizes some resulting values for the present value analysis. A point where all methods result in the same cost, is where the cost of failure $c_f = 30,000$ SEK/f. Although this equilibrium point $d_2 = 30,000\%$ seems unreasonable it is theoretically possible. However, the significant result is that it is possible to find an optimal balance between CM and PM based on cost considerations.

<table>
<thead>
<tr>
<th>Discount rate %</th>
<th>Present value of maintenance methods [MSEK]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$TCCMPV$</td>
</tr>
<tr>
<td>0</td>
<td>1.21620</td>
</tr>
<tr>
<td>7</td>
<td>0.43058</td>
</tr>
<tr>
<td>10</td>
<td>0.31003</td>
</tr>
</tbody>
</table>

Table 12.14. Present value analysis with the effect of different discount rates showing the results for the Cable Application Study and strategies $S_1$ and $S_2$. 
Figure 12.27. Present value analysis illustrating the impact of different maintenance strategies when applying preventive maintenance by rehabilitation, showing results for the Cable Application Study. Note that the first bar shows the present value which is the sum of the annual costs (the other bars).
Figure 12.28. Present Value analysis illustrating the impact of different maintenance strategies when applying preventive maintenance by replacement, showing results for the Cable Application Study. Note that the first bar shows the present value which is the sum of the annual costs (the other bars).
Figure 12.29. Summary of present value analysis for the Cable Application Study. Comparisons of two preventive maintenance strategies ($S_1$ and $S_2$) and two discount rates.
Chapter 13

Generic RCM Methodology for Distribution Systems

This Chapter provides the main results of the thesis. It summarizes the Cable Application Study and as a result formulates a generic RCM methodology for electrical power distribution systems.

13.1 Summary of the Cable Application Study

13.1.1 The Different Steps in the Cable Application Study

1. Different possible data sources and contacts for relating reliability and PM of components have been identified. It was decided that the best approach was to focus on one utility (Birka Nät AB), which would capture a deep rather than a broad knowledge, but also knowledge specific to the actual utility.

2. A comprehensive study of the causes of failures and their analysis have been made in cooperation with Birka Nät AB (as presented in Chapter 8).

   (a) The analysis focused on identifying information that is available for relating causes and occurrences of failures and preventive maintenance (PM), and how these data could be improved. This analysis started at the system level, where the critical area and
components were identified; constituting the 11 kV underground cable. Furthermore, a case system defined as the Birka system was defined for a more detailed data evaluation. This includes information about causes of failures and percentage contributions to failure. To find additional information, interviews were held with maintenance personnel from the maintenance contractor (Birka Service). More background information to the statistics was obtained, and difficulties regarding the failure reporting and communication between the different parties were identified.

(b) The approach for deducing the causes of failures in a cable system component is illustrated in Figure 8.3. It can be viewed as three different levels.

i. Basic knowledge about the cable system, including component function, failure modes, and failure events.

ii. Knowledge about the causes of failures deduced from the disturbance interruption system (DAR and FAR). These failure causes have two levels of detail.

iii. A deeper knowledge about failure causes obtained from discussions with maintenance personnel from Birka Service. This level summarizes the different underlying causes of failures and is a result of these discussions.

(c) At the deepest level of the causes of failures, six different causes have been identified and are all related to material and method, which was identified as the dominant cause of failure that PM could effect (with a contribution of 59%). It is at this level that the PM measure is applied.

(d) For RCM analysis using Approach I, the input data that use average values are sufficient. However, for Approach II a further deeper level of understanding of the component behaviour is required. For this purpose, one of the identified causes of failures for cables has been further investigated, being water treeing.

3. A simple RCM analysis has been undertaken on the Birka system using input data collected for that specific system (Approach I as presented in Chapter 10),
4. To obtain a relationship between reliability and PM in the form of a functional relationship \( \lambda(t, PM) \), an additional deeper level of understanding of the component is needed. The time parameter needs to be included as well as theory for component behaviour and the impact of PM.

5. Different possible data sources and contacts have been evaluated to provide support for a component model relating failure rate and maintenance. The outcome provides support for one contact able to provide experience on maintenance (preventing water-tree growth by the silicon injection method, SINTEF) and one contact able to provide information on component behaviour (diagnostic measurements of insulation degradation, KTH), as introduced in Chapter 9.

6. The information obtained has been analysed, and it is understood that it appears possible to achieve the aim of defining a failure rate model for the cable component affected by PM.

7. A failure rate model has been formulated for the relationship between failure rate and maintenance for a cable component affected by water treeing. The model includes the following PM methods:

   (a) the \( PM_{si} \) rehabilitation method,

   (b) the \( PM_{rp} \) replacement method, and

   (c) the \( CM \) or "no-PM" method.

   Table 11.1 and Figure 11.2 provide a summary description of the modelling process (page 227) denoted \( \lambda(t, PM) \).

8. The failure rate model has been implemented in MATLAB, which was discussed in Section 6.3.

9. The system effect of maintaining the cable component has been evaluated (presented in Chapter 12).

   (a) The failure rate model developed for a cable component affected by water treeing, has been superposed on the 11 kV underground
cable from the Birka System (Section 10.3). The resulting function, as defined in Equation 12.7, which is a composite failure rate function, is written as follows:

\[
\lambda_{\text{tot}}(t) = \lambda_{LH11} + \lambda_{\text{wt}}(t) \quad \text{[f/yr]} \quad t_0 \leq t \leq T \\
\text{where} \quad \lambda_{\text{wt}}(t) \subseteq \begin{cases} 
\lambda_{\text{old}}(t) & \text{if no PM} \\
\lambda_{PM_{si}}(t) & \text{if } PM_{si} \\
\lambda_{PM_{rp}}(t) & \text{if } PM_{rp}
\end{cases}
\]

(b) Two PM strategies have been defined. These both involve PM applied on three occasions (years \( t_{PM} = 9, 11, \) and 12), and with the following proportions of cables subject to PM per occasion: 10% for \( S_1 \) and 30% for \( S_2 \). An average 11 kV cable component in the Birka System affected by the defined PM strategies, therefore has a failure characteristic defined by four different failure rate functions.

(c) Both these strategies have been implemented for the two PM methods of \( PM_{si} \) and \( PM_{rp} \).

(d) The resulting average composite failure rate functions of the 11 kV cable in the Birka system have been evaluated,

\[
\lambda_{\text{tot}}(t, \text{no PM}), \lambda_{\text{tot}}(t, PM_{si}, S_1), \lambda_{\text{tot}}(t, PM_{si}, S_2), \quad \text{and} \\
\lambda_{\text{tot}}(t, PM_{rp}, S_1) \quad \text{and} \quad \lambda_{\text{tot}}(t, PM_{rp}, S_2)
\]

and defined by Equations 12.9 to 12.10.

(e) The resulting failure rate function (\( \lambda_{\text{tot}}(t) \)) provides input data for the average 11 kV cable component in the Birka System. Reliability analysis of the Birka System has been performed using the RADPOW program.

(f) Average load-point indices have been evaluated for comparing PM methods.

10. Cost and benefit analysis have been done comparing maintenance strategies.

(a) Three different cost functions have been defined:
i. the cost of Failure ($C_f$),
ii. the cost of PM ($C_{PM}$), and
iii. the cost of interruption ($C_{int}$).

(b) Total annualized costs have been evaluated.
(c) Present values have been evaluated for the total cost.
(d) The total present values for the different PM methods and strategies have been compared, and the conclusion drawn about which of the three PM methods and two PM strategies provides the lowest present value.

It is understood from the steps presented above, that to enable the carrying out of this RCM application study, comprehensive input data and knowledge were required, specifically about the cable component behaviour. Furthermore it can be identified that input data for the cable component behaviour were obtained primarily from two different types of sources: (i) data based on experience, which were used for predicting the failure rate characteristic, and (ii) knowledge about the cable condition by modelling the component behaviour. Furthermore, it can be seen that some of the steps in the approach are the same as those used as input data in the framework. This is an interesting result since it reflects that one of the greatest challenges and difficulties when applying RCM is to define the data required to support the model; not only because of difficulties in obtaining these, but because it is simply part of the analysis to define suitable data (for example choosing maintenance frequency).

It is important to recognize that firstly, a model for the component failure rate characteristic is defined and then secondly this is implemented for a PM strategy. The system analysis is consequently an analysis of the effect of implementing the model developed for different PM strategies.

Figure 13.1 illustrates the resulting logic for the Cable Application Study, which has been implemented and validated. This figure includes the different procedures in the RCM approach as well as the systematic process for analysing the included components and causes of failures in the system. Furthermore, this figure shows the logic of the model for the functional relationship between failure rate and PM. The choice of input variables that was used for the results presented are shown on the left hand side of this figure.
Figure 13.1. Logic used in the Cable Application Study, for Approach II of the RCM analysis with analysis of one component, one cause of failure, and two alternative preventive maintenance methods. Implementation of the systematic process has been made in MATLAB and the resulting program uses results from RADPOW for the reliability analysis in the steps noted with *. 

Default values

- Time step = 0.01 years
- T = 30 years
- $t_{PM} = 11$ year

Define cable component data

- Define input variables
  - Time step, T, $t_{PM}$

Develop parameter functions due to water-tree growth

$\lambda (t) \cdot \delta(t) \cdot U_{d}^{|d|} \cdot \epsilon^\Delta(t)$

Develop parameter functions with effect of $PM_{r}$ or $PM_{s}$

$\lambda_{(t,P\!M)} \cdot U_{d}^{|d|+\Delta_{(t,P\!M)}}$

Analyze the effect of the plans with: $PM_{r}$, $PM_{s}$, or no PM

PM three times with: $t_{PM} = 9, 11, 12$ years

Evaluate parameter functions
- With: $PM_{r}$, $PM_{s}$, or No PM

Compare the effect of different PM methods

Superpose component model on system component model

Default values

- PM strategy, three times with 10 or 30%

Evaluate composite cable failure rate

Evaluate average cable component failure rate

Evaluate reliability indices for the PM methods and strategies

Deduce cost functions for failure, PM, interruption

Evaluate the total cost for the PM methods and strategies

Cost-effective PM plan

Component level

System level
13.2  The Generic RCM Methodology

13.2.1  Presentation of the Generic RCM Methodology

From the descriptive summary of the steps performed in the Cable Application Study, the overall picture of a general RCM approach stands out. The resulting steps have been formulated after the previously defined three stages in the RCM analysis (Figure 6.1). This results in an RCM methodology with the two different approaches described below.

1. Approach I: this provides a simple analysis and is applicable only when average failure rate data are available.

2. Approach II: this provides a thorough analysis and is applicable when data are available to support a predicted functional relationship for failure rate and its effect on PM.

The steps in the RCM methodology for these two approaches are presented in Sections 13.2.2 and 13.2.3.

Figure 13.2 illustrates the resulting logic for the generic RCM methodology developed. This figure includes the different procedures in the RCM method as well as the systematic process for analysing the components and causes of failures included in the system. The result is a generic approach that includes a theoretical model for the relationship between PM and reliability, formulated for a specific case the Cable Application Study illustrated in Figure 13.1.

The following two general remarks can be made about the failure rate modelling. First of all, that determining the functional relationship with time for each failure cause, implies a subdivision of the overall failure rate into rates for each failure cause. This requires an understanding of the physical processes involved that relates component behaviour to lifetime. It may not be possible to do this for all the failure causes. It should also be kept in mind, that the present failure rates are a consequence of existing maintenance procedures and the effect is not known or easily extracted. Furthermore, estimation of the effect of maintenance on each of these functions must be made with knowledge of the physical processes involved. Secondly,
Figure 13.2. Logic used the RCM methodology developed. The steps that feature the asterisk (*) use RADPOW for reliability analysis.
that the combinations of the life functions associated with each cause of failure used for obtaining a new failure rate function for each component, must be made for specific systems because the location and use of a specific component determines whether a particular failure may exist.

13.2.2 Steps in RCM Methodology with Approach I

Stage 1: System Reliability Analysis

1. Define the system model.
   
   (a) Choose the power system to analyse.
   (b) Define system to analyse, by first defining:
       i. system boundary, and
       ii. included components (for example bus bars, transformers, breakers, and cables).
   (c) Define a reliability model for the system.

2. Collect, select and define the input data to the system model, including:
   
   (a) system network data,
   (b) customer and power data, and
   (c) component reliability data.

3. Evaluate system and load point reliability with RADPOW, by:
   
   (a) identifying critical components, and
   (b) identifying critical load points, voltage levels and so on.

Stage 2: Evaluation of PM and Component Behaviour

For each component identified as critical, do the following.

1. Evaluate component behaviour as follows.
   
   (a) Identify components that could be affected by PM. Once the critical components that could be affected by PM have been identified, denote these as component \((i)\) where \(i = 1, \ldots, n\).
13.2. The Generic RCM Methodology

(b) Perform a failure mode and effect analysis to obtain the causes of failures and identify the following for each component:
   i. functions,
   ii. failure modes,
   iii. failure events, and
   iv. failure causes.
(c) Evaluate causes of failures in statistics and from experience, and identify the percentage contribution of each cause to total failures.
(d) Identify causes of failures that could be affected by PM, and let these be referred to as critical, and denote them \( k = 1, \ldots, m \).

2. Model the effect of PM on reliability.
   For each failure cause identified as critical (cause \( k \)), do the following.
   - Assume that the effect of applying \( PM^j \) is a reduction of the failure cause of type \( k \), with \( x\% \) reduction, where \( x_k \in [0, a_k] \) and \( a_k \) is the percentage contribution to the total failures of that failure cause, and given as input data from statistics.
   - If several failure causes are impacted upon by the PM efforts, assume reduction in a similar way with the corresponding value from the statistics.
   - Assume that the failure rate for the component \( (\lambda^i) \) is reduced by the same percentage \( (x\%) \) as the failure cause \( (k) \).

**Stage 3: System Reliability and Cost/Benefit Analysis**

1. Evaluate the effect of PM on system reliability.
   (a) Define the PM strategy \( (S) \) for the system including:
      - which PM methods that are applied \( (PM^j) \), and
      - what percentage of the component type \( i \) that are effected by each measure \( s_1 \).
   (b) Implement the failure rate model developed for the component \( i \) applied with PM strategy \( S \).
13.2. The Generic RCM Methodology

- Define which failure causes are affected for each $PM^j$ measure in the PM strategy. Let $k \supseteq PM^j$ denote the affected causes, and $k \subseteq PM^j$ denote the non-affected causes ($k$).
- Define the extent of the effect for each failure cause ($x_k$).
- Evaluate the resulting composite failure rate for the component $i$ which is given as follows:

$$\lambda^i(\text{PM}) = (1 - s_1) \cdot \lambda^i + s_1 \cdot \lambda^i(1 - \sum_{k=1}^{m} x_k) \quad (13.1)$$

(c) Perform system reliability analysis using the RADPOW program. The output is the system and load-point reliability indices that show the different effects of the PM strategy (5) on the system.

(d) Analyse the effect on system reliability of using different PM strategies.

2. Evaluate cost functions [SEK/yr].

The resulting average reliability indices for the system load points and the system depending on different PM strategies, can be used to evaluate the cost of interruption. This cost varies depending of the PM strategy used.

13.2.3 Steps in RCM Methodology with Approach II

Stage 1: System Reliability Analysis

Proceed in the same way as described in Approach I presented in Section 13.2.2.

Stage 2: Evaluation of PM and Component Behaviour

For each component identified as critical, do the following.

1. Evaluate component behaviour.

   (a) Identify components that could be affected by PM.

   (b) Perform a failure mode and effect analysis to obtain the causes of failures, then identify the following for each component:
13.2. The Generic RCM Methodology

i. functions,
ii. failure modes,
iii. failure events, and
iv. failure causes.

(c) Evaluate the causes of failures in the statistics and from experience, and identify the percentage contribution from each cause to the total failures.

2. Model the effect of PM on reliability and evaluate the component behaviour in greater detail.

(a) Collect and select data and experience from:
   i. measuring and modelling the component condition, and
   ii. experience from maintaining the component relating to the effects on specific failure causes.

(b) Deduce a model for functional relationship between reliability and PM activities as a function of time.
   - For components $i$, $i = 1, \ldots, n$ and failure causes of type $k$, $k = 1, \ldots, m$ model the failure rate function ($\lambda_i^k(t)$).
   - Estimate the composite failure rate function for the component $i$ as:
     \[
     \lambda_i(t) = \sum_{k=1}^{m} \lambda_i^k(t) \tag{13.2}
     \]
   - Two different situations of PM can be identified as follows:
     i. where no PM is applied, but CM is, and the failure rate function for this situation is consequently given by
     \[
     \lambda_i(t, CM) = \lambda_i(t) \tag{13.3}
     \]
     ii. PM is applied by the method $PM_j$ and assumed to prevent failure causes of type $k$.
   - Assume that the PM method ($PM^j$, $j = 1, \ldots, z$) that prevents failure cause ($k$) is applied to component number $i$. Then deduce a functional relationship for $\lambda_i^k(t, PM^j)$. If $PM^j$ effects several causes, then include the individual effect on each defined failure cause type.
Stage 3: System Reliability and Cost/Benefit Analysis

1. Evaluate the effect of PM on system reliability.

   (a) Define a PM strategy \( (S_A) \) for the system for each component \( i \), and within the time period \( t \in [t_0, T] \) that includes:

   - how many times PM is applied \( (v) \),
   - the times PM is applied \( (t_{PM1}, t_{PM2}, t_{PM3}, \ldots t_{PMv}) \),
   - which PM methods that are applied \( (PM_1, PM_2, PM_3, \ldots PM_v) \), and
   - what percentage of the component type \( i \) that are effected by each measure \( (s_1, s_2, s_3, \ldots s_v) \).

   Let \( PM^j \) symbolize a general PM method that is included in a strategy \( S_A \).

   (b) Implement the failure rate model developed for the component \( i \) affected by PM strategy \( (S_A) \).

   - Define for each \( PM^j \) method that is included in the PM strategy \( (S_A) \) which failure causes that are affected. Let \( k \supseteq PM_1 \) denote causes that are affected at \( t_{PM1} \) \( (k \subset PM_1 \) non-affected causes).

   - Estimate the resulting failure rate function. This function captures the average composite failure rate characteristic for the component \( i \). The resulting failure rate function is made up of several parts, depending on the number of PM measures that are applied within the strategy (that is, depending on \( v \)). The following equations define the resulting failure rate function:

\[
\lambda^i(t, S_A) = \begin{cases} 
\lambda^i_0(t) & t_0 \leq t \leq t_{PM1} \\
\lambda^i_1(t) & t_{PM1} \leq t \leq t_{PM2} \\
\lambda^i_2(t) & t_{PM2} \leq t \leq t_{PM3} & [$/yr] \quad (13.4) \\
\vdots & \vdots \\
\lambda^i_v(t) & t_{PMv} \leq t \leq T
\end{cases}
\]
\[ \lambda_i^0(t, PM) = \lambda_i(t) \]
\[ \lambda_i^1(t, PM) = (1 - s_1) \cdot \lambda_i(t) + s_1 \cdot \sum_{k \subseteq PM_1} \lambda_k^i(t, PM_1) + \]
\[ + s_1 \cdot \sum_{k \subseteq PM_2} \lambda_k^i(t) \]
\[ \lambda_i^2(t, PM) = (1 - (s_1 + s_2)) \cdot \lambda_i(t) + \lambda_i^1(t, PM) + \]
\[ + s_2 \cdot \sum_{k \subseteq PM_2} \lambda_k^i(t, PM_2) + \]
\[ + s_2 \cdot \sum_{k \subseteq PM_2} \lambda_k^i(t) \]
\[ \vdots \]
\[ \lambda_i^v(t, PM) = (1 - (s_1 + s_2 + \ldots + s_v)) \cdot \lambda_i(t) + \lambda_i^{v-1}(t, PM) + \]
\[ + s_v \cdot \sum_{k \subseteq PM_v} \lambda_k^i(t, PM_v) + \]
\[ + s_v \cdot \sum_{k \subseteq PM_v} \lambda_k^i(t) \]
\hspace{10cm} (13.5) 

This failure rate function provides input data on the component type \( i \) to the system reliability model.

(c) Perform system reliability analysis using the RADPOW program. The output is the system and load-point reliability indices that show the different effects of the PM strategy (S) on the system.

i. Run RADPOW repeatedly.

ii. Translate output from RADPOW into functions in time.
(d) Compare the impact of PM strategy \(S\) on the system load-point reliability by evaluating the average load-point indices as follows:

\[
\lambda_{av,Lpi} = \frac{\sum_{t=0}^{T} \lambda_{Lpi}(t,PM)}{(T-t_0)},
\]

\[
U_{av,Lpi} = \frac{\sum_{t=0}^{T} U_{Lpi}(t,PM)}{(T-t_0)},
\]

\[
T_{av,Lpi} = \frac{\sum_{t=0}^{T} T_{Lpi}(t,PM)}{(T-t_0)},
\]

\[
LOE_{av,Lpi} = \sum_{t=0}^{T} LOE_{Lpi}(t,PM),
\]

where \(Lpi\) denotes a load point in the system model analysed.

(e) Analyse the effect of using different PM strategies on system reliability.

2. Evaluate cost functions [SEK/yr].

(a) Cost of failure \(C_f\):

\[
CCM_f(t) = \sum_{i=1}^{n} \lambda^i(t,CM) \cdot c_f^i \cdot (1 + d_1)^t
\]

\[
CPM_f(t, S_A) = \sum_{i=1}^{n} \lambda^i(t, S_A) \cdot c_f^i \cdot (1 + d_1)^t
\]

This cost refers to the total cost of repairing components causing system failure.
(b) Cost of PM $C_{PM}$

$$C_{PM}(t, S_A) \ [\text{SEK/yr}] = \begin{cases} 0 & : t_0 \leq t \leq t_{PM1} \\ \frac{C_{PM_{i,1}}}{(T-t_{PM1}+1)} & : t_{PM1} \leq t \leq t_{PM2} \\ \frac{C_{PM_{i,2}}}{(T-t_{PM2}+1)} & : t_{PM2} \leq t \leq t_{PM3} \\ \vdots & : \\ \frac{C_{PM_{i,1}}}{(T-t_{PM1}+1)} + \frac{C_{PM_{i,2}}}{(T-t_{PM2}+1)} + \frac{C_{PM_{i,3}}}{(T-t_{PM3}+1)} & : t_{PMv} \leq t \leq T \end{cases}$$

(13.8)

This cost refers to the total cost of PM measures applied to the system within the strategy $S_A$.

(c) Cost of interruption ($C_{int}$) which is evaluated for Load Point 1:

$$CCM_{int}(t) = \sum_{i=1}^{n_p} LOE_{Lp_{i}}(t, CM) \cdot c_{int}^{L_{p_{i}}} \cdot (1 + d_1)^t$$

$$C_{PM_{int}}(t, S_A) = \sum_{i=1}^{n_p} LOE_{Lp_{i}}(t, S_A) \cdot c_{int}^{L_{p_{i}}} \cdot (1 + d_1)^t \quad (13.9)$$

where $t_0 \leq t \leq T$

This cost refers to the total cost of interruptions for the different load points in the system where:
- $LOE_{Lp_{i}}$ is the energy-not-supplied function at the load point denoted by $Lp_{i}[\text{kWh/yr}]$.
- $c_{int}^{L_{p_{i}}}$ is the customer cost of interruption in [SEK/kWh], and
- $d_1$ is the inflation rate.

3. Evaluate the total annualized costs in [SEK/yr]:
\[ TCCM(t) = CCM_f(t) + CCM_{int}(t) \quad \text{where} \quad t_0 \leq t \leq T \]
\[ TCPM(t, S_A) = CPM_f(t, S_A) + CPM_{PM}(t, S_A) + CPM_{int}(t, S_A) \]
\[ \text{(13.10)} \]

4. Evaluate present values in [SEK]:

\[ TCCMPV = \sum_{t=t_0}^{T} TCCM(t) \cdot PV_f(t, d_2) \quad : \quad t_0 \leq t \leq T \]
\[ TCPMPV = \sum_{t=t_0}^{T} TCPM(t, S_A) \cdot PV_f(t, d_2) \quad : \quad t_0 \leq t \leq T \]
\[ \text{(13.11)} \]

where the present value factor defined by \( PV_f(n, d) = (1 + d)^{-n} \) (Equation 12.12), and \( d_2 \) is the discount rate.

5. The cost-effective solution is the PM strategy \( S_i \quad i = A, B, C, \ldots \), that provides the lowest present value of all the strategies analysed.

### 13.2.4 Input Data for the RCM Analysis

Input data required for the RCM analysis are summarized as follows.

- **System data**
- **Customer data**
- **Component data:**
  - reliability data,
  - causes of failures, and
  - condition parameters
- **Cost data:**
  - cost of failure (repair), PM measure and interruptions, and
  - economic factors such as interest rates.
13.2.5 Remarks about the Meaning of PM Strategy

The PM strategy provides a recommendation about performing an activity in the future. However on the actual day for the PM measure, the decision would be based on whether it would be beneficial to do the same at that time, or would it be more profitable to postpone it, or even to do something else. Also the policy or strategy may be to perform PM on a percentage of the components spread over a period of time, maybe several years. This policy is set up several years in advance of the actual time PM is to be done and therefore does not determine which specific components will be maintained. The actual components chosen for PM would be those that appear to be performing worst at the time PM is to be done.

The RCM methodology implies development of a policy based on predicted behaviour that should be used to set a policy for determining when and how to use resources for maintenance. The resulting logic can be illustrated as follows:

Failure rate → predicted result → policy.
Implement policy → measure component condition → apply PM.
Chapter 14

Closure

The objective of this work, as defined in Section 1.1.2, has been fulfilled by
(i) developing a computer program called RADPOW for reliability evaluation
of power distribution systems, (ii) performing RCM application studies on
two distribution systems, (iii) undertaking a detailed analysis of the cable
component, and (iv) formulating a generic RCM methodology. This chapter
includes conclusions about the different stages of work, as well as an iden-
tification of the extent to which the objective has been fulfilled, which then
leads into the final section of the work, which is future directions for this and
closely-related work.

14.1 Conclusions

14.1.1 Reliability Evaluation Program - RADPOW

A computer program called RADPOW (Reliability assessment of distribu-
tion power systems) has been developed and successfully applied.

The RADPOW program can compute basic indices for reliability (load-
point and system-performance indices), determine the impact of new tech-
nologies, determine the impact of protection and control in the system
([78],[34]), analyse general network configurations (radial, parallel and meshed),
and is flexible and easy to develop further (object oriented programming).

It has also been demonstrated that the RADPOW tool developed here
can be used for the analysis of a general distribution system. The program

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has been used for reliability evaluation of the two following distribution systems: the rural Flymen System and the urban Birka System.

14.1.2 RCM Application Studies

RCM application studies have been performed by analyzing: (i) real distribution systems (the Flymen System and the Birka System), (ii) the statistics available, (iii) experience from supply interruptions, (iv) component behaviour, and (v) the effect of performing preventive maintenance (PM). Detailed analysis has been performed on the underground cable component via a comprehensive survey of the causes of failures, and a study of the maintenance experience and results from research studies on the cable condition. The latter used diagnosis measurements and experience of PM by rehabilitation on water-tree cables. A model for relating the cable component failure rate and the effect of applying PM to reduce failure caused by water treeing has been developed and implemented in the Birka System, and applied according to different PM strategies. The application studies resulted in two different approaches for the RCM analysis; one simple denoted Approach I (applied for the Flymen System and the Birka System), and one thorough, denoted Approach II (applied to a cable component in the Birka System).

Using Approach I, the results clearly show the benefits for system reliability obtained by focusing maintenance on the following.

- The critical components: the overhead lines for the Flymen System, and the underground cables for the Birka Case System.
- The dominant causes of failures: trees and aging for the Flymen System, and material and method for the Birka case system.

Using Approach II, the effect of different choices of maintenance methods, frequencies of maintenance, and PM strategies have been analyzed. In the Cable Application Study, the effect of preventing water trees through maintenance efforts involving either rehabilitation or replacement has been analyzed. The results show that it is more cost-effective to rehabilitate the cable than to replace it, since the greater benefit in reliability by the replacement method is balanced by the higher investment cost. However, PM is also seen as a large expense even compared with the effect of greater unavailability when no PM is made (corrective maintenance or CM). However, the
underground cable is an extremely cost-expensive component for the system to handle and should also be considered with respect to the environmental benefit which is not included in the cost analysis.

A number of different general conclusions from the Cable Application Study have been made and presented below.

- The Cable Application Study has shown how the practical knowledge of the component behaviour from experience and statistics together with theoretical models for the component behaviour, can be related to achieve a relationship between reliability and PM.

- This attempt to relate failure rate and maintenance constitutes a significant development in which the results and knowledge gained from traditionally different fields have been combined into a common solution. This research contribution shows how possible it is to formulate a theoretical model that relates reliability and PM for a component, as well as how readily accessible data to support such a model is.

- The benefit of having data to support an RCM analysis has also been shown.

14.1.3 RCM methodology developed in this work

The different RCM application studies have resulted in the development of a generic RCM methodology and an RCM framework that is generally applicable to electric power distribution systems. The resulting RCM methodology developed has been presented as a generic approach that includes, for a specific case, a theoretical model for relating reliability and PM. Furthermore, the procedures required for the RCM analysis are formulated into three different stages: (i) system reliability analysis, (ii) evaluation of PM and component behaviour and (iii) system reliability and cost/benefit analysis.

The resulting methodology features the following main characteristics:

- it is easily adapted to the system and supports both a simple (Approach I) or thorough (Approach II) RCM analysis,

- it adopts a system-wide perspective, meaning that it analyses the components that are affected by PM efforts, but as parts of a system that operates for securing system function,
• it clearly shows the quantitative impact of PM on system reliability and cost,

• it shows the input data required to support the RCM analysis, that consequently could be justified by the benefit gained and shown by quantitative analysis.

The conclusion is that it is beneficial to apply PM strategies that are based on results from quantitative systematic techniques like the RCM methodology developed here. Furthermore, the benefit gained by supporting the RCM method with input data can be balanced against the effort required in achieving the benefit.

14.2 Discussions and Future Work

14.2.1 Final Remarks

In coming to the conclusion of this work, the problem formulation outlined in the introduction has been addressed in greater detail. It therefore seems appropriate to end the work by identifying and highlighting some of the special difficulties met while attempting to achieve the primary objective of this work, that is developing an RCM methodology for PM strategies of power distribution systems.

The technical system being analyzed, which is the power distribution system, behaves randomly and therefore it is essential to use probability methods in combination with the deterministic description not to make the model too complicated in attempts to find solutions. However, it has been realized during the work that the main difficulties are not only to be found on the technical side. It is not mainly the development of new materials, components, designs or theoretical models that present the greatest challenges for the future distribution system, as the time has come when these technical aspects need to be addressed alongside economic aspects. The system is required to be designed, operated and maintained in a cost-effective way. This in turn requires strategies that place the technical and economic issues alongside one another, in order to develop a total model for using system assets optimally.
14.2. Discussions and Future Work

This work has contributed to the body of knowledge in the area by relating the component and the system levels, while focusing on the objective of supplying energy to customers. It also contributes by relating practical knowledge about component behaviour from experience and statistics to theories focusing on the objective of developing a quantitative relation linking reliability and PM. Therefore, the work has stretched over a broad range of knowledge, from for example the practical handling of underground cable components, the modelling of the water-tree phenomenon and the modelling of system reliability and disturbance reporting systems, to the implementation of PM strategies to achieve cost-effective solutions for asset management. This is not surprising since RCM is a method that instead of contributing with new knowledge, creates knowledge by relating existing information and theories.

A vision for this work has been to provide a deeper understanding of the interconnection between system and component levels for obtaining the relationship between component behaviour and system reliability, and to show the great importance of using history to help shape the future, in other words a sound long-term collection of useful data.

The new market rules should be formed to stimulate sound development making it possible to maintain adequate long-term thinking to facilitate an effective system in which both customers and shareholders are satisfied. The responsibility for this rests with management and the authorities.

14.2.2 Difficulties for Achieving the RCM methodology

The main difficulties to overcoming the achievement of the RCM methodology have been identified as follows:

- finding supporting input data that can generate enough detailed information and cover a long enough period of time,
- issues relating to the new roles of contractor (utility) and subcontractor (maintenance company), and
- providing an organization with enough resources and knowledge (sound management).

Not all the problems have been solved, which leads into the next section, future work.
14.2. Discussions and Future Work

14.2.3 Future Work

All the problems have not yet been solved, and in future work the RCM methodology developed here could be either enhanced or considered in a wider context, namely as a part of asset management that is the overall handling of the maintenance question. As previously identified, there are major difficulties to overcome to fully realize the RCM methodology, and the second focus, that is asset management, would contribute in solving those issues.

Proposed refinements of the RCM Methodology

Figure 6.1 presents the RCM framework (that is summarised in Table 6.1) developed here, and divides the RCM analysis into three stages. This thesis has focused on the contribution to the second stage by the development of a theoretical model for a cable component, relating reliability and maintenance, as well as a comprehensive evaluation of input data to support it.

It would of course be of great interest to expand this application study to other types of causes of failure and components. However, how this could be solved would depend on possible access to data and knowledge. Consequently, the first task in future work would be to identify possible ways (if there are any) for supporting a further model for failure rate and PM. This focus for improvement would relate to further evaluation of the effect of PM on component behaviour and consequently to Stage 2 of the RCM methodology developed.

The objective in developing RCM plans is to establish the most cost-effective PM plan. This requires optimizing the balance between the cost of doing maintenance and of not doing maintenance. The RCM method developed includes a cost evaluation that compares different PM strategies to obtain the most cost-effective PM strategy. However, the resulting cost choice of the PM strategy is not apparently the optimal solution, since only selected strategies have been analyzed. An enhancement of the RCM methodology developed would therefore be to incorporate an optimization model for defining the optimal choice of PM strategy. A task for future work would therefore be to formulate and solve an optimization model for minimizing the cost of PM with requirements on the level of reliability. This task would relate to further evaluation of the system reliability and cost/benefit analysis and
consequently involve an improvement in Stage 3 of the RCM methodology developed.

**RCM as part of asset management**

There are also several interesting factors of a less technical nature that would be of great interest and importance to consider in greater detail. As discussed several times already, the driving forces have shifted from the technical to the economic, and a more complicated form of managing maintenance, including a formal contract and legislation. Another, aspect that has also been identified is the importance of support from Management for possible application and success of an RCM program. Systems and organizations are required that provide the necessary support for the analysis. All these issues lead to a wider perspective of RCM that could be included in the concept of asset management. One task for future research could therefore be to consider the RCM methodology developed as a part of asset management focusing on how the difficulties identified for the realization of RCM could be overcome.
Appendix A

Specification of Input Data to RADPOW

There are four types of data that are manipulated in RADPOW: network topology data, customer and power data, component reliability data, and load flow data.

These data are used as input for RADPOW in 10 files. The first six files relate to network data (bend, bcomp, nsp, nlp, nnop, and ctype); the following two relate to the power and customer data (ncuspow) and reliability data (crelia); and the last two relate to the load-flow data (pfl0 and pfrr).

A.1 Network topology data

The topology of the system is described by the branches of the system. A branch is defined as a set of components in series that start and end with a bus bar. Branches through which the power is permitted to flow in one direction only are defined as unidirectional branches, and those through which power is permitted to flow in both directions are defined as bidirectional branches. Furthermore, branches are identified by a branch number, from 1 to $n$, where $n$ is the total number of branches in the system.

All components considered in the analysis must be identified. These are identified by a number from 1 to $k$, where $k$ is the total number of components identified in the system.
The input data consist of:

- branch numbers, numbers of branch ends, and unidirectional branches,
- component numbers,
- numbers of supply points, load points to be analyzed, and normally open points.

### A.2 Customer and power data

For each load point in the system (Lp), the following customer and power data are specified:

- total number of customers (tnc),
- industrial (icp), residential (rcp) or commercial (ccp) customer percentages,
- total active power per customer (kW/cust) (tappc),
- industrial (iapp), residential (rapp) or commercial (capp) active power percentages,
- total reactive power per customer (kVar/cust) (trppc),
- industrial (irpp), residential (rrpp) or commercial (crpp) reactive power percentages.

### A.3 Component reliability data

For each component, the following reliability data are specified using expected values:

- permanent failure rate ($\lambda_p$),
- active failure rate ($\lambda_a$),
- temporary failure rate ($\lambda_{te}$),
A.4. Load-flow Data

- transient failure rate ($\lambda_{tr}$),
- maintenance outage rate ($\lambda_m$),
- repair time ($r_r$),
- switching time ($r_s$),
- replacement time ($r_p$),
- re-closure time ($r_c$),
- maintenance outage time ($r_m$), and
- the probability of switching devices being stuck ($P$).

A.4 Load-flow Data

The most significant restriction in RADPOW_1999 is that the criterion for failure is based on total loss of continuity (TLOC). TLOC means that a load point is interrupted and load disconnected only when all paths between the load point and the sources are disconnected [1]. However, TLOC has been extended to include partial loss of continuity (PLOC). This implies that the failure criterion also includes events that do not fully interrupt the connections between the source and the load point, but are sufficiently serious to require disconnection of some load. The development of a module for load-flow analysis has been done [73] and the resulting version of RADPOW is referred to as RADPOW_1999_PF.

A.4.1 Impedance Data

Due to the short length of the lines encountered in distribution systems, their susceptance is neglected. However their impedance is taken into account to achieve accuracy in the power-flow calculations.

For each branch in the system, the following input data should be specified:

- branch number (Brno),
- sending end (SE),
• receiving end (RE),
• resistance p.u. (R(pu)),
• reactance p.u. (X(pu)), and
• maximal current p.u. (Max\_current(pu)).

### A.4.2 Load data

For each load point in the system, the following input data should be specified:

• active power in p.u. (lapc(pu)),
• reactive power in p.u. (lrpc(pu)),
• load duration curve (ldcu).

In RADPOW\_0999\_PF three different load curves have been defined as follows:

- constant, where \( LDC = 1 \),
- sinusoid, where \( LDC = 1 - 0.3 \cdot (1 - \sin(2\pi \cdot 3t/N)) \), and
- linear, where \( LDC = 1 - (0.4 \cdot t/N) \),

and where \( N \) is the number of customers and \( t \) the time.

For further details about the Load-flow module please refer to [73].
Appendix B

The Flymen System
RADPOW Data

B.1 RADPOW Input Data

B.1.1 Component Reliability Input Data

Table B.1 presents reliability input data for RADPOW coming from the Flymen system. The input data needed for RADPOW that are not presented in this table have zero values, or have no impact on the analysis of the Flymen system.

B.1.2 Customer and Power Data

Tables B.2 - B.3 show the customer and power input data for RADPOW that come from the Flymen system. The input data for the reactive power are not presented in the tables since these were not used for the analysis.

B.2 Output Data from RADPOW

Tables B.4 and B.5 present the results for each load point in the analysis of the Flymen system (FlymenN).
### Table B.1. Component reliability input data used by RADPOW.

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<th>Comp.</th>
<th>$\lambda_t$</th>
<th>$\lambda_q$</th>
<th>$\lambda_{bc}$</th>
<th>$\lambda_m$</th>
<th>$r_r$</th>
<th>$r_c$</th>
<th>$r_s$</th>
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<td>0.018</td>
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<td>0.09</td>
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Table B.2. Customer and power input data for RADPOW.

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Appendix C

Input Data for the RCM Cable Application Study

This appendix summarizes the input data used when implementing the developed failure rate model in the Cable Application Study that is for the RCM MATLAB program.

The RCM algorithms implemented require input data from seven files. Five of these files relate to the cable component behaviour, and the other two to: (i) the reliability input data for the Birka system for RADPOW, and (ii) the input data for the cost and benefit analysis. These data are presented in detail below.

C.1 Input Data for the Cable Component Behaviour

The input data for the cable component behaviour are presented as follows:

- *indata_lambda_Svel* (source [104]), which are data for the modelling the cable component failure rate.
  - Total length for the different cable groups put into operation in the years, 1970-1975.
  - Numbers of failures for each cable group during the aging period of 13-18 years after coming into operation.
C.2 Input Data for the Birka System Cable Component

- The input data are presented in Table 11.2.

- \texttt{indata\_lambda}
  - The average failure rate for each year is evaluated based on the input data presented above.

- \texttt{indata\_wt\_KTHSINTEF} (Source [130],[126],[100])
  - Assumed maximum water-tree length: \( l_{\text{max}} = 100\% = 5.5 \text{ mm} \).
  - Year when water trees reach their maximum length: \( t_{\text{max}} = 13 \).

- \texttt{indata\_bd\_KTH} (Source [126],[100])
  - Maximum value for the normalized breakdown voltage, \( \max(U_{bd}/U_0) = 10 \).
  - Minimum value for the normalized breakdown voltage, \( \min(U_{bd}/U_0) = 2 \).

- \texttt{indata\_bd\_PM\_SINTEF} (Source [130])
  - Measurement points for breakdown voltage from the SINTEF study. Normalized for a 24 kV cable with resulting data as presented in Table 11.7.

C.2 Input Data for the Birka System Cable Component

The input data for reliability analysis for the Birka System were defined in Section 10.3. For the RCM Cable Application Study this data is accomplished with the previously presented component behaviour data. The component failure rate model is accomplished with the following system data:

\texttt{indata\_BirkaLH11}

- Average length for the 11 kV cable, \( l_{av} = (259.387/32) \approx 8.10584 \text{ km} \).

- Average failure rate for the 11 kV average cable, \( \lambda_{LH11} = 58/(18 \cdot 259.387) \cdot l_{av} \approx 0.10069 \text{ f/yr} \).
C.3 Input Data for the Cost and Benefit Analysis

\textit{indata\_Cost}

- Input data for the inflation, interest rate, repair and related items. Table C summarizes these data.
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[41] Glossary for electric power systems (elordlista). The Swedish Power Utilities Association (Svenska Elverksföreningen), 1993. (Today part of Sweden AB.)


References


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References


References


[107] Sven Jansson. Responsible for handling of the Swedish reporting system DAR. Swedenergy AB (now at ELFORSK), 1999.


[111] Stefan Arnborg. Statistics for Interruption of Voltage (Driftstörningsstatistik), the Swedish National Grid (Svk) Planning Department, 2000.


References


References


