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Probabilistic Reliability
A State of the Art Study

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Problem Description

These days' reliability analyses are being utilized to a certain extent, often part of the decision-making process of potential power system upgrades and new implementations. Thus, it is very useful to discuss techniques, data needs and methodologies describing such processes. It is also evident that the need for high quality statistical data related to system operation and development is important.

The purpose of the thesis is to demonstrate a state of the art probabilistic reliability methodology and the main activities include; establishing a computer model utilizing PSS®SINCAL, conduct a reliability analysis based on a real-life power system, assess the quality of available reliability data, develop a methodology describing the power system criticality (based on the reliability analysis) and conduct a comparative analysis of SAMREL and PSS®SINCAL.

The project is a cooperative effort between Norwegian University of Science and Technology, Siemens AS (department of network consulting) and Istad Nett AS. Siemens AS supplies the necessary tools whilst Istad Nett AS provides valuable information about their distribution system.

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Summary

Power system simulations, power market analysis as well as power system security and reliability analysis now serves as fundamental analysis tasks in power system planning and operation. Thus, it is very useful to discuss techniques, data needs and methodologies related power system reliability. This work is very important both in terms of operational and economical aspects of a modern power system. The task of determining the reliability of a given power system can be a complex and difficult process. Several methodologies exist and the terminology describing these calculations may differ from case to case. The work performed in this thesis demonstrates a known reliability methodology related to a real-life power system. In the latter, PSS®SINCAL and its reliability module ZUBER has been emphasized.

The development of a working test model has been an important part of this thesis. In the latter, statistical information describing the power system has been the main challenge, both in terms of availability and quality. The various reliability data have been calculated from annual failure statistics collected by Statnett and experience data from Siemens. The scope of the reliability analysis was to determine the affect of future load expansions. It is a known fact that load development can affect the reliability of the power system and potentially increase the frequency of supply interruptions causing higher CENS costs. However, this was not the case as the changes in frequency of supply interruptions were insignificant. The results showed a suspected CENS cost increase of 1.6 NOK. Thus, it is evident that this is due to the fact that the uninterrupted power is now substantially larger. The reliability analysis show that the given power system will sustain its high level of reliability even with the planned load expansion.

A comparative analysis of the ongoing development of a methodology (SAMREL) incorporating power market analysis via power flow and contingency analysis and PSS®SINCAL have also been presented. Comparing tools describing probabilistic reliability are important and can act as an incentive for future development of reliability tools. The major strength of PSS®SINCAL compared to SAMREL is simply the fact that PSS®SINCAL is a developed and commercialized tool. Unfortunately it was not possible conduct a reliability analysis using SAMREL, which was a major draw-back as a comparative analysis of both the tools relates to the same test model would have been very beneficial. SAMREL is comprised of several existing tools and therefore rely on the interaction between these tools, which after my opinion further complicate both the user friendliness and process of commercialization. From an educational point-of-view, the work related to SAMREL has several benefits contributing to increased general knowledge about power system reliability.

It is evident that the accuracy of any reliability analysis depends on the quality of the statistical data. The studies show that local statistical data e.g. data based on local knowledge or local statistics often pose as a better solution. However, such data are unfortunately often very difficult to obtain, leaving no alternative as to use the available more general data. However, it is evident that some uncertainties always will exist but need to be taken into

consideration when conducting such analysis. However, close cooperation with the utilities in combination with the utilization of high quality reliability data will after my opinion have a positive affect on the accuracy of the reliability analysis.

Another important subject related to reliability is the process of identifying the critical system components. As shown, the main tool presented in this thesis is the consequence matrix, which categories the results obtained from the reliability analysis. The categories indicate both the consequence and the corresponding probability. Such matrixes need to be the result of a joint effort from both the customer and the professionals performing the criticality analysis, including all relevant information needed to classify criticality. The strength of this method lies in the fact that the defined probabilities can be used to identify large elements, such as substations and then be further utilized on a component level for the critical substation.

The methodologies describing power system reliability have been emphasized throughout this thesis. The given test system and the performed reliability calculation demonstrates PSS®SINCAL as a tool for determining the reliability of a power system. The methodology utilized in this report is from the author's point of view a good representation of a state of the art reliability analysis.

Preface

The work presented in this report concludes the master thesis work preformed at the Norwegian university of science and technology part of the international master program; master of science in electric power engineering. The study deals with probabilistic reliability calculations and the development of a network test case model.

Personally, the reason for choosing this topic is the fact that I've always found the various aspects of power system operation, behavior and control very interesting. In the latter, the work performed in this thesis represents a new era in power system development, which I wanted to further investigate thereby broadening my area of expertise in the field of electrical engineering.

The project has been a cooperative effort between Norwegian University of Science and Technology, Siemens AS (department of network consulting) and Istad Nett AS. Siemens AS has supplied the necessary tools whilst Istad Nett AS has provided valuable information about their distribution system.

I would like to extend my gratitude towards Haakon Engen at Siemens AS who has supported and guided me throughout this process. I also thank my supervisor professor Eivind Solvang at NTNU and Tor Rolf Time at Istad Nett AS and Ole Bjørn Westad at Maintech AS for support and valuable information, making this project possible.

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1 Introduction

The purpose of any power system, large or small, is to supply customers with electrical energy at an acceptable degree of reliability and quality as economical as possible. Nowadays, after the liberalization of the power market, the increasing cost pressure forces utilities to operate their networks as efficient as possible. In the modern society, people have come to expect that the power supply should be continuously available on the demand. Combined with political requirements and directives to maintain high power quality levels, has forced the utilities in a new direction regarding operating and planning. In this area of conflict, comprehensive and detailed asset management methods considering both costs of network supply and delivered power quality are essential for long term success.

Power system simulations, power market analysis as well as power system security and reliability analysis are fundamental analysis tasks in power system planning and operation. Several tools are available for solving the various tasks involved in these processes. In the latter, reliability calculations serves as a useful tool, both related to the current network state and prediction of expected future scenarios considering the long term effects of decisions. The need for improving power system analyses has become evident e.g. demonstrated by recent blackouts, such as the one that hit major parts of Europe in November 2006. This was mainly due to overloading of power systems i.e. operation with very small margins and reserve power, making the system more vulnerable. Such scenarios work as incentives for the development of reliability analysis such as described in this thesis.

The task of determining the reliability of a given power system can be a complex and difficult process. Several methodologies exist and the terminology describing these calculations may differ from case to case. The purpose of this thesis is to give a precise presentation of the most important aspects related to probabilistic reliability. After my opinion, the work performed in this thesis demonstrates a state of the art overview of power system reliability methodology. In the latter, PSS®SINCAL and its reliability module ZUBER has been emphasized.

2 Power system development – operational and economical aspects

2.1.1 Operation management and development

Regarding operation and management of power systems world wide, it has been subject to major changes during the last 20-30 years. Going back to the 1950s, planning and construction of power systems were relatively straight forward. The power system planners faced an annual load growth of about 7-8% (doubling of load every 10th year), which made the development process very predictable [13]. In the 1960s unit sizes increased and the interconnections between the utilities expanded rapidly. Problems arose during the mid 1970s when inflation and an increase in of oil prices lead to a rise in consumer tariffs. This new trend caused major uncertainties when predicting future demands, and required extended methods related to development and cost calculations. Looking at the modern society, electricity now plays a major role in the economic and social wellbeing of people. This being said, it is very useful to discuss techniques, data needs and methodologies related to power system reliability. This kind of work is very important both in terms of operational and economical aspects of a modern power system.

2.1.2 Regulations

Examining some of the recent development in the Norwegian power market, the introduction of the Norwegian energy act has played an important role in the managing the power system. Enforced in 1991 it automatically led to a deregulation of the electricity market. The electricity utilities now need to optimize the transmission and distribution networks from a socioeconomic point of view. Since this introduction, the electricity utilities have been forced to handle the specific costs of capital investment, operation, maintenance and also customer interruption cost in explicit socioeconomic analyses. New regulations have been introduced continuously to ensure a reliable and secure supply. Also, the regulation is focused to enable the Norwegian Water resources and Energy directorate (NVE) to monitor the power quality performance of the electricity networks and to implement appropriate measures to safeguard appropriate power quality levels.

A model for incentive-based regulation of supply quality was introduced in 2001. This model is called the CENS-arrangement, and is based on estimates of energy not supplied and average specific interruptions costs for different customer groups [18]. Both planned and unplanned interruptions must now be taken into account. This arrangement aims at pushing the electricity utilities to both develop their network and secure a satisfactory quality of supply towards a socioeconomic optimum. The CENS-arrangement handles only the interruptions with duration over three minutes, and in the beginning it just had two different customers' categories. Now, it has been further developed, and distinguishes between six different categories. In 2003 all electricity utilities belonging to the power supply preparedness organization (PSPO) were forced to have an updated risk and vulnerability analysis as NVE implemented the regulation of contingency planning in the power supply systems [19]. This only heightened the need for methodologies implementing power system reliability analysis in the operation and development of the power system.

2.1.3 Reporting systems

Obtaining vital information about the power system performance is important as it is part of the process of determining the future behavior of the system. This thesis deals with the reliability of a power systems and one of the key elements of a reliability analysis is the availability of high quality statistically data. Looking at the history of failure registration in Norway, it all started in 1995 when NVE introduced a mandatory reporting of customer supply. Now, all electricity utilities use a standardized tool for the registration and reporting of equipment failures and supply interruptions. This FASIT tool was established based on a requirement specification. Initially, the electricity utilities only reported interruptions with the duration longer than three minutes. Prior to 1995, the registration and reporting of failures and disturbances was not mandatory. Nevertheless, failures since 1967 have been analyzed and registered for the voltage levels 132-420 kV in a common reporting system. From 1995 on, the registration and reporting of failures and disturbances is mandatory for the voltage levels 33-420 kV. Statnett also introduced a new system, Statnetts driftsforstyrrelseInformasjonssystem (SDI), in 1998, which handles all disturbances and failures. This regulation was later replaced in 2002 with the regulation of system operation, covered in an explicit paragraph [15].

2.1.4 Importance

This chapter gives a short overview of some of the power system developments which have the potential for gradually introducing reliability calculations as a standard tool for planning and operation of power systems. These days, such tools are being utilized to a certain extent, often part of the decision-making process of potential upgrades and new implementations (e.g. upgrading the generation / loads and introduction of new lines / cables). It is also evident that the need for high quality statistical data related to system operation and development is important.

3 Power system reliability in perspective

3.1 Introduction

The task of determining the reliability of a given power system can be a complex and difficult process. Several tools exist, however the terminology describing these calculations may differ from case to case. The purpose of this chapter is to give a short and precise presentation of the most important definitions that exist regarding probabilistic reliability calculations. The chapter also gives a state of the art overview of power system reliability methodology in general. In the latter, PSS®SINCAL and its reliability module ZUBER have been emphasized, as it is the number one tool available on the market regarding reliability calculations.

3.2 Terminology describing probability

3.2.1 Definition of power system reliability

Reliability is not easily defined as it has a wide range of meanings, therefore making it impossible to associate it with a single specific definition. However, generally it can be said that reliability is an indication of a systems ability to perform its function [13]. Other terms, like availability, serviceability and dependability, is used in the same contents. The general term describing availability and serviceability in the field of system engineering is dependability. Dependability according to DIN40041 is the condition of an entity relating to its capability to fulfill the dependability requirement during or after a given time span with given application conditions. The definition of dependability according to IEC 60050-191 is the collective term used to describe the availability performance and its influencing factors; reliability performance, maintainability performance and maintenance support performance. Hence, dependability is a partial aspect of the quality of service. Dependability not only includes the unit performance itself, but also considers options for maintenance and the ability of a responsible organization to perform this maintenance, therefore including the performance during outage situations [2].

Two subdivisions related to power system reliability have been presented in [13].

Reliability subdivisions:

- Adequacy can be explained as the power systems ability to satisfy the consumer load demand i.e. do the system have sufficient facilities to meet the actual demand. Adequacy is associated with static conditions like generation and transfer capabilities.
- Security on the other hand relates to the systems ability to withstand perturbations, both local and widespread. These perturbations can e.g. include loss of power generation and transmission facilities.

Most often, reliability evaluations are in the domain of adequacy assessment. However, some work has been done to include security problems such as spinning reserve capacities and power system stability.

3.2.2 Component and system states

Working with reliability, several definitions exist regarding the electric power system and its components. Components in the field of reliability calculation are defined as the smallest considered entities of a system for modeling, analyzing or calculating reliability which is not further subdivided [2]. Usually, several equipment entities are combined in one component and the component's macroscopic performance is considered. The main emphasis is on the components ability to fulfill its function and therefore the duration of the fault state is also important. The component definition utilized e.g. by PSS®SINCAL corresponds to the protection tripping area of the main protection systems. Therefore, components consist of all equipment entities being switched off simultaneously in accordance to the protection system.

According to IEC norm 60050-191, five different item-related states are distinguished, see Figure 3.1. These can be combined in an up state and a down state.

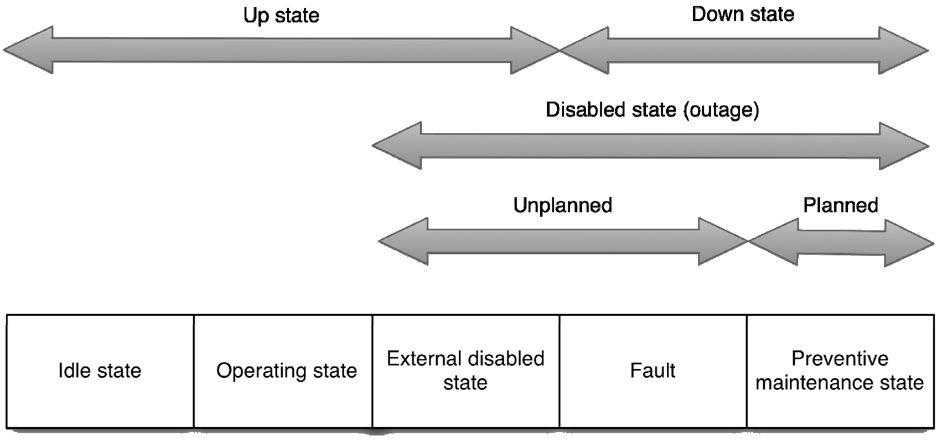

Figure 3.1 **Components states.**

The component states are:

- Operating state: The component is connected and is performing the required function.
- External disabled state: This state e.g. applies for thermal power stations suffering fuel shortage.
- Idle state: The component is able to operate but its performance is not required in the actual operation situation, so it is disconnected.
- Fault: This component state is caused by a failure.
- Preventive maintenance state: The component is disconnected, with the disconnection being planned for maintenance purposes and not being related to any failure.

Since the cause of the outage can not be assigned to the component, the external disabled state is included in the up state. The external disabled state is also combined with the preventive maintenance state and the fault state as a disabled state. The reliability of electric power systems is affected above all by unplanned outages.

In the field of reliability calculation, only the ability of the component to fulfill its function is relevant in the sense of the component's macroscopic consideration [2] e.g. the network components in PSS®SINCAL are modeled with two states only. The exceptions are for power station units, which are described using more states enabling the implementation for e.g. start up failures.

3.2.3 Failure, outage and supply interruption

The term fault is defined especially for use in the field of reliability analysis according to [12], is any unintended change of the system's normal operation state characterized by:

- Sufficient voltage level.
- Intact isolation state.
- Circuit state intended by the system management.
- Intact equipment.

The term fault refers to components as well as to the complete system and specifies the state that the component or system is in. This being said, it is incorrect to define the transition into the fault state as a fault. This transition is called a failure and defined as the termination of the ability of an item to perform a required function [2]. Hence, the fault state itself can not be designated as a failure. From this definition it is evident that the term failure duration, is not relevant in reliability analysis. The reason is that it only includes the state transition. The time span during which a component is in fault state is designated as the outage duration.

Within the scope of reliability analysis of electric power systems only the faults that lead to a supply interruption is of interest, as they are the only faults that will affect the reliability of the system. A supply interruption can be defined as the unavailability of the required power on a load bus. According to [12], successful automatic re-closings are not regarded as supply interruptions. However, it is possible to regard voltage band violations as supply interruptions. The system is in the state of supply interruption in case that at least one load node suffers an interruption.

3.3 The power system reliability process

3.3.1 Overview

Probabilistic reliability analysis of a given system is, like any other engineering analysis process, comprised of different aspects. These four "cornerstones" are depicted in figure 3.2.

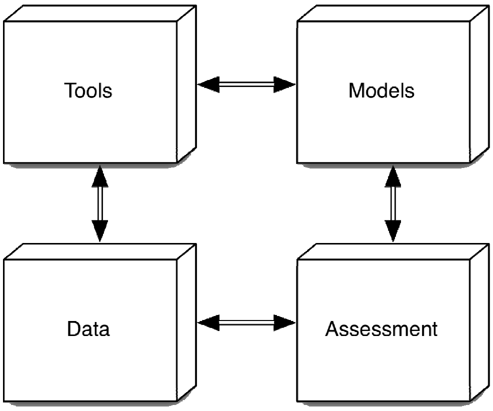

Figure 3.2 **Aspects of power system reliability.**

3.3.2 Models

George E. P. Box, a statistical pioneer, stated that no model is absolutely correct. However, some models are more useful than others [9]. Regardless of the analysis methods, the system under consideration has to be represented in a model suitable for probabilistic reliability analysis. In addition to the data required by classic methods like power flow or short-circuit calculations, reliability calculations is also based on data beyond topological and electric characteristics of the equipment. Statistical data for the system equipment is needed for the reliability calculation of the network. Another important aspect of reliability analysis is the systems ability to restore supply after being subjected to various disturbances. Therefore, redundancy i.e. switching possibilities and protection system configurations have to be included in the model.

Reliability analysis is complex and computationally an extensive task, it is therefore important establish suitable borders for the system under consideration with respect to the given problems. It is not advisable, or even possible, to consider the whole power supply system from generation to distribution in one enclosed analysis. These limitations can often cause problems when modeling network components. The challenge is to obtain correct reliability data for the components that contribute to the reliability but also obtain realistic results compared to the actual system [2]. One should also never forget that the model represent an idealized case i.e. it is a simplified model for the system. Furthermore, the derived results are only valid to the specific model and only correct to the extent that the model is realistic [9].

3.3.3 Data

The stochastic description of component failures, combined with the electrical and topological network data obtained from a standard dataset for load flow and short circuit current calculations are the input data for the actual reliability calculation [1]. This in mind, the model is useless unless the input data is of sufficient quality. Standard electrical data is often easy to acquire compared to probabilistic data describing the outage performance of the components [13]. A significant effort has been devoted to the collection and processing of reliability data during the last ten years. Since 1994, the new VDEW-Störungs- und Schadensstatistik has offered broad and reliable data for power systems of the 110kV level and above for usage of the corresponding failure models in reliability calculation. The data for these models can also be derived from Norwegian statistics, registered by the transmission and distribution companies. High quality data exist for voltage levels ranging from 132-420kV and has mainly been recorded by Statnett. Statnetts database consists of failure data for all components (e.g. protection device, overhead line, cable, transformer etc) registered from 1998 up to today (SDI database). The other Norwegian T&D-companies use a standardized registration tool called FASIT [16], which offers more or less the same statistical data. However, despite this effort, the quality of the available data is still not good enough [9]. The issues related to reliability data have been thoroughly investigated in this thesis.

3.3.4 Tools

Using the models which are parameterized with the appropriate input data; suitable tools must be available for the probability analysis. Probabilistic reliability calculation is already established as a standard method for performing detailed and quantitative reliability analyses in numerous studies and practical applications. Tools available such as models, procedures and software have already been in existence since the 1980s and, since then, have been continually improved and adapted to new requirements. Algorithms have been developed and successfully incorporated in commercial network calculation software packages, making them controllable via a graphical user interface. As a result, the usage of probabilistic reliability calculation has become much easier [1]. An example of such a tool is the PSS®SINCAL package, which has been utilized in this thesis. The reliability module part of this software has been further described in chapter 4.

3.3.5 Assessment

The results obtained in the probabilistic analysis are presented in the form of reliability indices which are expected values over an infinite period of time. This implies that the quality of the calculation results, compared to practical observations and statistics, only serve to determine the quality of the calculation results considering certain conditions. Typically, the statistical indices derived from relevant statistics will differ from the calculated probabilistic indices. Hence, the software calculations will always have a certain prognosis uncertainty. It has to be noticed that the reasons for this prognosis uncertainty of course include errors resulting from approximations, simplifications or inaccuracy of the models, data and tools used in the calculation. However, as long as there are no major errors in the calculation system, the by far most important reason for the prognosis uncertainty is the fact that supply interruptions are rare and thus the prognosis uncertainty is an intrinsic characteristic of the mathematical description. Another level of complexity concerning the assessment of reliability indices is the fact that reliability is made up of different aspects such as; frequency, duration and magnitude of supply interruptions. Therefore, no single reliability index alone, can describe the whole reliability situation. Instead, the indices focus on separate aspects or on individual combinations. So, in the assessment it is important to choose the right indices for further analysis in order to solve the given tasks [1, 2].

Considering these aspects of the assessment it shows that a probabilistic reliability analysis is a much more sophisticated task than deterministic methods like load flow and short circuit calculations.

3.4 Analysis method

3.4.1 General

In general, evaluation techniques can be classified as either analytical or as Monte Carlo simulation, described as:

- Analytic method: This method represents the system by a mathematical model and calculates the reliability indices from this model using mathematical solutions [13].
- Monte-Carlo method: This method simulates the actual process and random behavior of the system [2, 13]. The method allows for a more detailed modeling of the events in the power system but it consumes more calculation time correspondingly.

Analytic methods generate the component failure combinations to be analyzed one after the other with the help of appropriate algorithms. The separate failures and their effect on the power system and the supply situation are regarded independently from each other. The advantage of the analytic method is that the computation time is shorter in most cases, the calculation results are also easier to comprehend. The disadvantages is the lack of detailed modeling related to temporal succeeding events, like e.g. daily load curves or maintenance schedules [2]. These events contain a multitude of states to be considered and several simplifications have to be done when including such events.

The time sequential Monte-Carlo method on the other hand, simulates the operational performance of an electric power supply system in time. Starting with an originating state, points in time for failure events and restoration of failed elements are determined from the distributions of up-times and down-times caused by randomized failure combinations. The advantage of the simulative approach is that any distribution function for the component reliability data can be considered. Monte-Carlo simulations also enable modeling of temporal sequences, like e.g. daily load curves and maintenance schedules [2].

3.4.2 Minimal cut sets

The available cut sets can be describes as all of the possible fault events resulting in a supply interruption in a given system. A cut set is said to be minimal if the set cannot be reduced without losing its status as a cut set. The cut sets and minimal cut sets can be explained by the utilization of a fault tree (depicted in figure 3.3). Minimal cut sets can be used to understand the structural vulnerability of a system. The longer a minimal cut set is, the less vulnerable the system (or TOP event in fault trees) is to that combination of events. Also, numerous cut sets indicate higher vulnerability. Cut sets can also be used to discover single point failures (one independent element of a system which causes an immediate hazard to occur and / or causes the whole system to fail) [20].

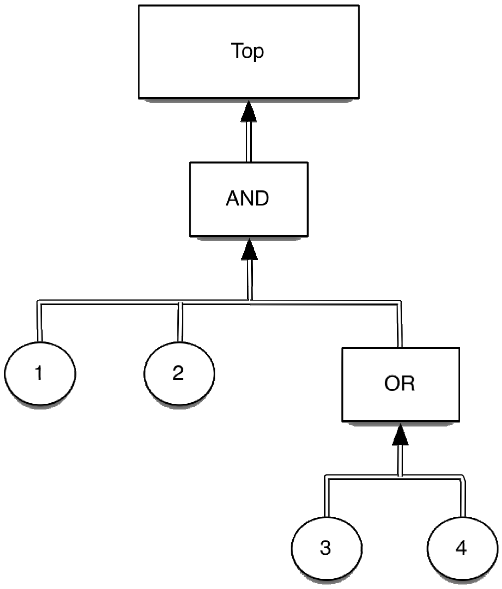

Figure 3.3 **Fault tree configuration.**

As an example, consider the fault tree shown in Figure 3.3. The system will fail if {1, 2, 3 and 4 fail} or {1, 2 and 3 fail} or {1, 2 and 4 fail}. All of these are defined as cut sets. However, the one including all components is not a minimal cut set because, if 3 or 4 are removed, the remaining events are also a cut set. Therefore, the minimal cut sets for this configuration are {1, 2, 3} or {1, 2, 4}. This may be more evident by examining the equivalent of Figure 3.3, as shown in Figure 3.4.

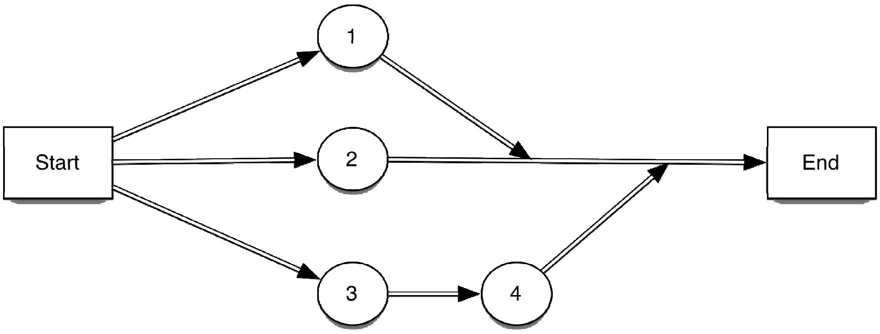

Figure 3.4 **Fault tree configuration equivalent.**

The identification of the cut sets in such a small model is simple. However, for large or complex systems calculation algorithms are necessary [9].

3.4.3 The Poisson process

Generally, the Poisson process can be defined as the stochastic process in which events occur continuously and independently of one another [9]. The process can be utilized when studying the occurrence of a certain event $\Re$ in a specified time interval (e.g. from time a to time b). The number of events between time t_1 and t_2 are given as $N(t_1) - N(t_2)$ and is said to be Poisson distributed (homogenous). Events such as e.g. telephone calls arriving at a switchboard, webpage requests, rainfall or in our case the failure distribution in a given power system can be assumed Poisson distributed.

The following assumptions are required regarding a homogenous Poisson process:

- $\Re$ can occur at any given time within the specified interval.
- The probability of $\Re$ occurring in the interval specified as $(t, t + \Delta t)$ is independent of t and can be written as $\lambda \cdot \Delta t + o(\Delta t)$, where λ is a positive constant ($o(\Delta t)$ denotes a function of Δt with the property that $\lim_{\Delta t \to 0}[o(\Delta t)/\Delta t] = 0$).
- The probability of more than one event $\Re$ in the interval $(t, t + \Delta t)$ is $o(\Delta t)$.
- Let $(t_{11}, t_{12}], (t_{21}, t_{22}], \ldots$ be any sequence of disjoint intervals in the specified time interval.
- Then, the events $\Re$ occurs in $(t_{j1}, t_{j2}]$, $j = 1,2,3, \ldots$ are independent.

When the event $\Re$ has occurred, the process starts over again. Thus the time between these occurring events in a homogenous Poisson process are exponentially distributed [9]. The Poisson process relation, in accordance to the above stated is given as:

$$E(N(t)) = \sum_{n=0}^{\infty} n \cdot \frac{(\lambda t)^n}{n!} e^{-\lambda t} = \lambda t \tag{3.1}$$

The homogeneous Poisson process is characterized by its rate parameter λ, which is the expected number of events that occur per unit time i.e. it expresses the intensity of the process. Regarding reliability the Poisson process is utilized regarding element failure frequency, which is often assumed Poisson distributed.

3.4.4 Markov models

Markov process

Chapter 3.2.2 deals with some of the possible component states. However, when dealing with component states in the field of reliability calculation, only the ability of the component to fulfill its function is relevant. The network components are therefore modeled with two states only. One of the most common analytical methods used in reliability calculations is the Markov process. The Markov models are based on the same assumption that the components can be in one of two possible states, a functioning state or a failed state. The system description also includes the transition between the states as is evident from the state-space diagram (Markov diagram) in figure 3.5.

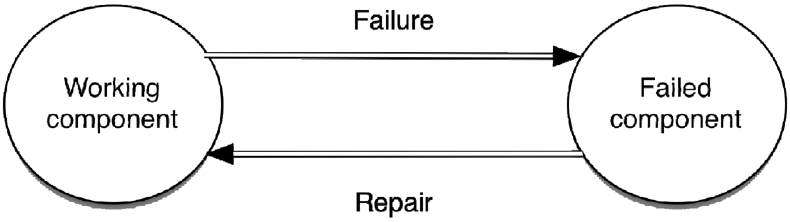

Figure 3.5 **Markov state space model.**

The Markov diagram is of course not only restricted to two states and the model can be used for relatively complicated systems. However, as the calculation time increases in accordance to the number of components and operating states, it is best suited for relatively small systems [9]. The following gives a short presentation of some of the theory related to the Markov process.

In probabilistic terms the Markov property is defined by:

$$P\left(X\left(t+v\right)= j \mid X(t)=i; X(u)=x(u); 0\le u<t\right)=P\left(X(t+v)=j \mid X(t=i)\right) \tag{3.2}$$

For all possible $x(u); 0 \le u < t$

The Markov term in (3.2) is valid under the assumption that the system is in state *i* at time *t* (i.e. *X(t)=i*), the future states *X(t+v)* do not depend on the previous states *X(u), u<t*. The system is also assumed to start in a specific state (e.g. state *i* at time *t=0*) and the transition between the states may be described by a stochastic process [9].

The transition probability of the Markov process (a stochastic process satisfying the Markov property) is defined as:

$$P\left(X\left(t+v\right)= j \mid X(t)=i\right) \qquad \text{for} \qquad i,j=0,1,2\ldots, n \tag{3.3}$$

In terms of mathematical modeling further simplifications can be done. If the transition probability $P\left(X\left(t+v\right)= j \mid X(t)=i\right)$ does not depend on time t but only the transition interval v, the process is said to be in steady-state (i.e. stationary process).

$$P\left(X\left(t+v\right)= j \mid X(t)=i\right)=P_{ij}(v) \qquad \text{for} \qquad t,v > 0; i,j=0,1,2\ldots,n \tag{3.4}$$

An example of a Markov process (process satisfying the Markov property) is the Poisson process.

The transition probabilities in (3.4) satisfy:

$$P_{ij}(t) \ge 0 \qquad \text{for} \quad t>0 \tag{3.5}$$

$$\sum_{j=0}^{n} P_{ij}(t)=1 \qquad \text{for} \quad t>0 \tag{3.6}$$

$$P_{ij}(t+v)=\sum_{k=0}^{n}P_{ik}(t)\cdot P_{kj}(v) \qquad \text{for } t,v>0 \tag{3.7}$$

Property (3.7) is known as the Chapman-Kolmogorov equation and follows from the Markov property and the rule for total probability [9].

The transition rate from state from *i* to state *j* can be defined as:

$$a_{ij}=\lim_{\Delta t\to 0}\frac{P\big(X(t+\Delta t)=j\mid X(t)=i\big)}{\Delta t} \tag{3.8}$$

Assuming that limit exist, using (3.4) gives

$$a_{ij}=\lim_{\Delta t\to 0}\frac{P_{ij}(\Delta t)}{\Delta t}=\dot{P}_{ij}(0) \tag{3.9}$$

Time derivate of (3.9) gives:

$$\dot{P}_{ij}(t)=\frac{d}{dt}P_{ij}(t)$$

Since the transition rate a_{ij} from state i to state j is constant, the time T_{ij} the system is staying in state i until transition to state j is exponentially distributed with parameter a_{ij} [9].

State equations

By letting Δt be a positive number and disregard the possibility of more than one transition in a given time interval of length Δt from (3.7) and assuming that $k\neq j$ we have:

$$P_{ij}(t+\Delta t)=\sum_{k=0}^{r}P_{ik}(t)\cdot P_{kj}(\Delta t)=\sum_{k=0}^{r}P_{ik}(t)\cdot P_{kj}(\Delta t)+P_{ij}(t)\cdot P_{jj}(\Delta t) \tag{3.10}$$

The probability $P_{jj}(\Delta t)$ is according to (3.6):

$$P_{jj}(\Delta t) = 1 - \sum_{\substack{k=0 \\ k \neq 0}}^{r} P_{jk}(\Delta t) \tag{3.11}$$

$P_{jj}(\Delta t)$ is the probability that the process does not leave the state *j* during the given time interval Δt. Therefore,

$$P_{ij}(t+\Delta t) = \sum_{\substack{k=0 \\ k \neq j}}^{r} P_{ik}(t) \cdot P_{kj}(\Delta t) + P_{ij}(t) \cdot \left[1 - \sum_{\substack{k=0 \\ k \neq j}}^{r} P_{jk}(\Delta t) \right] \tag{3.12}$$

The equation above can be solved by dividing it by Δt and letting $\Delta t \to 0$. This is in accordance to (3.9). The solution is called the state equation:

$$\dot{P}_{ij}(t) = -P_{ij}(t) \cdot \sum_{\substack{k=0 \\ k \neq 0}}^{r} a_{jk} + \sum_{\substack{k=0 \\ k \neq 0}}^{r} P_{ik}(t) \cdot a_{kj} \tag{3.13}$$

The process of solving such an equation can be a difficult task. However, some simplifications can be done. Let us assume that $X(0) = i$ i.e. that the process is in state *i* at time *t=0*, which can be expressed as:

$$P_i(0) = P(X(0) = i) = 1$$
$$P_k(0) = P(X(0) = k) = 0 \quad for \quad k \neq i$$

Further simplifications can be done if we assume that the initial state is known i.e. omitting the index *i* from (3.13):

$$\begin{gathered} \dot{P}_i(t) = -P_i(t) \cdot \sum_{\substack{k=0 \\ k \neq 0}}^{r} a_{jk} + \sum_{\substack{k=0 \\ k \neq 0}}^{r} P_k(t) \cdot a_{kj} \\ P_i(0) = 1, \quad P_k(0) = 0 \quad for \quad k \neq i \end{gathered} \tag{3.14}$$

The transition rates a_{ij} can be written in the form of a so called $\vec{A}$ matrix (transition rate matrix):

$$\vec{A} = \begin{bmatrix} -a_{00} & a_{10} & a_{20} & \dots & a_{r0} \\ a_{01} & -a_{11} & a_{21} & \dots & a_{r1} \\ a_{02} & a_{12} & -a_{22} & \dots & a_{r2} \\ \vdots & \vdots & \vdots & \dots & \vdots \\ a_{0r} & a_{1r} & a_{2r} & \dots & -a_{rr} \end{bmatrix} \tag{3.15}$$

The diagonal elements of the matrix (3.15) have the following notation:

$$a_{jj} = \sum_{\substack{k=0 \\ k \neq j}}^{r} a_{jk} \tag{3.16}$$

The state equations in (3.14) can now be written in matrix form in accordance to:

$$\vec{A} \cdot \vec{P}(t) = \dot{\vec{P}}(t) \tag{3.17}$$

Giving the matrix solution:

$$\begin{bmatrix} -a_{00} & a_{10} & a_{20} & \dots & a_{r0} \\ a_{01} & -a_{11} & a_{21} & \dots & a_{r1} \\ a_{02} & a_{12} & -a_{22} & \dots & a_{r2} \\ \vdots & \vdots & \vdots & \dots & \vdots \\ a_{0r} & a_{1r} & a_{2r} & \dots & -a_{rr} \end{bmatrix} \cdot \begin{bmatrix} P_0(t) \\ P_1(t) \\ P_2(t) \\ \vdots \\ P_r(t) \end{bmatrix} = \begin{bmatrix} \dot{P}_0(t) \\ \dot{P}_1(t) \\ \dot{P}_2(t) \\ \vdots \\ \dot{P}_r(t) \end{bmatrix}$$

The transition rates, $a_{jk}, k = 0,1,\dots, j-1, j+1,\dots, r$ from state *j* to the other states are called the departure rates. When the process enters state *j*, the system, will stay in this state in the duration T_j. The sum of the departure rate from state *j* is according to (3.16) a_{jj}. The duration T_j is exponatially distributed with the parameter a_{jj}. So, the mean duration of the state *j* is thus:

$$E(T_j) = \frac{1}{a_{jj}} \quad for \quad j = 0,1,,2,...,r \tag{3.18}$$

From (3.15) and (3.16) it is evident that the sum of the columns of the transition matrix $\vec{A}$ is zero i.e. that the matrix is singular. This also determines that the state equations (3.17) do not have a unique solution. However we know that the system must be in one of the $(r+1)$ states:

$$\sum_{j=0}^{r} P_j(t) = 1 \tag{3.19}$$

Finally, by combining the state equations (3.17) and (3.19) and the known initial state $\left(P_i(0) = 1\right)$, we are know able to compute all the state probabilities $P_j(t)$ for $j = 0,1,2,...,r$. The state equations (3.17) are a set of linear, first order differential equations. The most common method for solving these kinds of equations is to utilize Laplace transforms. However, this has not been included as the purpose of this chapter is to present the method involved in the Markov models, not the actual calculations.

3.5 Schematic sequence of a reliability analysis

Figure 3.6 depicts the basic schematic sequence for a reliability analysis. The basis for the analysis is the past performance of the actual system i.e. the statistical reliability input data. Component outages and corresponding input data for the failure models are derived from appropriate outage statistics. In the reliability calculation part, contingency states or failure combinations are generated using stochastic methods. Then, the contingency states are analyzed for their effect on the customers, regarding reliability of supply. In case of supply interruptions, the complete sequence of events until restoration of supply to all customers or until the temporal expiration of the failure combination is also modeled. Finally, the probabilistic reliability indices for the system and for each customer are calculated.

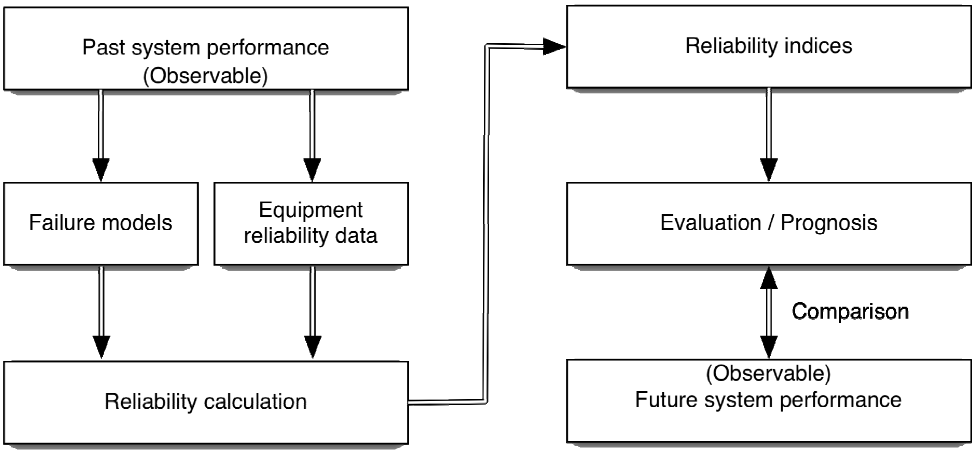

Figure 3.6 **Schematic sequence of a reliability analysis**

3.6 Reliability indices

3.6.1 Overview

When determining the reliability of a power system some indicators describing the simulation results is needed. The quantitative description of supply reliability is therefore calculated through appropriate characteristic indices. In the field of reliability calculation there exists a multitude of different indices being more or less meaningful and widespread. PSS®SINCAL however calculates certain basic indices and from those basic indices further sizes (table 3.1) can be calculated [2].

Index	Name	Unit
H	Frequency of supply interruptions	1/a
T	Mean duration of supply interruptions	H or min
Q	Unavailability	1 (common: min/a)
L	Interrupted power (Cumulated)	MVA/a
W	Energy not supplied (Cumulated)	MVAh/a
K	Interruption cost (Cumulated)	NOK/a
A	Reimbursement (Cumulated)	NOK/a

Table 3.1 **PSS®SINCAL reliability indices.**

Some internationally recognized reliability indices have also been included. These international standard indices, according to the IEEE 1366 standard are related to the network areas. Several IEEE 1366 standard indices exist (table 3.2). The IEEE 1366 standard indices are commonly used by the utilities to compare their power system to other worldwide systems [23]. The necessary calculations for the IEEE 1366 indices have been presented in appendix 3.

Index	Name	Unit
SAIFI	System average interruption frequency index	1/a
SAIDI	System average interruption duration index	min/a
CAIDI	Customer average interruption duration index	min

Table 3.2 Reliability indices according to the IEEE 1366 standard.

When calculating the probabilistic reliability indices it is important to remember the prognosis uncertainty, which is not related to the quality of the models and data used in the calculation, but is an intrinsic characteristic of the systematic description of rare events like supply interruptions.

3.6.2 Frequency of supply interruptions

The frequency of supply interruption index is the number of interruptions in a given period, a.

3.6.3 Mean duration of supply interruptions

The mean duration of a supply interruption specifies the mean time span ranging from the start to the end of a supply interruption on a load node or the system respectively. It is given in h or min. A supply interruption is eliminated when the load can be fully re-supplied, by the means of switching operations, implementing of provisional equipment or repair of the failed element.

3.6.4 Probability of supply interruption / unavailability

The probability of supply interruptions, also called unavailability, describes the possibility to find the power system or a single load node in the state of supply interruption on a randomly given point in time. The probability is the product of frequency and mean duration of supply interruptions.

3.6.5 Interrupted power

The interrupted power index describes the sum of interrupted power in a given interruption period. The interrupted power depends on the frequency of supply interruptions and the sum of interrupted power of each affected load. However, it does not depend on the duration of the interruption but gives an indication on the magnitude of the interruption.

3.6.6 Energy not supplied

The energy not supplied is the sum of the energy that can not be delivered to a load or to all the loads in a system in the period under consideration. In addition to interrupted power index listed above, the energy not supplied also depends on the duration of the interruption.

3.6.7 Interruption cost

Interruption cost reflects the attempt to monetarily value the damage to the customers arising from supply interruptions. There are many differences in the customers cost structures e.g. customer classifications like household, trade, commercial, industrial or agricultural. Therefore this evaluation can only give a rough idea of the actual economic damage. When including the time of the day and seasonal changes this only becomes more evident. The Norwegian energy act and some of the laws regulating the energy market in Norway have been described in chapter 2.

3.6.8 SAIFI

SAIFI (system average interruption frequency index) is a measure of the number of times the average customer experiences an interruption of supply. For SAIFI, an interruption is a loss of supply for longer than one minute [23].

3.6.9 SAIDI

SAIDI (system average interruption duration index) is a measure of duration. It measures the number of minutes over an annual period that the average customer is without power.

3.6.10 CAIDI

CAIDI (customer average interruption duration index) is a measure of duration that provides the average amount of time a customer is without power per. interruption.

4 PSS®SINCAL probabilistic reliability calculation module – ZUBER

4.1 Introduction

The ZUBER program package, implemented in PSS®SINCAL, is the reliability calculation module. Development of the software started in the 80's at the Darmstadt University of Technology and the Saarland University. Further development and commercialization of the tool has been conducted at the Siegen University and the Forschungsgemeinschaft für Elektrische Anlagen und Stromwirtschaft e. V. As a result of this new development, the usage of probabilistic reliability calculation has become an essential tool for maintaining power systems and allows the practical application in any required field [1].

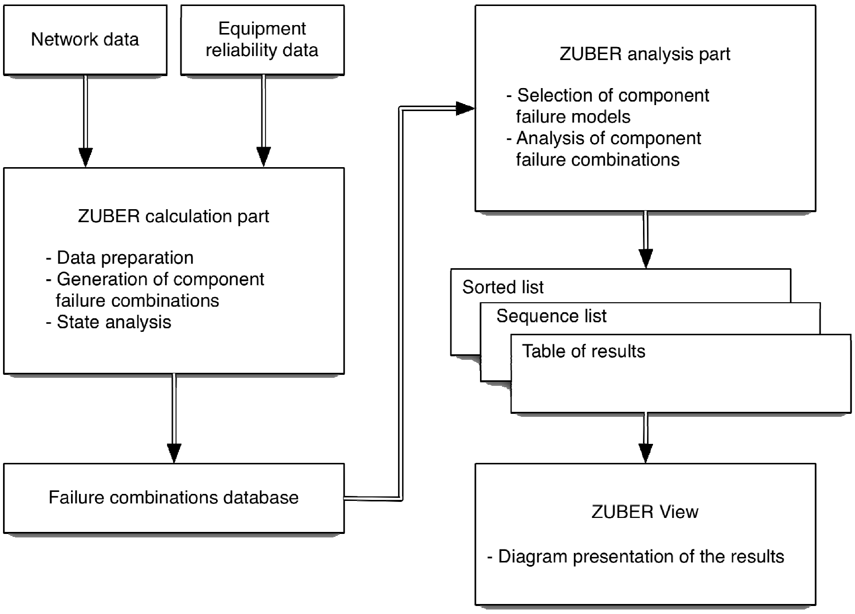

Figure 4.1 **ZUBER program structure.**

Figure 4.1 depicts the program structure of ZUBER, consisting of three modules; ZUBER calculation, ZUBER analysis and the ZUBER view. The calculation part generates the failure combinations and models their sequence until restoration of supply. The analysis conducts an overview of the failure sequences and the finally the results can be viewed in the visualization tool ZUBERview.

4.2 Analytic method

The reliability calculation module performs the generation and analysis of the relevant failure models (contingency states), including the modeling of supply restoration after interruptions. Results for these contingency states are presented as reliability indices.

Then, the indices are evaluated by the analysis module. In the latter several different analyses might be of interest and it is therefore beneficial that the calculation module and the analysis module are separated. This eliminates time-consuming calculations for each evaluation.

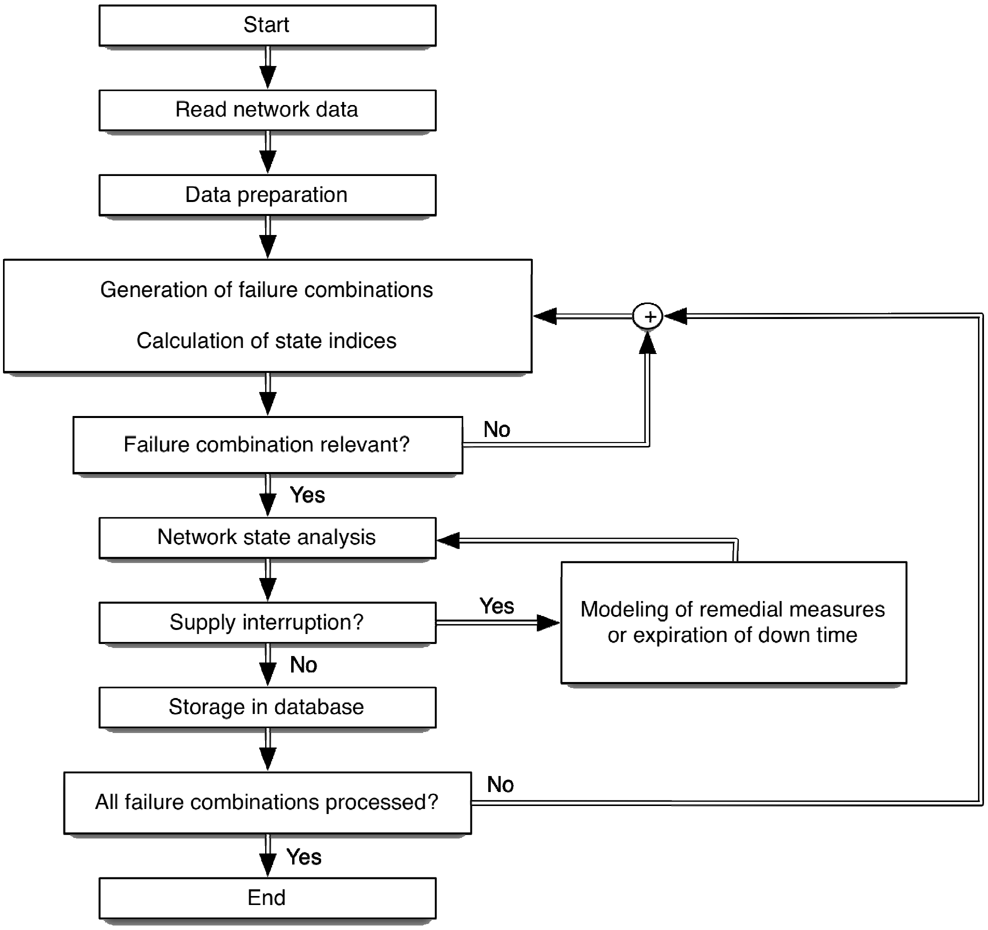

Figure 4.2 **Calculation sequence.**

Initially, the calculation sequence (figure 4.2) reads the input data compiling them into a computational model. The input data consists of standard topological and electrical data of the network and the components. Additionally, the input data includes rudimentary information on the protection system (location and type of protection relays). Regarding reliability analysis, stochastic data describing the outage performance of the network components are also needed. This component reliability data is closely related to the failure models (e.g. independent single failure, common mode failure, malfunction of protection device etc.) which are implemented in the software. PSS®SINCAL, as well as several other tools, uses models which were derived from the German statistic of outages in public power supply networks. If the actual network is comparable to German networks, statistical data is available. For other networks, the component reliability data has to be derived from suitable outage statistics. Finally, the input data includes some key data on the possibilities, time requirements of switching operations and other methods available for restoration of supply to interrupted customers.

The end result of the reliability analysis is the calculation of the state indices which is based on the contingency states (failure combinations) and the reliability data of the involved components. The PSS®SINCAL module uses a homogenous Markov approach, described in chapter 3.4.4, for the generation of the various failure combinations. It is assumed that the failure probability of the components is exponentially distributed in time, meaning that the number of possible combinations grows exponentially with the number of network components. In a given time interval the failure probability for the network elements does not depend on the location of the time interval and disregards the previous history of the component. Therefore, the frequency of a component failure is assumed to be Poisson distributed. If the network contains large amounts of reliability elements, also the possible combinations grow, due to the exponential distribution of failure combinations. The high number of failure combinations generated by PSS®SINCAL requires a limitation for analyses purposes. This can be done by setting limits either for the minimum probability or for the order of simultaneously failed combinations.

The generated failure combinations are then analyzed for their effect on the supply situation of the customers in the network. This analysis is based on a standard load flow calculation, using different algorithms. In case of a supply interruption suitable remedial measures have to be taken. The next step of the probabilistic reliability calculation is the modeling of the complete process until restoration of supply to all customers. This process is modeled time sequentially. Relevant indices are stored in a database for later evaluation.

The ZUBER Analysis Part (figure 4.3) reads the component failure combination sequences generated in the calculation part and computes the appropriate reliability indices for certain load nodes or the complete system. Filtering the failure combinations with regards to specified selection criteria, enables the analysis of combinations regarded as most interesting. Finally, the sequence of all selected component failure combinations is listed in detail. The list contains information about the initial supply restrictions and any remedial measures. Also, their effect on the customers until full supply is reestablished can be read.

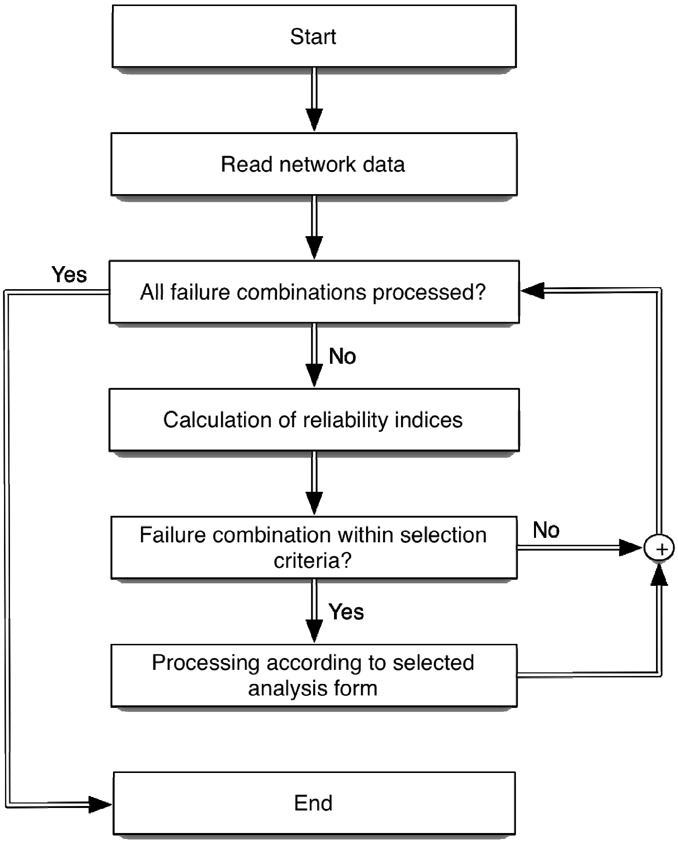

Figure 4.3 ZUBER analysis flow chart.

The evaluation method available in the ZUBER Analysis Part gives an overview of the system's reliability level, especially for the detailed analysis of individual aspects.

4.3 PSS®SINCAL failure models

4.3.1 Introduction

The goal of a reliability analysis is to achieve precise results that are representative for the actual network. Therefore, modeling of the failures occurring in power system operation needs to be as accurate as possible. The failure models described in this section as well as the methods for remedial actions serve for qualitatively correct modeling of failure events. Reliability data have been collected from the sources described in chapter 6 and the calculations of the probabilities have been presented in appendix 4. Information about the various failure models have been collected from the PSS®SINCAL manual [2].

4.3.2 Independent single failure

An independent single failure is the failure of one unique component. The independent single failure as the name suggests is independent and therefore not related to any other incident or failure that may occur at the same time. For each element, frequency and outage duration caused by the independent single failure are declared.

Figure 4.4 shows an example of an independent single failure. The line L2 is disconnected after a short circuit according to the protection plan. No other disconnection is related to this event.

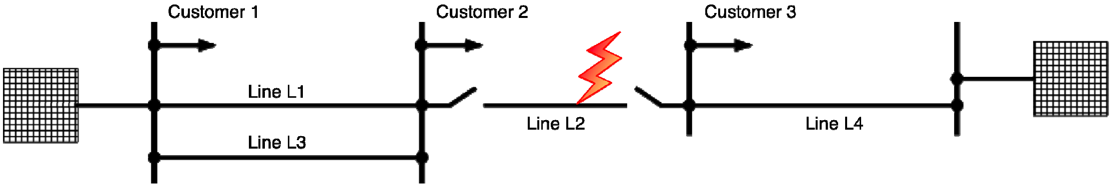

Figure 4.4 **Independent single failure example.**

This failure mode includes:

- Automatic protection tripping caused by short circuits.
- Unnecessary disconnections of protection tripping areas.
- Double earth faults in power systems with earth fault compensation, if only one earth fault is disconnected automatically and the remaining element affected by an earth fault remains in operation.

Single failures can occur simultaneously without a causal relation between these failures. This usually is the case e. g. with weather related failure accumulations. Though this causes several components to be in fault state at the same time, each failure is independent and the overlapping is accidental. Self-extinguishing earth faults and successful automatic re-closing are not regarded as failures.

The necessary calculations have been presented in appendix 4.

4.3.3 Common mode failure

Common mode failures are characterized by the synchronous failure of multiple protection tripping areas caused by one fault situation. A frequent example for a common mode failure is shown in figure 4.5 were lightning strikes into the pylon or overhead earth wire and back flashover on two or more circuits of a multiple line. This causes disconnections of the affected circuits by the protection system. This type of fault situation is predominant in the 110kV level electrical networks.

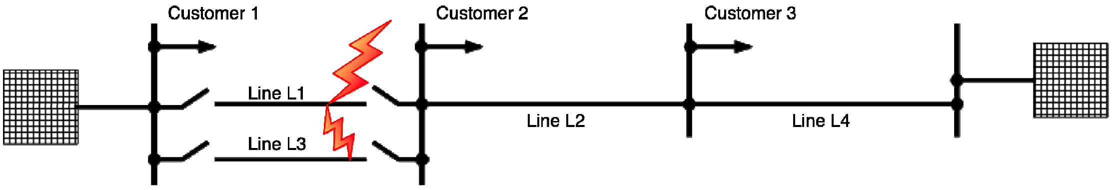

Figure 4.5 **Common mode failure example.**

Other typical examples include:

- Disconnection of two or more circuits of a multiple line because of wire oscillations.
- Pylon fracture with multiple lines.
- Damage to several cables in one cable pit because of e. g. landslides or excavator works.

When modeling common mode failures of multiple overhead lines the voltage level has to be considered. Multiple lines including circuits with a nominal voltage below 110kV suffer common mode failures mainly because of lightning strikes and back flashover. The electrical breakdown caused by lightning strikes is due to the reduced distance between conductors at lower voltage levels i.e. reducing the dielectric strength between the conductors. Circuits with a nominal voltage above 110kV suffer common mode failures because of wire oscillations. Thus, common mode failures at this voltage level occur at a much lower frequency.

In the case of multiple lines consisting of more than two circuits, double failures of any two neighboring circuits of the multiple lines have to be modeled. Thus, the configuration of the mast and the separate circuits is required. With multiple lines including circuits with nominal voltage exciding 110kV and bellow 110kV, one common mode failure for the circuits with the lowest voltage level and additionally failures according to the geometric configuration have to be modeled. In principle, common mode failures of components other than lines are also possible, e. g. of a bus bar and a transformer in case of fire, explosion or flooding of a switching station. Analyzing the VDEW-Störungs- und Schadensstatistik / VDN Störungstatistik shows that in recent years this kind of common mode failure is extremely rare.

The tripping of a circuit breaker caused by a short circuit and the following disconnection of another circuit breaker because of overloading is not regarded as a common mode failure. While the cause for the first disconnection is a short circuit, the cause for the second is overloading. Hence, the disconnections in such a scenario don’t have a common cause.

The necessary calculations have been presented in appendix 4.

4.3.4 Malfunction of protection device

A multiple element failure caused by malfunction of protection device starts with the failure of one element, normally caused by a short circuit. Normally, the element affected by the short circuit is disconnected selectively by the protection system according to the protection concept. In case that this does not happen, the backup protection system has to conduct the disconnection. This is an unwanted situation, as it extends the effect of the original failure, causing unnecessary disconnection of the elements in the backup zone (see figure 4.6).

This sequence is described by the conditional probability ρ_{sv}. Here, ρ_{sv} is the probability for a malfunction of protection device in the protection tripping area of element i, with failure on element i. The outage after malfunction of protection device is ended after the time needed to recognize and unlock the fault-affected element and reconnecting the elements in the backup tripping area. The backup protection tripping areas are defined in the protection plan, i.e. which protection devices represents the main protection for the fault affected element under consideration and which protection devices represent reserve systems.

Figure 4.6 depicts an example of a malfunctioning protection device after a short circuit on line L2. If the protection system on the bus bar of customer 2 fails, also lines L1 and L3 have to be disconnected by the backup protection system according to the protection concept. This implies an extension of the incident; customer 2 now suffers an unnecessary supply interruption.

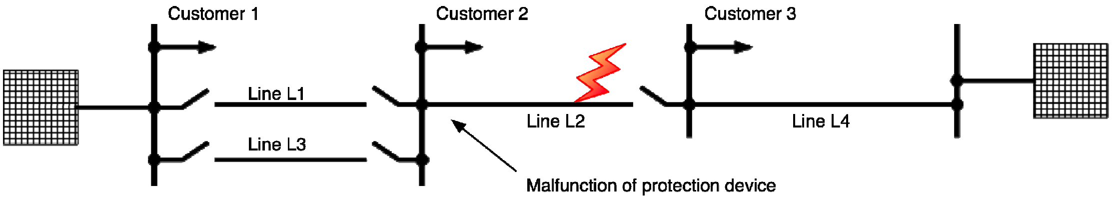

Figure 4.6 **Malfunctioning of a protection device**

The difference between malfunction of circuit breaker and malfunction of protection device is that circuit breaker malfunctions only include one backup tripping area, and not like in case of a malfunction of protection device, all related backup tripping areas are affected. In power systems that are only equipped with graded distance protection relays there is no difference between the failure models of malfunction of circuit breaker and malfunction of protection device.

The necessary calculations have been presented in appendix 4.

4.3.5 Unnecessary protection operation with multiple outages

Short circuit in a protection zone, can in some cases also affect protection devises in other protection zones. The partial short circuit currents produced by a fault can provoke a response in several protection devices and may trigger unnecessary protection operations. As a result, protection-tripping areas in contrary to the protection concept can be disconnected

Thus, the failure model of unnecessary protection operation can only occur as a succeeding failure within the scope of an extension of the incident. This is described by the conditional probability ρ_{sue}. ρ_{sue} is the probability of an unnecessary protection operation on element j while short circuit on element i. The outage duration caused by an unnecessary protection operation is the duration for the reconnection of the elements disconnected unnecessarily.

For determining the protection devices carrying a partial short circuit current above the starting threshold, a short-circuit calculation is required. Only these devices are able to cause an unnecessary protection operation.

The cause for unnecessary protection operations may be:

- Insufficient protection adjustment.
- Measurement errors.
- Wrong direction decisions.
- Transformer saturation.
- Damages to the protection device.

Figure 4.7 shows an example for the unnecessary protection operation failure model. A short circuit on L2 causes the disconnection of this line according to the protection concept. A relay of the protection system on L4 responds to the partial short circuit causing an unnecessary operation. Thus, the effect of the original failure is extended on customer 3, now suffering a supply interruption.

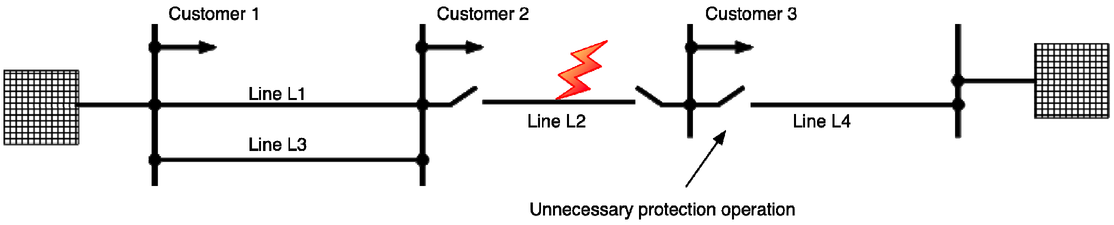

Figure 4.7 **Unnecessary protection operation with multiple outages.**

The necessary calculations have been presented in appendix 4.

4.3.6 Multiple earth faults with multiple outages

The multiple outages by multiple earth faults start off with a permanent fault on element i. The permanent earth fault causes the voltage to increase in the unaffected parts of the system. In case another single pole fault occurs, the permanent earth fault becomes a double short circuit to earth, causing a protection operation. In 90% of those cases, both protection tripping areas affected by the faults are disconnected, which does not correspond to the protection concept. It should be mentioned that this failure model is only relevant for power systems with earth fault compensation. To prevent supply interruption to certain customers, only one of the affected protection tripping areas is disconnected automatically while the other one has to be disconnected by manual operation. The occurrence of a multiple earth fault failure is described by the conditional probability ρ_{me}. ρ_{me} is the probability for a second fault on an element on condition that a permanent earth fault already exists in the power system. The outage duration of the multiple earth fault failure normally is the duration for reconnection of the affected elements.

The probability for the occurrence of a second fault is much higher than the probability for the first earth fault because of the voltage increase in the conductors is not affected by the first fault. The permanent earth fault also has to be disconnected in cases where no multiple earth faults occur, which may cause a supply interruption. Using the Monte Carlo simulation this situation can be modeled correspondingly.

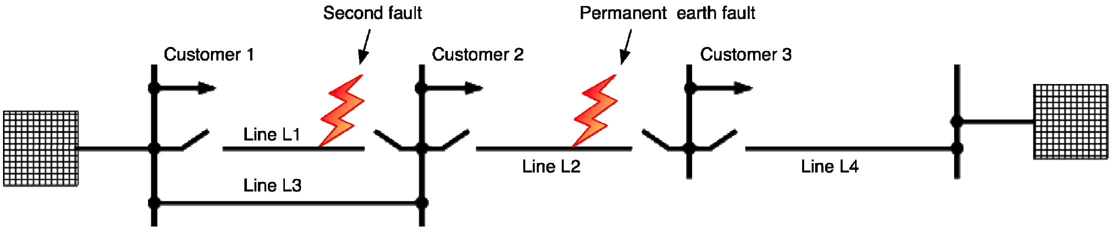

Figure 4.8 **Multiple earth faults with multiple outages.**

Figure 4.8 shows an example for the above failure model. After a permanent earth fault on line L2 the voltage increase in the power system, causing another single-pole failure on another conductor of line L1. This invokes a fault current similar to a short-circuit current, causing the protection system to disconnect both fault affected elements in contrary to the protection concept.

The necessary calculations have been presented in appendix 4.

4.3.7 Independent unnecessary protection operation

This failure model deals with independent unnecessary protection operations, i.e. operations of the protecting system without a preceding failure. This failure model corresponds in great parts to the independent single failure. In some cases, though, the resulting outage situation is different, as only individual protection devices trigger, and not necessarily a complete protection tripping area like with an independent single failure.

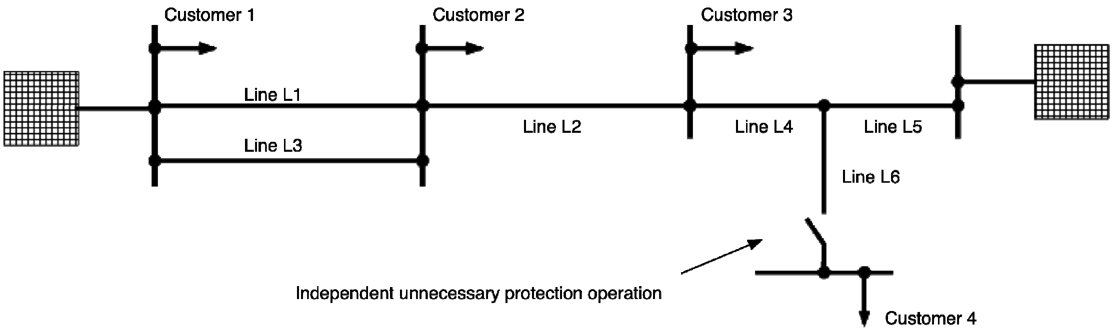

Figure 4.9 **Independent unnecessary protection operation.**

An example is the line tripod shown in figure 4.9. In contrary to the independent single failure on line L6, which would also cause lines L4 and L5 to be disconnected, thus separating the power system in two partial systems, the independent unnecessary protection operation only causes a supply interruption for customer 4. Such failures are often caused by work related human errors resulting in unwanted disconnections.

The necessary calculations have been presented in appendix 4.

4.4 Reliability analysis evaluation

4.4.1 Presentation of the results

Dealing with the reliability calculation results can often be a daunting task as the results are comprehensive and rather difficult to interpret. Therefore, regarding the analysis of the calculated results it is very important how the results can be presented.

The results in PSS®SINCAL can be accessed as follows:

- log files
- SINCAL database
- Network diagram

All reliability indices can be exported to Excel sheets, and be used as a basis for further calculations and in the decision making processes. The log files are comprehensive text based files, which contain all important user-defined output information from the reliability calculations.

The following information can be found in the log-files:

- Network model for reliability analysis
- Sequence of separate failure combinations
- Results
    - Results table
    - Sorted lists
    - Details on failure combinations

There are two main types of the results:

- Network reliability indices
- Customer reliability indices

PSS®SINCAL also enables the possibility to differentiate the results i.e. filtering the results related to specific user-defined choices such as:

- Differentiation regarding failure models
- Differentiation regarding involved components
- Differentiation regarding voltage levels
- Differentiation regarding power system areas
- Component oriented results
- Affected customers
- Interval definitions

The reliability analysis has been further described in chapter 7, in relation to the PSS®SINCAL network test model.

5 SAMREL – Requirement specification for reliability analysis

5.1 Introduction

This chapter deals with the ongoing development of a methodology (SAMREL) incorporating power market analysis via power flow and contingency analysis. The end goal of this work is to deliver point reliability analysis, including societal impacts, such as high energy prices and interruption costs. The motivation for including this chapter is the fact that a comparison between these tools could be beneficial. The main focus has been the methodology for the reliability calculation and available results.

The SAMREL methodology is based on a power market simulator, a power flow model and a newly developed methodology for delivery point reliability and interruption cost assessment. SAMREL incorporates available computer based simulation and analysis tools which is part of the power system analysis. The problem today is that many existing tools are fragmented because of lack of methodical links between them. The main purpose of SAMREL is to improve this information exchange. Heightened information exchange and improved interaction between the models are advantageous because it have the potential for improving both the market simulations and the reliability analysis.

5.2 SAMREL methodology

As mentioned above, the development of a method for enhanced power system reliability utilize known computer based tools and models. Figure 5.1 depicts the SAMREL modules, making the reliability analysis possible. The integrated methodology will cover the chain of analyses from spot market clearing for electricity, via power flow in the system and contingency analysis to reliability studies for regional areas and delivery points.

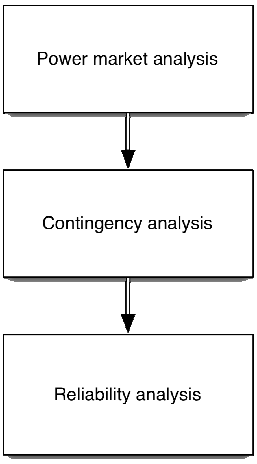

Figure 5.1 **SAMREL program structure.**

The first part is the power market simulator (EMPS) which is optimized for hydro power generation. It takes into account demand, supply, transmission constraints and hydrological conditions. The model requires information about the transmission capacities between areas. Considering this, the available capacity in a particular transmission line may be affected by the flow on other lines. Secondly, one has to account for operating limits to prevent frequency drop and system instability (angular or voltage). This information is often not easy to obtain and as a consequence the user of the EMPS model needs detailed analysis of the power flow and system stability to set proper values for the transmission capacities.

The power injections on the local nodes of the given system are calculated by the transmission model. The input data for the transmission model is the area power balance e.g. calculated by the EMPS model. The results of the power flow calculation give information about the consumption profiles and the transmission capacities that are possible to utilize in a given situation. Since these capacities are exogenous input to the EMPS model, there is a need for interaction between the aggregated models for regional energy balance and more detailed models for the power flow in the electrical network [5].

The detailed information about production and load in all nodes are needed to calculate the power flow of the system and for the contingency analysis. The power system reliability analysis is the final part of the SAMREL methodology and is the analysis which predicts the long-term reliability of supply in the system. The power market and power flow models and the contingency analysis are the core engines in these analyses. The contingency analysis comprises the simulation of component outages and their consequences for the power flow and system problems in terms of violations of different operating constraints [5]. This provides input to both part 1 and part 3 in figure 5.1. Finally, the reliability of supply analysis is being preformed for estimation of frequency and duration of interruptions for delivery points and the corresponding societal costs (costs of energy not supplied – CENS).

Figure 5.2 depicts a simplified view of the SAMREL methodology and the steps involved in calculating the reliability indices.

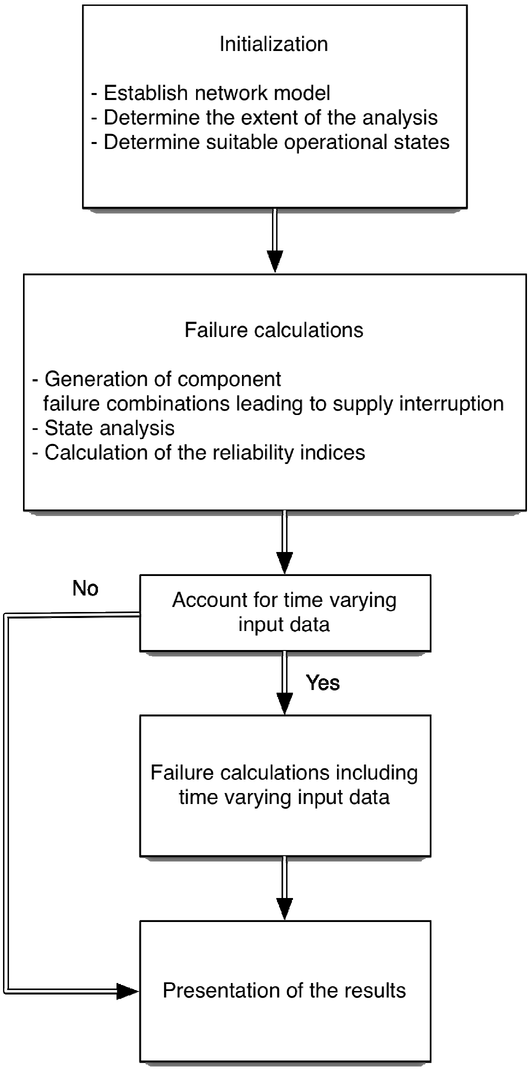

Figure 5.2 **SAMREL methodology.**

5.3 Modules

This chapter explains in detail the modular structure of SAMREL and figure 5.3 depicts the three integrated modules. These modules utilize three different enabling methodologies being a market model (EMPS or other), power flow model (PSSE or other) and the reliability model (OPAL).

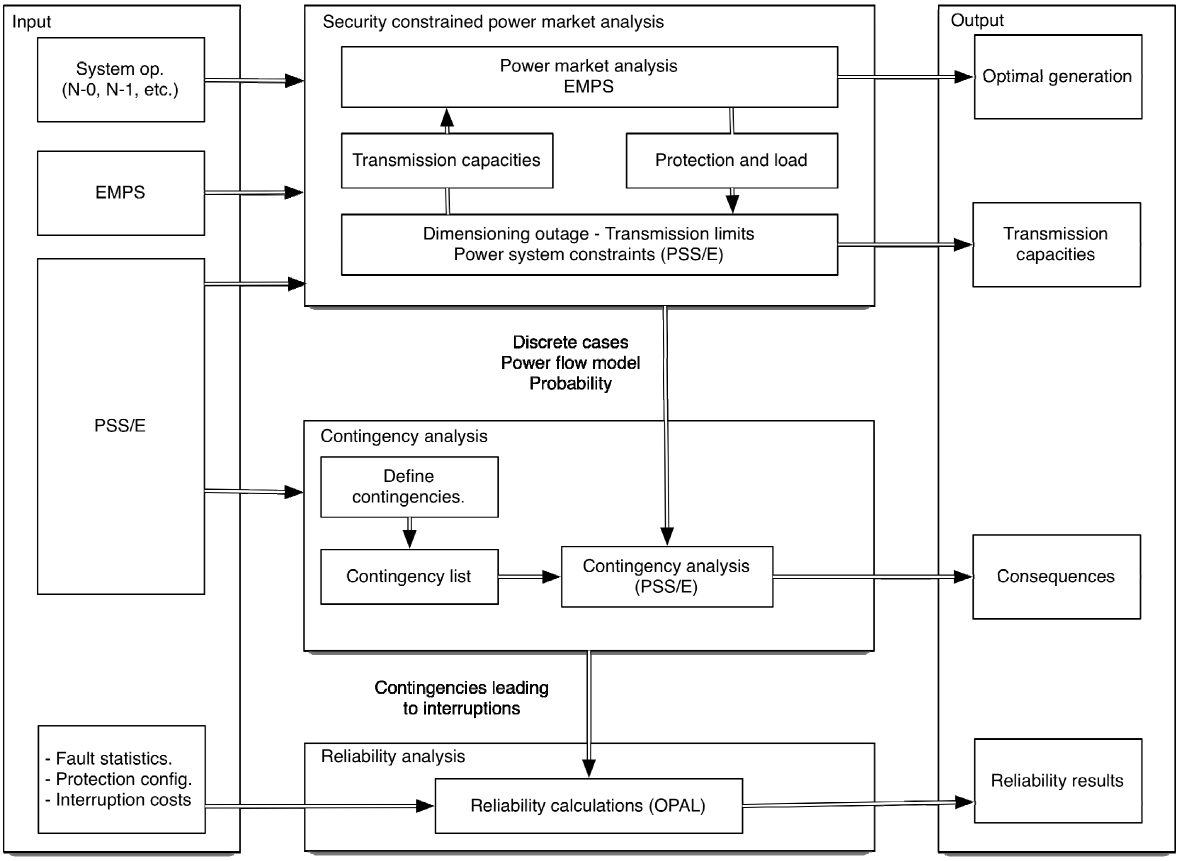

Figure 5.3 **SAMREL modules.**

5.3.1 Power market analysis

The purpose of the power market analysis is to identify the hydrological optimal operation based on statistical data (Statistical series of up to 75 hydrological years are available). The EMPS model described in [6] calculates the value of stored water for different reservoir fillings, and it simulates the optimal operation of the power system for a sequence of hydrological years. As depicted in figure 5.3 there is an interaction between the EMPS model and the power flow analysis, which is necessary when determining the system power transfer capabilities. The EMPS model provides a set of production and load scenarios with the actual system transfer capabilities. Finally, through an iterative process, the constraints and limits (e.g. voltages, thermal rating, voltage stability and angular stability) are checked. Through this iterative process the realistic transmission capacities as well as the feasible operational states are found as input to the next step of the analysis [5].

5.3.2 Selection of operational states

Regarding long term planning of a power system it is beneficial to carry out the analysis with all possible operational states. However this is often not possible as the number of possible combinations is extensive, giving a near impossible calculation effort. Utilizing this EMPS model with 75 hydrological series over a total of 52 weeks and 7 price sections per. week it would give 27300 different operational states. Including the number of contingencies in relation to the transmission capacities it results in millions of operational states. This implies the need for an approximation, limiting the number of states, and selecting representative cases e.g. for one or several months. This is a challenge and a topic under ongoing work [5].

5.3.3 Contingency analysis

For each of the selected operational states a distribution of production and load per unit and delivery point is determined and a contingency analysis is carried out [5]. The main emphasis of the contingency analysis is to verify the systems ability to maintain power delivery at certain contingencies (i.e. contingencies leading to interruption or reduced supply for each of the investigated delivery points). The analysis utilizes standard power flow or dynamic simulations at various contingencies selected manually or automatically. A contingency list must be generated for each of the chosen operational states, and the contingency analysis is carried out for each operational state.

5.3.4 Reliability analysis

In the reliability analysis the objective is to determine the reliability of supply indices for the delivery points under study, i.e. to estimate the frequency and duration of interruptions (or reduced supply), energy not supplied and the corresponding cost of energy not supplied (CENS) e.g. according to the Norwegian quality of supply regulation [5]. The reliability analysis in this case was performed with the OPAL methodology (optimization of reliability of supply in power networks) described in [4]. OPAL takes into consideration the interruptions due to primary faults on the power system components and protection system faults leading to unwanted breaker operation. The input to the reliability analysis consists of information about which delivery points will experience interruptions or reduced supply in combination with fault statistics and specific interruption costs [4, 5]. For each of the operation states the model establishes a minimal set of cuts for each of the delivery points. These are deduced for each operational state, based on the contingencies leading to interruptions or reduced supply. Then the reliability indices are calculated per minimal cut for each operational state and each delivery point with fault rates, outage times and specific interruption costs as input.

5.4 Time-dependent correlations

SAMREL calculates reliability indices deduced from minimal cuts related to the chosen operational states. However, calculations can also include time-varying parameters and time-dependent correlations between them for each delivery point. Generally SAMREL divides the statistical material into appropriate groups e.g. component fault rates can be grouped in three typical time periods, namely 24 hours, 7 days and 24 months. The observed time-dependent fault rate pattern found in statistics is the aggregated result of all causes contributing to faults of a particular component, representing weather related, technical or human related faults. A model which is able to generate this pattern, analytically or by simulation, will therefore produce outage events according to what is expected to happen in the real system [4]. SAMREL enables the possibility for including these fault rate variations both in analytical calculations and Monte Carlo simulations for calculating the reliability indices, utilizing the same representation of the time-varying parameters. The Monte Carlo approach is additionally capable of handling the stochastic variations in the parameters, thus providing the probability distributions of the reliability indices in addition to expectation values. Further descriptions of the time-varying parameters included in the OPAL methodology can be found in [4].

5.5 SAMREL failure models

SAMREL considers four different fault types or failure models that potentially contribute to degradation of the power system reliability.

These failure models are:

- Failure model 1: Primary fault in primary equipment where protection and breakers clear the fault correctly.
- Failure model 2: Primary fault in secondary equipment or circuit breaker, leading to unwanted spontaneous tripping of circuit breaker.
- Failure model 3: Primary fault in primary equipment combined with fault in circuit breaker or secondary equipment, leading to missing operation of circuit breaker.
- Failure model 4: Primary fault in primary equipment combined with fault in circuit breaker or secondary equipment, leading to unwanted unselective tripping of circuit breaker.

Where,

- Primary equipment: Equipment such as transformers, lines, cables etc. (i.e. high voltage equipment).
- Secondary equipment: Equipment such as measurement transformers, power supply etc. (i.e. low voltage equipment part of a control system).
- Primary fault: The primary failure (e.g. a short circuit).
- Secondary fault: Preceding failure either directly caused by the primary failure or occurring after a given primary failure (e.g. unwanted behavior related to a protection system).

Failure models 2-4 deal with faults related to the protection system while failure model 1 covers faults in primary components with the premise that the faults are cleared correctly [4].

5.6 Reliability indices

Results from the reliability analysis are presented in the form of reliability indices. Minimal cut sets and corresponding reliability indices are calculated for each operational state and each delivery point. Table 5.1 shows the SAMREL indices.

Index	Name	Unit
$P_{\text{int},DP,j,OS}$	Interrupted power in delivery point caused by each cut j per operational state.	[kW per interruption]
$ENS_{DP,j,OS}$	Energy not supplied in delivery point caused by each cut j per operational state.	[kW per interruption]
$IC_{DP,j,OS}$	Interruption costs in delivery point caused by each cut j per operational state.	[NOK per interruption]
$\lambda_{DP,j,OS},_a$	Number of interruptions in delivery point caused by each cut j per operational state.	[interruptions per year]
$U_{DP,j,OS,a}$	Annual interruption duration in delivery point caused by each cut j per operational state.	[hours per year]
$P_{\text{int},DP,j,OS,a}$	Annual interrupted power in delivery point caused by each cut j per operational state.	[kW per year]
$ENS_{DP,j,OS,a}$	Annual energy not supplied in delivery point caused by each cut j per operational state.	[kWh per year]
$IC_{DP,j,OS,a}$	Annual customer interruption costs in delivery point caused by each cut j per operational state.	[NOK per year]

Table 5.1 SAMREL reliability indices.

6 Case model for probabilistic reliability calculations

6.1 Introduction

A case model for reliability calculations has been developed part of the master thesis and further explained in this chapter. The PSS®SINCAL network model has been included for demonstrative purposes, giving a practical example of the methodology describing the power system reliability. The data preparation both for load flow and reliability calculations has been presented. The main target of the study is to quantify the supply reliability for a given distribution network based on the performance of the network components and the network topology.

As mentioned earlier, probabilistic reliability calculation imposes special demands on the data basis i.e. the commonly known data for power flow calculations are not sufficient. Modeling of the power system topology must therefore e.g. include the exact bus bar configurations (sectionalized busbars, multiple busbars etc.). The reason for this is that the possibility for remedial switching actions in relation to failure events has an impact on the reliability results.

Other important reliability data include:

- Load duration curves
- Failure model reliability data
- Protection schemes
- Generation curves

Regarding the calculations performed by PSS®SINCAL, the basic data model has to cover both power flow and three-phase short-circuit calculations, with representative and acceptable operating conditions (typically peak-load operation). In this process, the modeling of voltage profiles and equipment loading has to be as exact as possible.

The case simulations have been performed on a high voltage distribution system owned by Istad Nett AS. The following chapters give a detailed description of the process of creating a working test model.

6.2 Limitations and challenges

6.2.1 General

The purpose of reliability analysis is to determine the reliability of a given power system being small or large. However, achieving this is not necessarily an easy task. Like all other mathematical analysis some limitations and challenges do exist. The work presented in [24] gives a short overview of the aspects concerning a reliability analysis and includes some of the well known challenges related to the analysis of large technological systems.

These challenges are:

- Lack of knowledge of the system and its components.
- Lack of relevant input data.
- Lack of knowledge on the reliability of the human components.
- Lack of knowledge on the quality of the computer software.
- Lack of knowledge of the dependences between the system components.

These are known obstacles often part of a reliability analysis which potentially introduces several analytical uncertainties. These uncertainties can in many cases have a negative influence on the analysis, making it very hard to assess the failure probability and the overall risk assessment of a power system. The general rule of computer analysis applies; insufficient input data will produce insufficient results. However, a valid risk assessment of a power system can be carried out through the use of reliability analysis as long as there is awareness of such limitations. This implies that reliability analysis often cannot only rely on the computed result. Thus, in many cases expert opinions need to be included in the analysis. A general problem when using such resources is the actual process of selecting the experts [24]. In many cases were the overall reliability assessment on the system level is less clear, it is often advantageous to include human resources, like expert opinions and people with local knowledge. However, too much influence directly on system level assessments should be prevented as it often again could introduce uncertainties. These uncertainties can be avoided by using correct information (e.g. statistical data) about the power system. However, in many cases this is difficult or not possible. In general the prognosis of component reliability performance in dependency of the chosen asset management strategies is a vital necessity. However, suitable models and data for such prognosis are not easily available [14]. These are among the key factors that need to be considered when performing a reliability analysis.

6.3 Reliability of medium voltage components

6.3.1 General

The network components connected at voltage levels ranging from 22kV and below are assumed non-failure affected elements (i.e. 100% reliable components). The motivation for doing so is directly linked to the scope of the analysis. If the main emphasis is to determine the reliability in the regional network (132kV-420kV), there is no need for including the lower level components. Statistically, failures that occur at these levels, seldom lead to any supply interruptions in the 132kV-420kV network. Failures occurring at these voltage levels get disconnected and isolated from the power system. However, this may lead to potential loss of generation, but in most cases, due to high generation capacity and high level of interconnections, this is not a problem.

6.3.2 Failure of generation sources

Concerning reliability in power systems, it is worth mentioning the modeling of generation sources. It is a known fact that generation units fail more frequently than typical network components, which is mainly due to higher mechanical and thermal stress [10]. Usually, generation sources are modeled either by a two state model or by a more detailed model e.g. including reserves, start-up, incident operation etc. [2]. In a two-state model, generation sources are either "on" or "off" and compared to the e.g. a six-state model, it is evident that the level of accuracy is much lower.

Regarding power system reliability it is also possible to exclude the effect of generation unit outages from the stochastic failure modeling. In this case, the load flow and reliability calculations have to be performed separately with the generator units switched off. Comparing these two methods it is evident that excluding the generation sources has its advantages. First of all, the complexity of the reliability calculations increases dramatically when including the generation sources, due to the high failure rate and high number of operational states. Therefore, results without generation units are easier to interpret and more meaningful. The method also allows for changing the load flow situation, adapting it to certain operation states, enabling the studies of these individually. Last but no least, in many cases it will be difficult to obtain meaningful input data for the state models representing the generation sources [8].

Examining some of the available statistics it is evident that the influence off generation system outages on the supply reliability in public power systems is very small, which is supported by the work described in [10]. However, there are certain aspects that need consideration. The effect of an outage depends on the type of customer e.g. industrial and regional utilities and on the systems ability to supply the peak power demand. Finally, economical influence compared to the technical influence may be significant. However, the economical influences have not been dealt with in this thesis.

Conclusively, the fact that the generation capacity in Western European countries is available via highly meshed grids, with short transport distances, the generation sources can be regarded as non failure components as they have little or no affect on the power system reliability. This has clear advantages both for the complexity of the mathematical models and the understanding of the analysis results.

6.4 Time dependent load modeling

Power flow calculations usually model the separate customer loads by their annual peak-power value, representing a worst case scenario. However, this method is insufficient for reliability calculations were it is evident that the customers normally do not require their annual peak-power during the complete period under consideration. So, when conducting reliability calculations, the need for including time dependencies is evident. The most common approach is to represent the loads according to a standardized annual load duration curve. The annual load duration curves are strongly dependent on the type of the power system under consideration. Especially the configuration of the customers connected to the power system (e. g. urban / rural, industrial / residential, mixtures, etc.) has a great effect on the duration curve.

The various load operating states represented by the load duration curve will also have an impact on the reliability indices.

The indices commonly affected are:

- Frequency of supply interruptions
- Mean interrupted power
- Energy not supplied.

The actual loading situation will in many cases have an effect on the reliability calculations and is therefore an important part of the network modeling. It is often seen that some supply interruptions are caused by additional disconnection of equipment directly related to overloading. Overloading strongly depends on the power demand state of the affected customers at the time of the failure. So, when running the various failure combinations this needs to be taken into consideration. In case of overloading in the power system, PSS®SINCAL calculates the power threshold when the overloading occurs. This power threshold marks the point below which the system operates as normal and above which an overloading occurs, related to a given failure combination. The frequency of supply interruptions at this incident is the frequency of this failure combination weighted with the temporal part of the load duration curve above this power threshold. Further, the mean interrupted power is affected by the load situations given by the load duration curve. The reason are that the mean power demanded by a customer increases with the load ratio. The reliability index "energy not supplied" depends, among other factors, on the frequency of supply interruptions and the mean interrupted power. Thus, the index strongly varies with the form and load ratio of the load duration curve [2].

In addition, a load priority or a load duration curve different from the default value can be assigned to individual loads. Higher priority loads are allocated power preferentially in case of supply interruptions caused by power shortages. Such load methods also, in many cases, gives a more realistic picture of the actual loading situation (e.g. representing large industrial areas or seasonal changes).

6.5 Network description

Some details about the network have been made available in appendix 1 and 2. Figure 6.1 depicts a section of the network model.

UNDERLAGT TAUSHETSPLIKT

Iht. BfK § 6-2, jf. off.loven § 5a

Figure 6.1 Section of the PSS®SINCAL model.

The Netbas single line diagram for the Istad network has been attached in appendix 1. Some simplifications related to the size of the network were necessary to limit the extent of the reliability calculations. Generally, a complete modeling of neighboring systems is normally not reasonable, as it would evoke substantial effort regarding data procurement and computing time. The most important simplification regarding the network model is the elimination of a neighboring 132kV network. The motivation for doing so is the fact that this part of the network is not owned by Istad Nett AS and would have a limited affect on the reliability results. However, as mentioned above, some network borders have to be established in this kind of analysis. Other simplifications worth mentioning are a power station equivalent made up of all the small generation sources. The main objective in doing so is due to the lack of data for these sources, which are often the case regarding small power stations. The purpose of the power equivalent is to recreate the power flow as accurate as possible in this area. Also, regarding reliability, all of the components connected at 22kV or lower have been regarded as 100% reliable. Thus, these components are irrelevant regarding the actual reliability calculations.

6.6 Relevant input data

6.6.1 General

In this case, all the detailed information about the network and the network components have been exported from PSS®E and presented in tabular form. It should be mentioned that it is possible to import a PSS®E model directly into PSS®SINCAL. However, it requires several additional data elements in the preparation process related to probabilistic reliability analysis. Therefore, for educational purposes, it was deiced to construct the network model in PSS®SINCAL without exporting data from PSS®E, manually. This off course, is more time consuming, but on the other hand has many advantages when it comes to getting to know both PSS®SINCAL and the network topology.

The following subchapters provide information about the relevant input data (power flow and reliability) used in the data model. However, it should be pointed out that the values presented in this chapter are the minimum data foundation for performing a liable reliability analysis. PSS®SINCAL enables several other possibilities both in terms of input data and available calculation methods. However, the main focus in this report is the reliability methodology and therefore, the input data most relevant, have been chosen.

6.6.2 Busbars and switching stations

The information needed for these network elements are:

- Busbar topology (i.e. single or double busbars)
- Busbar redundancy (i.e. switching possibilities / busbar transfer)
- Switching times

The network topology and information about system redundancy was provided by Istad Nett AS. In this case all of the double busbars have been modeled with coupling breakers, enabling the possibility of busbar transfer. Busbars, connectors and busbar couplings are assumed 100% reliable, meaning that they are never failure-affected. From experience, the switching times are assumed to be 0,5h representing a worst case scenario, after an initial disconnection.

6.6.3 Transformers

The basic data needed for the transformers are:

- Rated values (Voltage levels, nominal power etc.)
- Short circuit voltages (both total and ohmic part)
- Vector group
- Voltage control information (tap changers)

All the rated values are available from the PSS®E data export and the basic short circuit calculations have been performed using this data. This is also the case regarding the voltage control.

6.6.4 Over head lines

The basic data needed for the over head lines are:

- Rated values (length, resistance and capacitance charging etc.)
- Number of parallel systems.
- Calculation of thermal limits

All the rated values are available from the PSS®E data export and the thermal limits have been calculated using this data. Regarding reliability calculations (common mode failures) it is also important to determine the topology of the over head lines (i.e. the number of parallel systems). This information was made available by Istad Nett AS.

6.6.5 Generation sources

The basic data needed for the generation sources are:

- Rated values (Voltage levels, nominal power etc.)
- Operation state (maximum and minimum power generation)
- Control ability
- Power limits

All the rated values, operation states and the controller limits are available from the PSS®E data export. Power flow calculations are based on this information and in this process it is especially important to include generation and transfer capabilities. In the latter, it is also necessary to define a swing bus of the system. Further analysis of the network revealed that the best suited generation area were Viklandet. This generator has sufficient generation capability and serves as the swing bus, maintaining the frequency and voltage in the network.

The generators are assumed 100% reliable i.e. they are never failure-affected.

6.6.6 Reactive elements

Reactive power production and absorption (i.e. capacitors and reactors) are present and have been included in the test model.

The basic data needed for the reactive generation sources are:

- Rated values (Voltage levels, nominal power etc.)
- Operation state (maximum and minimum power generation)

- Control ability

All the rated values, operation state and the controller limits are available from the PSS®E data export. Normally, switching capacitors have the ability for a stepwise controller action. However, in this case all the reactive sources have been modeled operating at full capacity or as out of service.

6.6.7 Loads

The reliability calculations have been performed utilizing a sorted annual load duration curve, standardized to the annual peak power of the Norwegian transmission network, with a mixture of different customers. The data for the load duration curve (figure 6.2) have been provided by Siemens AS.

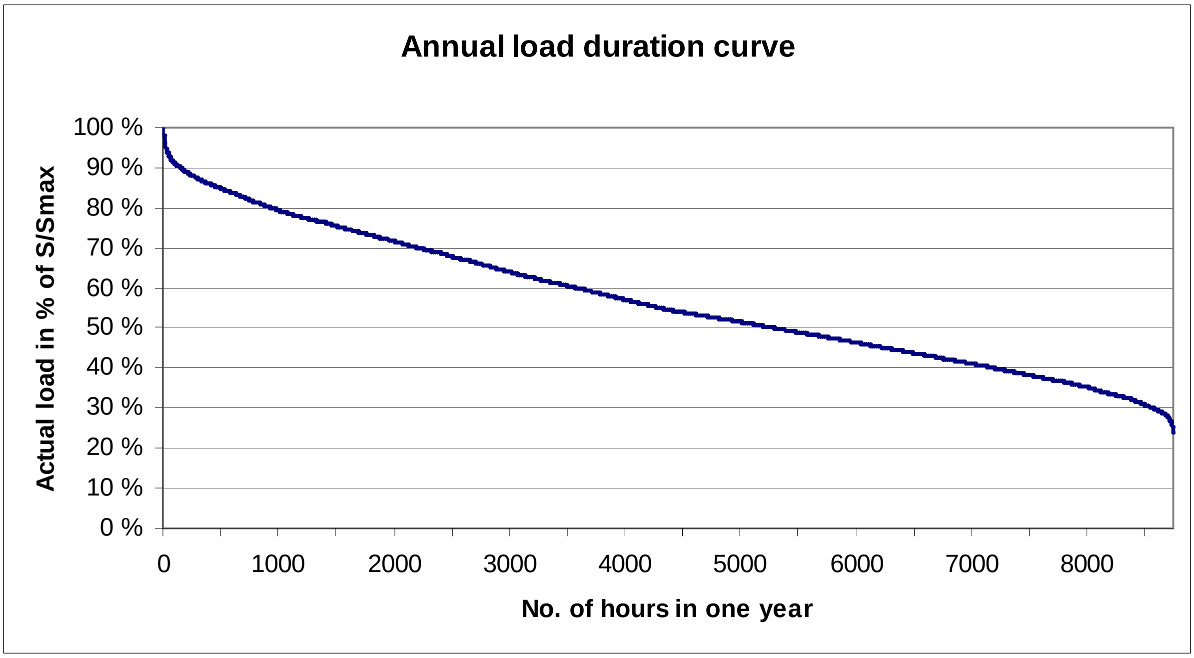

Figure 6.2 **Sorted and standardized annual load duration curve.**

Regarding the test model, both the substations Hustadmarmor and Nyhamna are examples of industrial areas where a more thorough load modeling, reflecting the actual loading situation, could be beneficial. The reason for this is the possibility for load variations deviating from the average load duration curve. However, this is only relevant for the reliability analysis if the loads and the load variations are of substantial size. In this case the loads of Nyhamna and Hustadmarmor stand for approximately 50% of the total system load. Thus, it would have been more accurate to model these loads in accordance to locally available data including the actual time variations. However, after an agreement with Istad Nett AS, it was decided to use the same standardized annual load duration curve for all the system loads, empathizing on the reliability methodology.

6.6.8 Protection system

The protection system is very important when it comes to the reliability of a system. Therefore, when analyzing different failure scenarios and their effect on system reliability some basic information on the protection devices used in the power system is needed. Most importantly, the protection system defines the systems reaction to given failure situations i.e. which components will be disconnected and which parts of the network can still maintain operation after failures have occurred.

Some information about the protection system was made available by Istad Nett and has been implemented. However, after an agreement with Istad Nett, it was decided to implement standard protection systems if no information was available. Information about the Norwegian protection system in general was based on conversations with [7].

Protection system overview:

- Overhead lines and cables
  - 22kV-132kV: Single distance protection devices in each termination.
  - 300kV-420kV: Double distance protection devices in each termination.
- Transformers (22kV-420kV)
  - High voltage side: Differential protection devices and overcurrent protection devices.
  - Low voltage side: Distance protection devices.
- All double bus bars with connector switches have differential protection devices.
- The generator sources have no protection.

6.6.9 Failure models

The various reliability data have been calculated from annual failure statistics released by Statnett for 33-420kV networks [30] and experience data from Siemens AS. The derived reliability data are listed in appendix 5. The necessary calculations according to [31] have been presented in appendix 4.

The reliability data for the failure model multiple earth faults with multiple outages, is based on the failure statistics of the public networks in Germany [12]. Comparing the reliability data available in German statistics it is evident that generally the reliability data in Germany are 25% higher compared to the collected data. This has been taken into consideration and the German failure data have been adapted for the Norwegian power system.

7 Reliability calculations of Istad Nett

7.1 Introduction

Some of the most relevant results related to reliability have been presented in this chapter. It also includes information about the test cases and the chosen simulation parameters. In general, when determining the reliability in a given network a multitude of operation scenarios can be tested. However, it clearly has its advantages in this case if the simulations first of all reflect real life operating scenarios. Some statistics from the past performance of the system is often available and it could be beneficial comparing them to the PSS®SINCAL calculation results. In this case, three scenarios related to load expansion have been chosen. Further information about the simulation cases, results and description of the various analysis methods has also been presented.

In this context it should be mentioned that the main focus of the presented reliability analysis is to give an example of the possibilities that exist in PSS®SINCAL. Thus, emphasizing on the reliability methodology.

7.2 Simulation parameters

7.2.1 General

The PSS®SINCAL calculation part reads the topological and electric power system data as well as the reliability data for the equipment units. The next step involved in the analysis is to examine the respective component failure combinations according to the user defined simulation parameters. The read data at first are first subject to plausibility and integrity checks. Afterwards, the protection zones are determined starting from the error-free equipment and protection data. Accordingly, the system is organized into separate components. The component failure combinations are generated either by the analytic method or by the Monte Carlo simulation.

7.2.2 Relevant failure models

The following failure models have been chosen part of the reliability calculations:

- Independent single failure

- Independent unnecessary protection operation
- Common mode
- Unnecessary protection operation with multiple outage
- Multiple earth faults

The failure model describing malfunctioning of protection devices have not been included due to lack of statistical data.

7.2.3 Simulation parameters

Appendix 6 gives an overview of the simulation input parameters both for the calculation and analysis part of PSS®SINCAL. ‘Considering the parameters most relevant for the reliability results some comments can be made:

- Consider only Supply Interruption: This parameter means that PSS®SINCAL does not consider failure combinations that do not lead to any power failure of consumers.
- Isolated operating permitted: This parameter defines whether or not the network is allowed to break up, leading to island operating scenarios.
- Execution of Switching Operations: Enables the possibility to switch on specific network elements during reliability calculations to improve supply security.
- The fields limiting of failure combinations, min. unavailability threshold, min. failure order component and max. failure order component; These settings determine if a malfunction is considered or not. PSS®SINCAL have the possibility to filter the failure calculations. The software does not consider failure combinations with less than minimum unavailability, nor does it consider failure combinations as small as the minimum or larger than the maximum failure order.

7.2.4 Legend

Abbreviations commonly used related to the reliability results have been listed.

Reliability indices:

- H: Frequency of supply interruption [1/year]
- T: Average duration of supply interruption [h]
- Q: Non-availability or Probability of supply interruption [min/year]
- L: Interrupted Power [MVA/year]

- E: Expected energy not supplied (EENS) [MVAh/year]
- K: Cost for energy not supplied (CENS) [NOK/year]

Failure models:

- UN: Independent single failure
- CM: Common-Mode failure
- SV: Malfunction of protection device
- ME: Multiple earth faults
- SUE: Unnecessary protection operation
- SP: Independent unnecessary protection operation

7.3 Test case descriptions

7.3.1 Overview

At closer inspection two major industrial areas stand out, which is Nyhamna and Hustadmarmor. Nyhamna is the onshore process terminal for the submerged Ormen Lange gas field [22]. Hustadmarmor is the world's biggest producer of pigments for the international paper industry [21]. Together, they represent over 50% of the total installed load in the system and are under constant development. Istad Nett has provided information about the planned load expansion decided to take place over a period of years (see table 7.1-7.3). Generally, it is common practice to account for an annual net load growth of about 1% of the various loads in a given power system. This load growth has also been included in the three test cases, using the base case as a starting point.

7.3.2 Input data

Bus	Load
Hustadmarmor	93MW
Nyhamna	135MW
Remaining load	199.16MW (base case)
Total load	427.16MW

Table 7.1 Test case 1: Base case representing year 2008.

Bus	Load
Hustadmarmor	101MW
Nyhamna	210MW
Remaining load	203.14MW (including two percent growth)
Total load	514.14MW

Table 7.2 Test case 2: Load expansion representing year 2010.

Bus	Load
Hustadmarmor	136MW
Nyhamna	210MW
Remaining load	213.1MW (including seven percent growth)
Total load	559.10MW

Table 7.3 Test case 3: Load expansion representing year 2015.

7.4 Results

7.4.1 Overview

The end result of the reliability analysis is to identify possible weak points/areas in the power system that does not have the necessary configuration for an adequately stable and reliable operation.

As mentioned before, PSS®SINCAL has a wide array of possibilities when it comes to presenting the results. The possibilities for differentiating the results are especially useful in the process of identifying the critical components of the system. The results have been presented in the form of quantitative reliability indices, which is the number one tool in the process of determining if the various operating scenarios are acceptable or not. Reliability indices according to IEEE 1366 have also been included. These reliability indices are SAIDI and SAIFI and PSS®SINCAL calculates these indices for all areas of the network.

The conclusion of the final analysis can e.g. include necessary changes of the network topology (e.g. new lines/cables or improving the busbar transfer-capability) and making changes to the system power generation (e.g. optimizing the power flow in certain areas). The most important results have been presented in appendix 7-13 and further explained in the next subchapters.

The results include reliability indices for the total power system, which is the network model in the whole. However, the results from Istad Nett exclude Brandhol, Nyhamna and Grytten substation. Other results are related to failure models, the substations, voltage levels and relevant system components.

All of the statistical data describing disturbances in the Norwegian power system have been collected from the annual disturbance statistics made available by NVE (Norges vassdrags- og energidirektorat) [26].

7.4.2 Power system results

The total power system results have been presented in appendix 7 in the form of reliability indices. The results for Istad Nett (total power system excluding Grytten, Nyhamna and Brandhol) have also been presented. The results for the total power system indicate an annual frequency of supply interruptions of 0.72 with average interruption duration of 3.30 hours. The results for Istad Nett show an annual frequency of supply interruptions of 0.64 with average interruption duration of 2.86 hours. These results are related to test case 1. It is evident that as the load increases (test case 2 and 3) both the frequency of supply interruption and the average interruption duration also increases. These changes, however, are very small but the uninterrupted power is now substantially larger causing higher CENS costs. The total CENS cost for the total power system increases from approximately 3.0 million Norwegian kroner to 4.6 million Norwegian kroner. The total CENS cost for Istad Nett increases from approximately 0.95 million Norwegian kroner to 1.4 million Norwegian kroner (see figure 7.1).

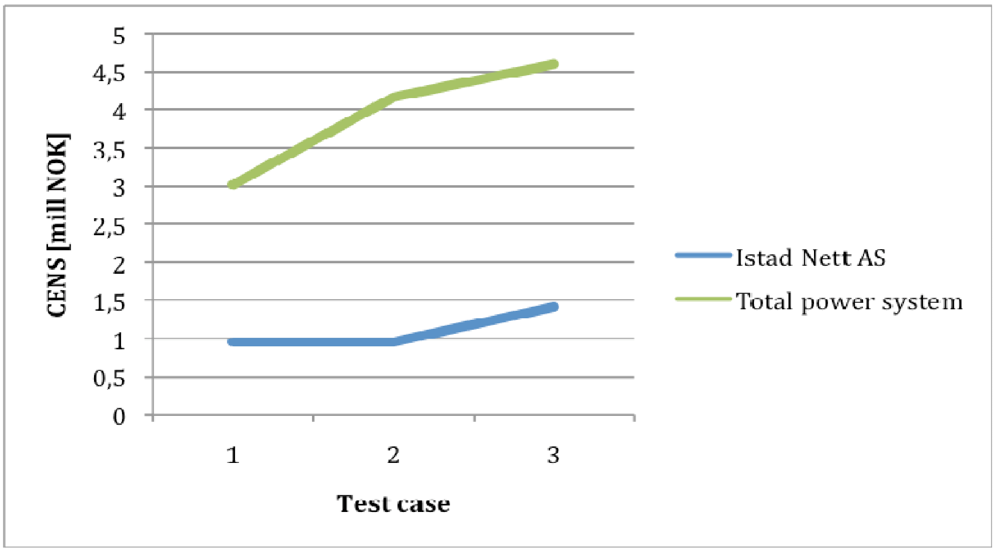

Figure 7.1 **CENS cost Istad Nett AS and total power system.**

7.4.3 Power system results differentiated according to failure models

The results differentiated according to the failure models have been presented in appendix 8 in the form of reliability indices (i.e. the contribution from the various failure models). Figure 7.2 depicts the results for test case 1.

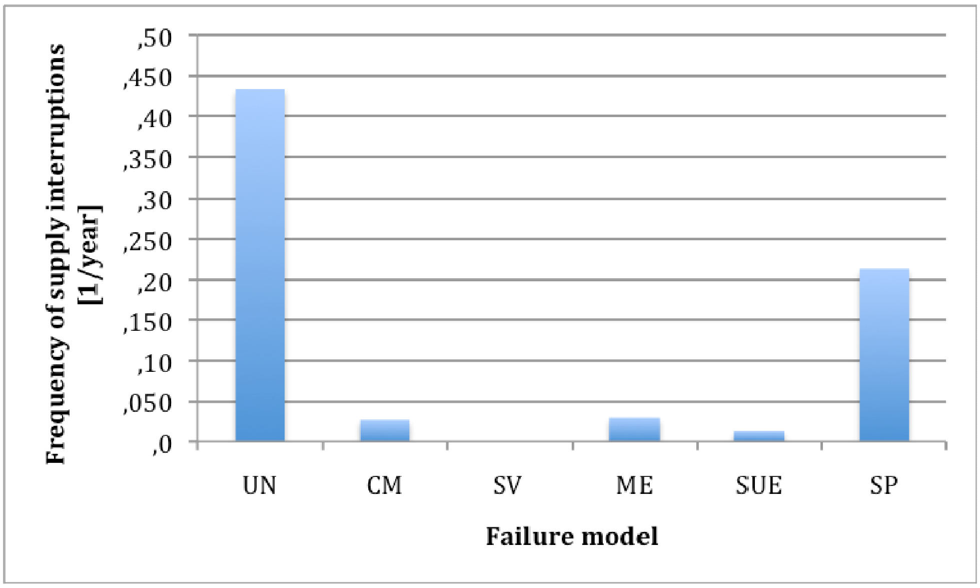

Figure 7.2 **Results differentiated according to the failure models.**

The results depicted in figure 7.2 clearly indicate that the highest frequency of supply interruptions is caused by independent single failures. However, this doesn't necessary mean that average duration of supply interruption for these failures are longer. Both common mode and multiple earth faults failures have the same or longer duration of supply interruption than the failures caused by independent single failures i.e. these failures are equally serious regarding power system operation. However, the probability for such failures occurring is lower, hence the annual ramifications are therefore limited. The energy not delivered directly related to these failures is much lower due to the fact that the frequency of supply interruptions is lower. The fact that independent single failures are the most common failures leading to a supply interruption in the power system is not unexpected as these kinds of failures are most likely to occur (supported by the most occurring types of failures in [26]).

Regarding the failure model, independent unnecessary protection operation, it is evident that scenarios leading to such failures have a relatively high probability compared to the other failure models, which is to be expected. From experience these failures are often caused by human error (work related errors causing unwanted disconnections) and are very common. This is supported by [30] which rank human error second on the list of disturbances differentiated according to cause.

7.4.4 Results differentiated according to voltage level

The results for the different voltage levels have been presented in appendix 9 in the form of reliability indices. Examining the results for the different voltage levels it is important to remember that the 132kV network results actually reflect the 22kV network results. This is also the case for the 420kV network results, which reflect the 132kV network results. The reason for this is the fact that PSS®SINCAL calculates the reliability indices for the load nodes i.e. where the supply interruptions occur. Thus, the reliability in the 420kV and 132kV networks will in fact be related to supply interruptions in the 132kV and 22kV networks (i.e. supply interruptions in 420kV and 132kV networks are related to failures in the 132kV and 22kV network). The lower voltage levels (1-22kV) are not included as the components at these voltage levels have been regarded as 100% reliable. It should also be mentioned that in this case the reliability of the 420kV network is actually the reliability of Nyhamna substation since this is the only 132kV load in the system. One could therefore argue that the reliability indices for the 420kV network are not directly comparable to annual statistics such as in [26] but have been included for demonstrative purposes.

Statistically the number of interruptions and especially the duration of the interruptions are higher at 132kV and lower than in the upper voltage levels. The reason for this is that many substations at the 132 kV levels operate on a single line. The substations at 420kV levels are however often more interconnected. This secures a more reliable operation and also decreases the frequency of supply interruptions and the average duration of the interruptions. This is supported by [26] that states that only about 3% of all failures leading to a supply interruption actually occurs in the 420kV networks. The results presented in appendix 9 supports this. The numbers of supply interruptions at the lower voltage levels are approximately 0.7 annual interruptions compared to the 420kV voltage level at 0.2 annual interruptions. However, for the 420kV voltage level this is just an approximation due to the insufficient statistical information mentioned above.

Generally, it is also important to remember that the ramifications of failures in the 420kV network are much higher compared to the lower voltage levels. So, even tough the frequency of supply interruption is lower at 420kV voltage level than e.g. at a 22kV voltage level, it doesn’t necessarily mean that the reliability is better at this voltage level.

7.4.5 Results differentiated according to substations

The results for the substations have been presented in appendix 10 in the form of reliability indices. The results have been differentiated in accordance to the annual CENS cost which is the most important reliability indicator for the utilities. Figure 7.3 depicts the five substations contributing to the highest CENS costs related to test case 1.

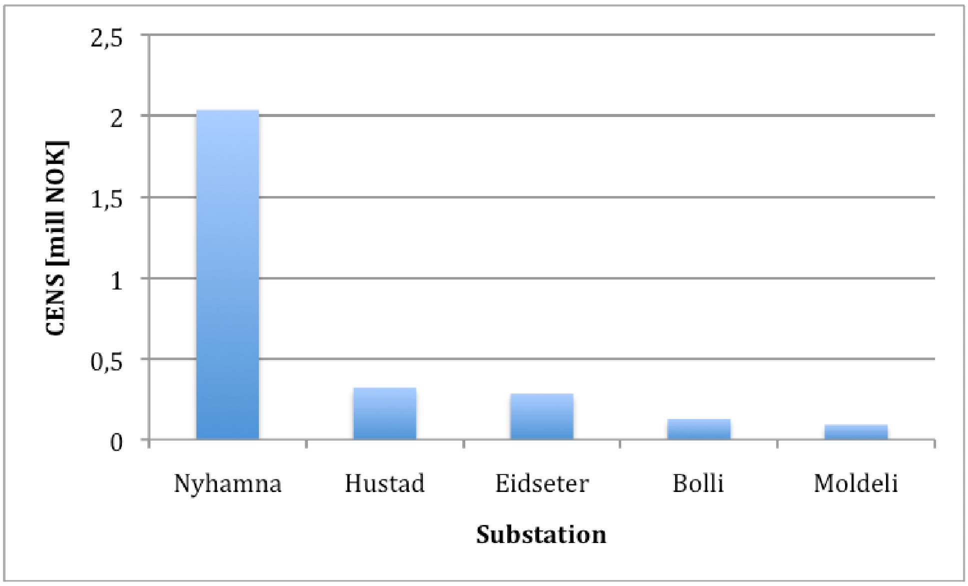

Figure 7.3 **Results differentiated according to the failure models.**

The two major contributions related to CENS cost is the substations Nyhamna and Hustadmarmor. This is to be expected since the majority of load is connected to these substations. The topology of the Nyhamna station makes it vulnerable as it is connected to the main grid through one cable only. Hustadmarmor, on the other hand, is connected via two cables, heightening the level of redundancy and improving the reliability.

Eidseter substation has a much higher frequency of supply interruptions than both Nyhamna and Hustadmarmor but the total connected load is substantially smaller, which is reflected in the annual CENS cost. The frequency of supply interruption at this station is 0.32, which is high compared to the other stations. The reason for this is the lack of a sufficient protection system (station only equipped with disconnectors not circuit-breakers). At closer inspection, it is clear that failures on the lines connecting Eidseter with Istad and Årødal will in fact lead to a total disconnection of the Eidseter substation. Both distance protection systems (protecting Årødal and Istad) will react to such failures.

7.4.6 Component oriented results

The component oriented results have been presented in appendix 11 and 12 in the form of reliability indices. Component oriented results can be very beneficial in the process of identifying critical components in the power system. This information may act as an incentive for future investments improving the power system reliability and hence the power transfer capability.

Figure 7.4 depicts the results for test case 1 and depicts some of the components in the test system differentiated according to the frequency of supply interruptions.

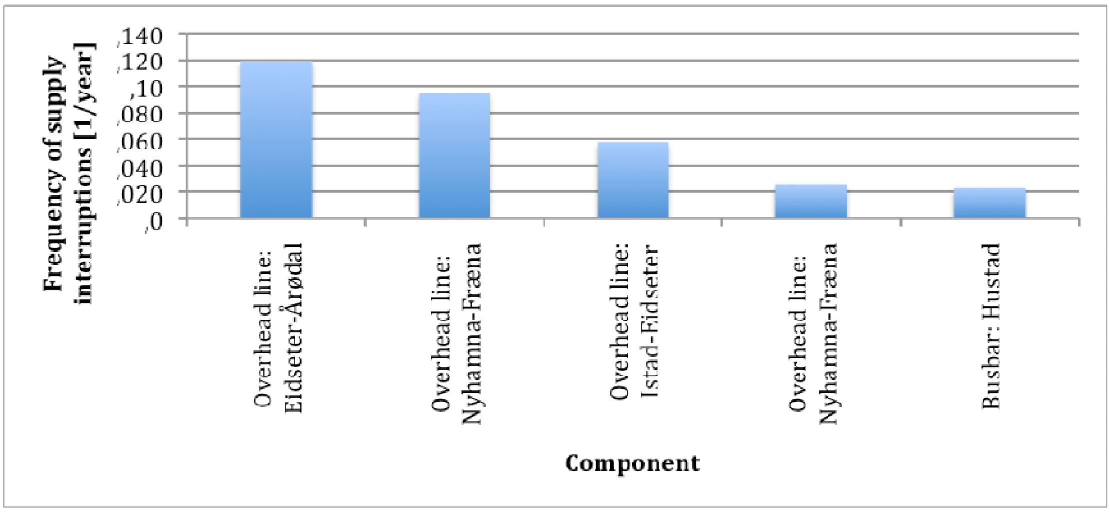

Figure 7.4 Component oriented results differentiated according to frequency of supply interruptions.

The results, as to be expected, show that independent single failures on the overhead lines of the system have the highest frequency of supply interruptions.

Test case 3 represent the potential load situation year 2015 and represent the worst-case scenario related to CENS cost. Figure 7.5 depicts the results for test case 3.

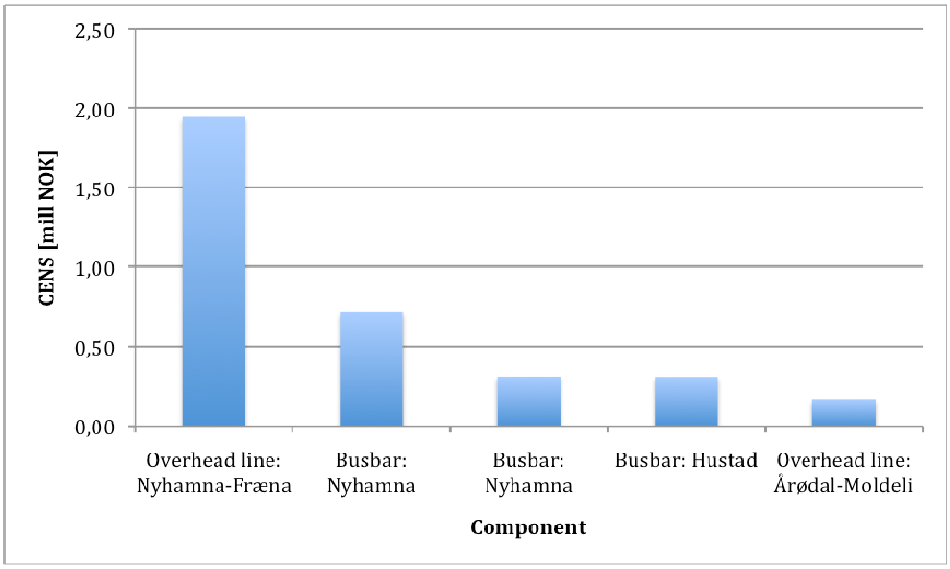

Figure 7.5 Component oriented results differentiated according to CENS cost.

The results show that independent single failures on the cable connecting the substation Nyhamna with the substation Fræna gives the highest isolated CENS cost. The reasons for this are both related to the power system topology and the high load connected to this station. Nyhamna substation is connected to Fræna (the link to the main power system) through one cable, making it particularly vulnerable to failures leading to disconnections. Taking this into consideration, combined with the fact that the larges connected load is being fed from this station, one could conclude that this is a major weak-point in the system. However, in this case the off-shore cable between Nyhamna and Fræna has unfortunately been modeled as an overhead line due to lack of data. This of course needs to be taken into consideration as experience show that cables are less failure affected. Off-shore cables sometimes inhabit back-up systems enabling power transfer at failure system, which also would have a positive affect on the reliability.

Appendix 13 show some results from which components that contributes to the highest duration of supply interruption. From the results it is evident that failures involving the system transformers give higher outage duration than e.g. failures on the overhead lines. This is plausible since failures on transformers often require time consuming revisions, compared to overhead lines, which in many cases can be directly re-connected.

PSS®SINCAL enables several other component oriented results to be collected but they have not been included in the thesis. The main goal is to give an example of a reliability analysis emphasizing the reliability methodology.

7.4.7 Reliability indices according to IEEE 1366 standard

The results for the IEEE 1366 indices have been presented in appendix 14. However, in this case only the indices that can be calculated by PSS®SINCAL have been included. These indices have only been included for demonstrative purposes as the test system doesn’t have any defined areas that could be comparable to other systems. However, these indices are very beneficial regarding large power systems with defined areas such as e.g. the different counties and voltage levels. Such information is comparable to annual statistics such as in [26].

7.5 Conclusion

Appendix 7-13 presents an overview of some of the most important reliability results differentiated according to the total power system, failure models, substations, voltage levels and components. The reliability indices give an indication of the reliability of Istad Nett. However, several uncertainties related to the analysis must be taken into consideration. In the latter, the quality of the statistical reliability data, describing the network components is very important. The analysis is based on reliability data derived from annual disturbance statistics and may or may not be directly comparable to the statistics related to Istad Nett. The statistical data available covers all types of network topologies i.e. not necessarily representative of the type of network under examination.

It is evident, from the results, that the planned load development will affect the reliability of the power system and potentially increase the frequency of supply interruptions causing higher CENS costs. However, this is not the case as the changes in frequency of supply interruptions are very small. The reason for the increased CENS cost is due to the fact that the uninterrupted power is now substantially larger. Thus, the small change in the frequency of supply interruption seen from test case 1 to test case 3 indicates high level of reliability even with the planned load expansion.

Off course, the most important questions still remains unanswered; what is reliability of the power system and is it possible to identify the potential critical elements? Answering these questions are not easy because in order to determine the reliability levels reference points need to be established for comparative analysis. These reference points can e.g. be reliability indices obtained from statistical data. Such statistical data can be found in [26, 30] which contain information about annual disturbances reported in the Norwegian power grid. The problem with this is that the statistics are derived from all disturbances at voltage levels from 1kV to 420kV. The network model and the corresponding reliability results obtained from the analysis only include failures at 132kV voltage levels. Since the number of occurring failures at 22kV greatly excides the number of failures at 132kV it could be argued that the available statistics are to pessimistic and therefore not comparable. However, as stated before the main emphasis has been the methodology describing the reliability.

The given test system and the performed reliability calculation demonstrates PSS®SINCAL as a tool for determining the reliability of a power system. The methodology utilized in this report is from the author’s point of view a good representation of a state of the art reliability analysis.

8 Criticality

8.1 Introduction

The work performed in this master thesis deals with the reliability of a given power system. In the latter, it is important to remember that some of the results presented in the previous chapters clearly have a limited relevance regarding operation and network planning. This is due to the fact that the results are more or less, representing the network model and not necessary the real-life power system. In fact, several factors need to be included if the results can be compared.

These factors can include:

- Quality of reliability data
- Modeling accuracy
- Computer software limitations
- Relevant failure modeling

However, the above mentioned factors are more or less related to the reliability calculation process and not the actual analysis of the results. So, in order to support decisions related to power system development, it is necessary to develop indices that would be helpful in further analyses and decision making processes. This analysis is of course based on the assumption that the reliability calculations are correct (i.e. the above mentioned factors are within acceptable limits). In the latter, methodologies identifying the criticality both for substation and component are necessary. The following chapter presents an example of how this could be made possible by utilizing methods developed for preventative maintenance. The presented proposal describing a criticality methodology concludes some of the work presented in [28, 29].

8.2 Methodology describing criticality

The number one tool in the determination of the system criticality, utilizing the described method, is the consequence matrix. Table 8.1 shows an example of such a matrix with the given levels of probability and consequence. The green and yellow cells represent acceptable situations and the red cell represents a situation that requires risk reducing measures.

	Consequence		
Probability / frequency	**Level 1**	**Level 2**	**Level 3**
Level 1	3	4	5
Level 2	2	3	4
Level 3	1	2	3
Level 4	0	1	2

Table 8.1 Criticality consequence matrix.

If this method is to be successful, the development of the consequence matrix needs to be defined by the customer (e.g. the utilities). What this means is that both the probability levels and the consequence levels have to be defined in accordance to what the customer desires.

The probability can e.g. be the number of failures or types of failures leading to supply interruptions having different impact on the system (e.g. in relation to CENS cost). Several aspects related to the levels consequence need to be taken into consideration and not just the CENS cost.

Other consequence measures could be:

- Human safety (e.g. what is the level of danger involved at a given failure).
- Laws and regulations (control of the power system beyond the normal power demand criteria).
- Special agreements (e.g. higher level of supply reliability for important customers).

These are all examples of other consequence matrixes which can be taken into consideration when determining the actual consequence of a given failure/operating scenario.

The next step is to determine the criticality for each of e.g. the components, network areas or substations according to the consequence matrix. Finally, the chosen components violating given criticality thresholds determined be the customer can be identified. This information could then work as an incentive for alternative courses of actions improving the reliability.

The following subchapter describes an example of how the implantation of a consequence matrix could be used in the process of identifying critical components in the PSS®SINCAL test case.

8.3 Criticality of the network described in the test case

8.3.1 Introduction

As part of the determination of the criticality, most importantly, the consequence matrix needs to be defined. In this case the probability levels have been described by the frequency of supply interruptions index available from the PSS®SINCAL reliability analysis (test case 3). The consequence levels have been divided into three groups (S, M and L) and are related to the actual estimated CENS cost.

The consequences are as follows:

- S: CENS cost: K < 100 000 NOK
- M: CENS cost: 100 000 NOK < K < 500 000 NOK
- L: CENS cost: K < 500 000 NOK

The probabilities are as follows:

- Very likely occurrence: H > 0.2
- Likely occurrence: 0.1 < H < 0.2
- Not very likely occurrence: H < 0.1
- Unlikely situation: H = 0

This only serves as an example and the values describing the probability and the consequence levels are fictive values.

8.3.2 Criticality

Table 8.2 is the consequence matrix defining the criticality (probability * consequence) for the test case substations.

	Consequence		
Probability	**S**	**M**	**L**
Very likely occurrence	3	4	5
Likely occurrence	2	3	4
Not very likely occurrence	1	2	3
Unlikely situation	0	1	2

Table 8.2 **Criticality consequence matrix related to CENS cost.**

The results from test case 3 have been subject to investigation and the criticality in accordance to the consequence matrix has been listed in the table below (table 8.3).

Substation	H [1/a]	K [NOK]	Criticality
Brandhol	0.03205599	3957.93	S1
Nyhamna	0.21114582	3154374.25	L5
Hauglia	0.02703738	21311.18	S1
Fræna	0.03365767	10324.83	S1
Eidseter	0.32283068	304434.84	M4
Bolli	0.11052679	136748.89	M3
Hustad	0.07413208	721606.38	L3
Moldeli	0.04509064	106206.45	M1
Grytten	0.03619903	26090.31	S1

Table 8.3 **Substation criticality related to test case 3.**

Table 8.4 shows the substations violating a given criticality thresholds (e.g. all substations with the criticality from L2-L4) have been identified. This is also just an approximation and an example of a criticality threshold. However, the level of consequence between L2-L4 identifies the two substations previously estimated to give the highest CENS cost.

Critical substation (L3 – L5)	Criticality
Hustad	L3
Nyhamna	L5

Table 8.4 **Critical substations.**

Table 8.5 has been included for demonstrative purposes and it shows an example of how one could determine the criticality of a given substation. In this case, the circuit breakers have been considered and the criticality has been calculated from the same defined consequence matrix given in table 8.2. From this example it is evident that from the defined consequence matrix, the circuit breaker Q2 could be the reason for the high criticality rating of the substation Nyhamna (table 8.5).

Circuit breaker (example)	Criticality (example)
-Q1	S2
-Q2	L5
-Q3	S1
-Q4	M3

Table 8.5 **Example of the criticality related the circuit breakers of Nyhamna substation.**

Finally, alternative courses of action can be purposed, with the end result of improving both the circuit breaker and the substation criticality.

Such improvement, in this case, could be:

- Overhauling the circuit breaker.
- Replacing the circuit breaker.
- Revision of the control system.

This component orientated criticality system can also be utilized for other substation components such as transformers, lines, cables etc.

8.3.3 Procedure determining the criticality

As mentioned the criticality analysis often include other factors equally or more important than CENS cost. Both human safety and laws and regulations are factors that potentially have a greater affect on the criticality. Take human safety for example; if a certain failure are likely to cause human injuries, it of course doesn’t matter if the CENS cost is low. This is also the case related to laws and regulations; if a certain failure are likely to violate statutory laws, it of course doesn’t matter if the CENS cost is low. These are all factors that need to be taken into consideration. In the latter, it is necessary to establish a predefined procedure for interpreting the criticality results.

Including human safety

Let say the utility whish to implement human safety to the criticality analysis, then a second matrix need to be included (table 8.6).

	Consequence		
Probability	**S**	**M**	**L**
Very likely occurrence	3	4	5
Likely occurrence	2	3	4
Not very likely occurrence	1	2	3
Unlikely situation	0	1	2

Table 8.6 Criticality consequence matrix related to human safety.

The consequences are now as follows:

- S: No danger of human injuries.
- M: Possible human injuries.
- L: Human injuries (death or permanent impairment).

The probabilities as before:

- Very likely occurrence: $H > 0.2$
- Likely occurrence: $0.1 < H < 0.2$
- Not very likely occurrence: $H < 0.1$
- Unlikely situation: $H = 0$

This extended criticality analysis now include two matrixes, one related to CENS cost and the other related to human safety, affecting the procedure describing the criticality. The criteria for preventative interventions now consist of both the consequences.

Example of a simple procedure describing criticality:

- Human safety criticalities rated from M3-L5 (regardless of the CENS cost criticality) are not acceptable and preventative interventions must be put into action.
- CENS cost criticalities rated from L2-L5 are not acceptable and preventative interventions must be put into action.

Including Laws and regulations

Let say human safety is not an issue but the utility are heavily regulated, then a second matrix including the e.g. special agreements can be included (table 8.7).

	Consequence		
Probability	**S**	**M**	**L**
Very likely occurrence	3	4	5
Likely occurrence	2	3	4
Not very likely occurrence	1	2	3
Unlikely situation	0	1	2

Table 8.7 Criticality consequence matrix related to laws and regulation.

The consequences are now as follows:

- S: No special customer interruption (no fines).
- M: Partial special customer interruption (small fines).
- L: No power transfer to special customers (large fines).

The probabilities as before:

- Very likely occurrence: $H > 0.2$
- Likely occurrence: $0.1 < H < 0.2$
- Not very likely occurrence: $H < 0.1$
- Unlikely situation: $H = 0$

This extended criticality analysis now include two matrixes, one related to CENS cost and the other related to special customer agreements, affecting the procedure describing the criticality. The criteria for preventative interventions now consist of both the consequences.

Example of a simple procedure describing criticality:

- CENS cost criticalities rated at M3-L3 are not acceptable and preventative interventions must be put into action as long as the special agreement criticality is rated from L4-L5.
- CENS cost criticalities rated from L4-L5 are not acceptable and preventative interventions must be put into action regardless of the special agreement criticality.

8.4 Conclusion

The motivation for including this chapter is to show a methodology for determining the power system criticality i.e. the process of identifying the critical system components. As shown, the main tool is the consequence matrix, which categories the results obtained from the reliability analysis. The categories indicate both the consequence and the probability levels. The procedure of producing the consequence matrix is a challenging task, since it often not only includes CENS cost, as in the previously described example. Factors such as human safety, special agreements and laws and operational regulations are examples of other possible factors. Such matrixes need to be the result of a joint effort from both the customer and the professionals performing the criticality analysis, including all relevant information needed to classify criticality.

It should be pointed out that the work involved clearly depends on the level of accuracy. In theory, the consequence matrix could be utilized in categorizing all of the system components. However, this would result in a very time consuming process. The strength of this method lies in the fact that the defined probabilities doesn’t change. Thus, it can be used to identify large elements, such as substations, and then be further utilized on a component level for the critical substation. Finally, the predefined procedures classify levels of criticality. Hopefully evoking substantial effort from the utilities to deal with the critical parts of their power system, thereby improving the reliability based on both safety and a financial point of view.

9 Discussion

9.1 Limitations related to reliability analysis

9.1.1 Average failure frequency

Recent customer surveys related to interruption costs show that the cost per interruption has a considerable variation with the time of occurrence of interruptions. Analyses of available data from failure statistics verify this and show similar variations in failure rate and repair duration. Time dependent load variations are well known and have been included in the test model describes in the previous chapters. However, it is evident that time dependencies such as average failure frequency may affect the annual number of interruptions and interruption costs for delivery points. In the latter, one could argue that the average time dependent failure frequency should be taken into consideration when conducting reliability analysis as described in this thesis.

The subject of reliability analysis and the time dependencies of relevant input data are under on-going work and development. The information presented in this chapter is part of recent work in relation to the PhD presented in [27]. The presented work describes a modeling approach, which include all types of failures e.g. caused by weather, technical, or humans. The idea is to use observed failure rate patterns shaped by all types of failures mentioned above implementing them into a new and improved model for describing the power system.

Such average failure frequency modeling has clear advantages and gives a more accurate reliability model. However, such information has not been included in the PSS®SINCAL model as the motivation is to demonstrate the methodology for reliability calculations. Also, such detailed statistical data from Istad Nett AS are unobtainable.

9.1.2 Exponential distribution

Another important aspect of the reliability analysis is the limitations of the exponential distribution models often used in these kinds of analysis. The exponential distribution models the behavior of the system components in such a way that they fail at a constant rate, regardless of the accumulated age. The work performed in [25] states that this property greatly simplifies the analysis, making the distribution inappropriate for most reliability analyses, because it does not apply to most real world applications. All power system components will wear out over time and hence not inhabit a constant failure rate. This may result in reliability estimates that are too low in the early stages of life and too high in later stages.

PSS®SINCAL does enable the possibility to model specific component life cycles. However, this is soli related the utilized input data and need to be analyzed according to chosen periods. For example, if the performance of a certain circuit breaker in known to worsen over a period of time, this can be taken into consideration by modifying the statistical input data including two operating scenarios. One is representing the early stages of "life" and the other representing the worsened case. The problem with such modeling is the availability of input data describing different stages of life, which is very difficult to obtain.

Although the exponential distributed failure rate it is not applicable to most real world applications, the use of the exponential distribution still has some value to reliability analysis. The distribution can be effectively incorporated into reliability analysis if the constant failure rate assumption can be justified, which all depends on the scope and degree of accuracy of the reliability analysis. The work performed in [25] states that one should not underestimate the exponential distribution's contribution to the development of current reliability theory. However, today's high product reliability goals require the use of more sophisticated analysis methods and metrics that more accurately reflect real world conditions. Such models have been developed and computer technology addresses the more complex mathematical formulations they require.

9.2 Some aspects concerning the quality of reliability data

9.2.1 Introduction

The core in any reliability analysis is the statistical data describing the behavior of a power system. If the reliability calculations are to be successful it is essential that the reliability data corresponds to the power system subject for testing. As previously stated; the process of obtaining vital information about the power system performance is important as it is part of the process of determining the future behavior of the system.

This chapter deals with some of the aspects related to the reliability data and the reliability failure models. In the latter, the quality of available input data has been empathized and further discussed.

The quality of any reliability analysis is highly dependent on the quality of the available reliability data and several factors could potentially influence the analysis. However, the accuracy and the comprehensiveness (i.e. the total number of disturbances) of the statistical data play an important role. This is evident when comparing e.g. failure models such as independent single failure and malfunction of a protection device. Closer inspection of these failure modes reveal that the total number of independent single failures greatly excides the number of malfunctioning of protection devices. This clearly poses as a challenge as the number of malfunctioning protection devices is very low i.e. resulting in a higher statistical uncertainty. The process of determining the actual sequence of events leading to unwanted operations of a protection system is complex. Such failures often include secondary equipment or software related issues. In the latter, high quality data representing protection system failures are much harder to obtain than let say an independent single failure caused by a lightning strike. The failure models representing the system protection devices have therefore been further discussed. Some information about the utilization of outage duration and time of repair has also been included.

9.2.2 Failure models

As mentioned above, failure models related to protection systems have the potential to include uncertainties in the process of determining the reliability of a given power system.

PSS®SINCAL enables the use of three different protection system failure models, which are:

- Malfunction of protection device
- Unnecessary protection operation with multiple outage
- Independent unnecessary protection operation

These failure models give a good representation of possible failures related to protection systems, but as demonstrated throughout this thesis, they are highly dependent on statistical input data, which need to be taken into consideration.

Potential sources for incorrect reliability data:

- Low number of occurrences.
- Inaccurate failure registration.

9.2.3 Outage duration and time of repair

Figure 9.1 depicts an example of the utilization of outage duration and time of repair. In terms of registration of disturbances and reliability analysis, outage durations need to be discussed.

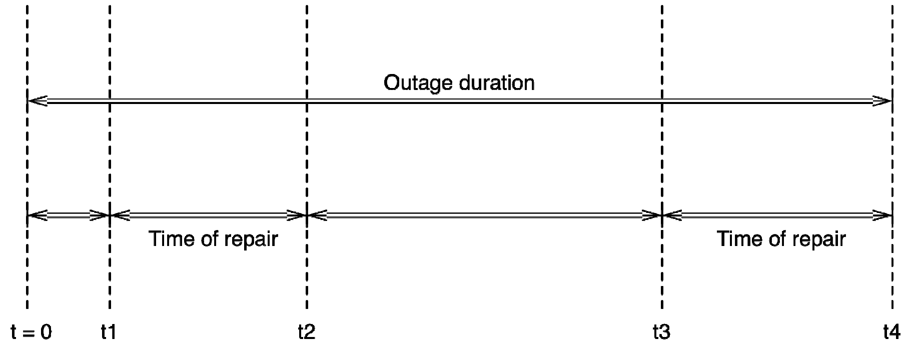

Figure 9.1 **Component oriented results differentiated according to CENS cost.**

The outage duration is defined as the total time from component failure, t=0 until restoration, t4. Repair time, however, only includes the actual work-related period of time e.g. from t1-t2 and t3-t4 and therefore could be misleading regarding the performance / reliability of a power system or components. The problem today is that there is no collective procedure regarding the registration of the total outage period. The reasons are more or less related to individual practice and existing disagreements. Regarding the gathering of statistical data it is important to remember that some of the outage times may reflect the actual time it took to repair the component and not the actual interruption time period.

Failures leading to interruptions and disconnections of components are not always severe and in some cases the failure affected component can be up and running followed by a later repair. In this case the time of repair doesn't reflect the performance of the component. Another example is the possibility of alternative redundant or backup systems that can maintain the power transfer after a given failure. The time of repair compared to the actual outage time in this situation can differ drastically. In the latter, it is important to be some what skeptical to statistical data and take this into consideration i.e. disregarding events with extremely long outage duration or time of repair. Again this emphasizes the importance of close corporation with the utilities in the process of selecting correct reliability data.

9.2.4 Conclusion

Considering the test model utilized in this report, one could argue that the reliability data collected from a variety of different parts of the Norwegian power system, reflects the performance of the test system pessimistically. The main reason for this assumption is the fact that the utilized statistics cover disturbances at all network topologies and therefore not necessarily a good representation of a given test network. In this case, the network test model is based on a highly interconnected and very reliable distribution system. Istad Nett states that failures very seldom occur supporting the above stated. This only demonstrate the importance of high quality statistical data and also the fact that local statistical data e.g. data based on local knowledge or local statistics in many cases pose as a better solution. However, such data are unfortunately often very difficult to obtain, leaving no alternative as to use the available more general data. The question is; will the data have an optimistic or pessimistic affect on the results compared to the actual performance of the power system under investigation? These uncertainties will always exist and need to be taken into consideration. However, close cooperation with the utilities in combination with the utilization of high quality reliability data will after my opinion have a positive affect on the accuracy of the reliability analysis.

9.3 Comparing PSS®SINCAL and SAMREL

9.3.1 Introduction

As demonstrated throughout this report the various aspects comprising a probabilistic reliability analysis can be both challenging and complex. This in mind, it is always beneficial to examine other developed methods and tools related to reliability. The motivation for including this chapter is the fact that a comparison between a commercialized and highly developed tool such as PSS®SINCAL and the newly developed tool SAMREL could be beneficial. The main focus has been the reliability methodology.

9.3.2 Reliability analysis

SAMREL utilize the known power planning software PSSE in the power flow calculations and compared to PSS®SINCAL there is not actually any differences. Both PSSE and PSS®SINCAL utilize standard methods in the process of determining the power system power flow. In the latter, the main difference lies in the selection of operational states. The EMPS model in SAMREL provide a set of production and load scenarios including the given transmission capacities. Then, the necessary constraints and limits (e.g. voltages, thermal rating, voltage stability and angular stability) are checked. Through this iterative process the realistic transmission capacities as well as the feasible operational states are found as input to the next step of the analysis. Contingency analysis then investigates the affect on the system at each of the selected operating states. This process is some what similar in PSS®SINCAL the only difference is the process of selecting these operational states. PSS®SINCAL simulates all possible failure combinations (Poisson distributed) above certain probability threshold. All failure combinations not in violation of this probability are then subjected to power flow calculations determining the affect on the system. The end result is the same as in SAMREL, a set of failure combinations leading to supply interruptions.

The final part is the calculation of the reliability indices describing the power system reliability. In the reliability analysis the objective is to determine the reliability of supply indices for the delivery points under study, i.e. to estimate the frequency and duration of interruptions, energy not supplied and the corresponding cost of energy not supply (CENS). For this purpose, SAMREL and PSS®SINCAL utilize either an analytic approach or Monte Carlo simulations. The strength of SAMREL compared to PSS®SINCAL is the time-varying parameters methodology which estimates the time of the occurrences (Year, month and day, hour). The methodology also includes the expected load, the expected duration and the expected specific interruption cost when the interruption occurs. A model which is able to generate this pattern, analytically or by simulation, will therefore produce outage events according to what is expected to happen in the real system. Time-dependent correlations such as this can also be included in PSS®SINCAL. However, this requires the analysis of various periods individually. Meaning, conducting a reliability analysis based on statistical data from a specific month of week, which evidently is more time consuming.

9.3.3 Conclusion

Comparing tools describing probabilistic reliability are important and can act as an incentive for future development. PSS®SINCAL and SAMREL are more or less based on the same methodology and one would therefore assume equal reliability results. The problem is that SAMREL is still under development and a working software demo is not available. This pose as a major draw-back as a comparative analysis of both the tools relates to the same test model would have been very beneficial. Other processes such as network/component modeling, power flow simulations, failure models and result presentation are more or less the same in both tools.

SAMREL is comprised of several existing tools and therefore rely on the interaction between these tools, which after my opinion further complicate both the user friendliness and process of commercialization. This interacting requires a tool that can handle the processes (e.g. import and export) between the various tools described in the SAMREL methodology. The strength of SAMREL is the highly developed methods for including time-varying parameters and time-dependent correlations between them for each delivery point. SAMREL divides the statistical material into appropriate groups distributing the failure rate over a given time-period, resulting in a model describing the outage events according to what is expected to happen in the real system. The major strength of PSS®SINCAL compared to SAMREL is simply the fact that PSS®SINCAL is an available highly developed commercialized tool. PSS®SINCAL is a compact solution and therefore doesn't depend on other tools. Seen from an economical (one license) point-of-view, this is also a good argument.

One aspect however remains; the methodology described in SAMREL can not yet be put to the test, but that doesn't necessarily mean that the work performed is useless. The work on the reliability module ZUBER, now part of PSS®SINCAL started in the 80's at the Darmstadt University of Technology and the Saarland University. However, commercialization has led to a more hidden development of the reliability methodology, making it harder to obtain detailed information about PSS®SINCAL. SAMREL on the other hand, is developed at SINTEF energy research with close cooperation from the Norwegian university of technology and science and the utilities. From an educational point-of-view, this has several benefits and has contributed to increase the general knowledge about power system reliability.

10 Conclusion

10.1 Introduction

The work presented in this report concludes the master thesis work preformed at the Norwegian university of science and technology part of the international master program; master of science in electric power engineering. The study deals with probabilistic reliability calculations and the development of network test case model. In the latter, both reliability calculations, comparing available tools and literature studies have been performed with the sole purpose of describing a state of the art reliability methodology. This methodology includes all of the steps involved in a reliability analysis and for demonstrative purposes includes an example from a real-life power system (Istad). This chapter gives an overview of the most important results, challenges and conclusions.

10.2 Challenges

Regarding reliability calculations several aspects related to the utilization, purpose and degree of importance have been discussed throughout this report. The core in any reliability analysis, except the actual tools, is the statistical data describing the power system performance. It is critical that this information is of sufficient quality and give a good representation of the network components and possible failure situations. Unfortunately, dealing with statistical data some uncertainties always exist and must be taken into consideration.

Uncertainties related to reliability data however are in many cases negligible, which all depend on the scope of the analysis. Consider e.g. a detailed study of a given power system and its components compared to a general study of the Norwegian regional power system. Both studies require statistical data, but it is evident that the detailed power station analysis require higher quality data if the results is to be trustworthy. It is evident that more detailed reliability studies require close cooperation with the owner of the power station, were more general statistics can serve as a starting point. The challenge is to be aware of these limitations including them in the analysis process.

10.3 Utilization of reliability calculations

Even tough some uncertainties dealing with computer based simulations are present, the probabilistic reliability analysis serves as an excellent tool working with power system operation and development.

The areas of applications include:

- Quantification of the quality of supply.
    - System level reliability.
    - End-user reliability.
- Documentation of expected power system reliability.
- Analysis related to different network topologies.
    - N-1 topologies.
    - Load scenarios.
    - Power system configuration.
- Decision-making processes.
    - Incentive for development.
    - Incentive for operation.
- Identification of criticality.
    - Components.
    - Failure models.
- Preventative maintenance.
    - Identify critical components.

10.4 State of the art description

Generally, the core of any reliability analysis consists of four corner stones, the model, statistical data, reliability calculation tools and assessment. These subjects have all been thoroughly dealt with through literature studies and the development of the test case model. In the latter, PSS®SINCAL and its reliability module ZUBER were emphasized representing a state of the art description of such analysis methods.

10.4.1 Reliability model

Regardless of the analysis methods, the system under consideration has to be represented in a model suitable for probabilistic reliability analysis. Classic methods like power flow and short-circuit calculations require standard topological and electric characteristics of the power system equipment and its components. Reliability calculations on the other hand require statistical data describing the system. Reliability analysis deals with a systems ability to restore supply after being subjected to various disturbances. Therefore, redundancy i.e. switching possibilities and protection systems configurations needed to be included in the model. The process of establishing the network model has been presented in chapter 6.

10.4.2 Reliability data

The core in any reliability analysis is the statistical data describing the behavior of a power system. If the reliability calculations are to be successful it is essential that the reliability data corresponds to the power system subject for testing. As previously stated; the process of obtaining vital information about the power system performance is important as it is part of the process of determining the future behavior of the system. The various reliability data have been calculated from annual failure statistics collected by Statnett and experience data from Siemens AS.

10.4.3 Reliability calculations

The reliability calculations have been performed utilizing the PSS®SINCAL methodology. This method is based on the past performance of the actual system i.e. the statistical reliability input data. Component outages and corresponding input data for the failure models are derived from appropriate outage statistics. Contingency analysis generates states or failure combinations using stochastic methods. These states are then analyzed for their effect on the customers, regarding reliability of supply. In case of supply interruptions, the complete sequence of events until restoration of supply to all customers or until the temporal expiration of the failure combination is also modeled. Finally, the probabilistic reliability indices for the system and for each customer are calculated. The PSS®SINCAL methodology has been described in chapter 4 and chapter 6.

10.4.4 Analysis / assessment

As previously mentioned PSS®SINCAL has a wide array of possibilities when it comes to presenting the results. The possibilities for differentiating the results are especially useful in the process of identifying the critical components of the system. The results have been presented in the form of quantitative reliability indices. These indices are the number one tool in the process of deciding if the selected operating situations are acceptable or not. Results have been differentiated according to failure models, substations, voltage levels and relevant system components. The results also include indices related to the total power system and the part of the network owned by Istad Nett AS. It is of the author's opinion that these results are diverse, severing as good indicators of the power system reliability at various levels. The results and assessments have been described in chapter 7.

10.5 Reliability calculations of Istad Nett

It is evident, from the results, that the planned load development will affect operation of the power system and potentially increase the frequency of supply interruptions causing higher CENS costs. However, this is not the case as the changes in frequency of supply interruptions are very small. The reason for the higher CENS cost is due to the fact that the uninterrupted power is now substantially larger. Thus, the small change in the frequency of supply interruption seen from test case 1 to test case 3 indicates high level of reliability even with the planned load expansion.

Off course, the most important questions still remains unanswered; what is reliability of the power system and is it possible to identify the potential critical elements? Answering these questions are not easy because in order to determine the reliability levels one need to establish reference points for comparative analysis. These reference points can e.g. be reliability indices obtained from statistical data. Such statistical data can be found in [26] which contain information about annual disturbances reported in the Norwegian power grid. The problem is that the statistics are derived from all disturbances at voltage levels from 1kV to 420kV. The network model and the corresponding reliability results obtained from the analysis only include failures at 132kV voltage levels. Since the number of occurring failures at 22kV greatly excides the number of failures at 132kV on could argue that the available statistics are to pessimistic and therefore not comparable.

Some low probability “special” failure combinations may not have been detected in the reliability analysis. This should be taken into consideration as some unlikely situations could lead to critical CENS costs. However, as previously stated the main emphasis has been the methodology describing the reliability.

The given test system and the performed reliability calculation demonstrates PSS®SINCAL as a tool for determining the reliability of a power system. The methodology utilized in this report is from the author’s point of view a good representation of a state of the art reliability analysis.

10.6 Criticality

The motivation for including this chapter is to show a methodology for determining the power system criticality i.e. the process of identifying the critical system components. As shown, the main tool is the consequence matrix, which categories the results obtained from the reliability analysis. The categories indicate both the consequence and the probability. Producing the consequence matrix can pose as a challenging task since it often not only includes CENS cost as in the previously described example (e.g. factors such as human safety, special agreements and laws and operational regulations). Such matrixes need to be the result of a joint effort from both the customer and the professionals performing the criticality analysis, including all relevant information needed to classify criticality. It should be pointed out that the work involved clearly depends on the level of accuracy. In theory, the consequence matrix could be used to categories all of the system components. However, this would result in a very time consuming process. The strength of this method lies in the fact that the defined probabilities doesn't change. Thus, it can be used to identify large elements, such as substations and then be further utilized on a component level for the critical substation, as shown in the previous example. Finally, the predefined procedures classify levels of criticality. Hopefully evoking substantial effort from the utilities to deal with the critical parts of their power system, thereby improving the reliability based on both safety and a financial point of view.

10.7 Future work

For future work, I would first of all recommend a closer reliability study using the methods describes in this master thesis. More detailed studies could e.g. include local input data, which in term will require closer cooperation with the owner of the power system. I think it would be very interesting to see how accurate the reliability calculations could be compared to the real-life system. Such local statistical data describing the network components are not easily obtained. However, I think that expert opinions and local knowledge should not be underestimated in such analysis. In the latter, more accurate modeling of the off-shore cable between Fræna and Nyhamna and the more detailed load modeling of Hustadmarmor would be interesting.

Finally, further development of a methodology identifying the critical components should be the main focus for future work. Such work is equally important compared to the actual reliability calculations. Reliability indices alone doesn't quantify reliability, several other factors also need to be included. The criticality studies part of this thesis clearly show that factors such as human safety, laws and regulations and special agreements need to be taken into consideration. In the latter, a consequence matrix reflecting all of the above factors is needed and after my opinion should be prioritized for future work.

11 Literature

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Appendix

Appendix 1 Istad Netbas model

UNDERLAGT TAUSHETSPLIKT

Iht. BfK § 6-2, jf. off.loven § 5a

Appendix 2 PSS®SINCAL computer model

UNDERLAGT TAUSHETSPLIKT

Iht. BfK § 6-2, jf. off.loven § 5a

Appendix 3 Calculation of the IEEE 1366 reliability indices

SAIFI (system average interruption frequency index)

$$SAIFI = \frac{\sum N_i}{\sum N_T} \tag{A3.1}$$

Where,

N_i : Total number of interrupted customers
N_T : Total number of served customers

SAIDI (system average interruption duration index)

$$SAIDI = \frac{\sum r_j N_j}{\sum N_T} \tag{A3.2}$$

Where,

$r_j N_j$: Customer interruption duration
N_T : Total number of served customers

CAIDI (customer average interruption duration index)

$$CAIDI = \frac{\sum r_j N_j}{\sum N_i} \tag{A3.3}$$

Where,

$r_j N_j$: Customer interruption duration
N_T : Total number of interrupted customers

Appendix 4 Calculation of the failure models

Independent single failure

Frequency of supply interrruptions:

$$H_{\mathrm{UN}} = \frac{n_{\mathrm{UN}}}{G_{\mathrm{EA}}} \tag{A3.1}$$

Where,

N_{UN}: Total number of independent single failures.
G_{EA}: Total length / number of components *.

* The total length is the appropriate parameter for failures on overhead lines. The number of components is the appropriate parameter for failures on other components such as transformers and generators.

Multiple earth faults

Probability of supply interruption:

$$p_{\mathrm{ME}} = \frac{n_{\mathrm{ME,K}}}{\left(n_{\mathrm{Erd}} + n_{\mathrm{ME}}\right) \cdot \frac{G_{\mathrm{EA}}}{n_{\mathrm{galv.\ Netz}}}} \tag{A3.2}$$

Where,

$n_{\mathrm{ME,K}}$: Total number of multiple earth failures.
$n_{\mathrm{E,rd}}$+ n_{ME}: Total number of earth faults and total number of multiple earth failures.
G_{EA}: The total length of overhead lines / cables in the network.
$n_{\mathrm{galv.\ Netz}}$: Correction factor related to the voltage level*.

*Normally equal to 1.

Common Mode failures

Frequency of supply interrruptions:

$$H_{\mathrm{CM}} = \frac{n_{\mathrm{CM}}}{G_{\mathrm{CM}}} \tag{A3.3}$$

Where,

n_{CM}: Total number of common mode failures.

G_{CM}: The total length of overhead lines / cables in the network*.

* Length of overhead lines / cables in parallel operation for a given voltage level.

Malfunction of Protection Device

Probability of supply interruption:

$$p_{\mathrm{SVS}} = \frac{n_{\mathrm{SVS}}}{n_{\mathrm{SA}} \ f} \tag{A3.4}$$

Where,

n_{SVS}: Total number of situations where the protection system have been malfunctioning.

n_{SA}: Total number of protection system responses.

f: Correction factor*.

* Normally equal to 2.

Unnecessary protection operation with multiple outages

Probability of supply interruption:

$$p_{\mathrm{SUE}} = \frac{n_{\mathrm{SUE}}}{n_{\mathrm{SA}} \cdot f} \qquad \text{(A3.5)}$$

Where,

n_{SUE} Total number of Independent unnecessary protection operations.
n_{SA} Total number of protection system responses.
f: Correction factor*.

* Normally equal to 2.

Independent unnecessary protection operation

Frequency of supply interrruptions:

$$H_{\mathrm{SPS}} = \frac{n_{\mathrm{SPS}}}{G_{\mathrm{EA}}} \qquad \text{(A3.6)}$$

Where,

n_{EA}: Total number of independent single failures.
G_{EA}: Total length / number of components *.

* The total length is the appropriate parameter for failures on overhead lines. The number of components is the appropriate parameter for failures on other components such as transformers and generators.

Appendix 5 Reliability data for the failure models

Failure mode	Component	132kV earth-fault compensation				420kV directly earthed			
		N	*H*	*T*	*p*	*N*	*H*	*T*	*p*
			in 1/a*	in h	*		in 1/a*	in h	*
UN	LINE	472	0,00559	6,28		129	0,006259	2,19	
	CABEL	15	0,00892	90,6		0	0,000000	0,00	
	TRAFO	26	0,00451	23,23		4	0,008065	68,75	
	SS	13	0,00302	6,48		7	0,015909	9,43	
	F-AA	222	0,00755	31,21		67	0,020036	10,80	
	F-SS	19	0,00065	2,08		4	0,001196	17,04	
E1P	LINE		0,00076						
	CABLE		0,00417						
	TRAFO		0,00122						
	SS		0,00053						
	F-AA		0,00065						
	F-SS		0,00026						
ME	LINE	94		7,93	0,0004				
	CABLE	5		218,03	0,0004				
	TRAFO	3		28,03	0,0019				
	SS	2		6,92	0,0001				
	F-AA	26		9,82	0,0001				
	F-SS	2		4,44	0,0002				
COM	Line	119	0,00141	9,64		8	0,000388	0,46	
SVS		28			0,000697	20			0,001122
SUE		94			0,002339	31			0,001739
SPS		144	0,02319			39	0,02544		

Legend	
N	Number of faults
H	Frequency of supply interruptions
T	Mean duration of supply interruptions
P	Probability of supply interruption
UN	Independent single failure
COM	Common mode failures
SVS	Malfunction of protection device
SUE	Unnecessary protection operation
SPS	Independent unnecessary protection operation
ME	Multiple earth faults
E1P	Earth fault

Appendix 6 Simulation input parameters

PSS®SINCAL calculation parameters	
Function	**Setting**
Calculation method	Analytic Method
Min. failure order	0
Max. failure order	8
Malfunct. of prot. dev. not limited	Yes
Unavailability threshold	1e-008
Limitation criterion	Unavailability
Period under consideration [h]	8760.0
Algorithm for power flow calculation	AC-LF/Newton-Raphson
Simultaneity factor	1
Permissibility of solitary operation	Yes
Time dependence of load	Annual load duration curve (DL)
Power allocation model (only DL)	Pessimistic
Time dependence of load	Annual load duration curve (DL)
Switching operations	Yes
PSS®SINCAL analysis parameters	
Function	**Setting**
Type of analysis ZUBER Analysis Part	Results table
Consideration of failure modes	CM SV ME SUE DA SP UK UL
Limits for the failure order	No
Limits for the frequency	No
Limits for the duration	No
Limits for the unavailability	No
Limits for the interrupted power	No
Limits for the energy not supplied	No
Limits for the interruption cost	No
Limits for the reimbursements	No
Limits for the MC-time span	No
Only failure comb. with supply interr.	Yes

Appendix 7 Reliability analysis results: Power system

Total power system results

Test case	H [1/year]	Q [min/year]	T [h]	L [MVA/year]	E [MVAh/year]	K [NOK/year]
1	0.71573031	142.20309590	3.31137538	28.77574921	93.07236481	3015548.00
2	0.71611398	142.29412819	3.31171966	38.21158981	128.80671692	4173332.75
3	0.73146850	146.84072519	3.34579730	41.55124283	141.81159973	4594698.00

Istad Nett AS results

Test case	H [1/year]	Q [min/year]	T [h]	L [MVA/year]	E [MVAh/year]	K [NOK/year]
1	0.64307535	102.7056422	2.85912500	11.4909467	29.3579857	951199.73
2	0.64347626	102.7981232	2.86114983	11.9229407	30.5629184	990238.22
3	0.6588797	107.3818231	2.92850544	15.21923206	43.52699824	1410274.92

Appendix 8 Reliability analysis results: Differentiated according to failure models.

Test case 1

Failure model	H [1/year]	Q [min/year]	T [h]	L [MVA/year]	E [MVAh/year]	K [NOK/year]
UN	0.43340737	119.07388873	4.57898283	20.31118774	81.12426758	2628427.00
CM	0.02679000	7.76289653	4.82947350	0.81647456	6.09797907	197574.53
SV	-	-	-	-	-	-
ME	0.02946952	8.58434400	4.85492802	0.60046887	2.32634354	75373.85
SUE	0.01283708	0.38511284	0.50000066	0.31677774	0.15838887	5131.80
SP	0.21322402	6.39671954	0.49999991	6.73080730	3.36540365	109039.07

Test case 2

Failure model	H [1/year]	Q [min/year]	T [h]	L [MVA/year]	E [MVAh/year]	K [NOK/year]
UN	0.43343350	119.14368117	4.58139038	27.33817482	115.40292358	3739047.25
CM	0.02679000	7.76289653	4.82947350	0.83882904	6.28008556	203474.78
SV	-	-	-	-	-	-
ME	0.02947675	8.59508534	4.85981083	0.61996561	2.41635513	78289.80
SUE	0.01294969	0.38849096	0.50000024	0.37925375	0.18962720	6143.93
SP	0.21346229	6.40386706	0.49999985	9.03535938	4.51767969	146372.84

Test case 3

Failure model	H [1/year]	Q [min/year]	T [h]	L [MVA/year]	E [MVAh/year]	K [NOK/year]
UN	0.43561199	122.91153220	4.70263767	28.50660324	125.69746399	4072597.75
CM	0.02679000	7.76289653	4.82947350	0.91261822	6.90763855	223807.50
SV	-	-	-	-	-	-
ME	0.02975321	8.98696129	5.03416920	0.72336626	3.50209832	113468.31
SUE	0.01304526	0.39135845	0.50000066	0.40900427	0.20450214	6625.87
SP	0.22626555	6.78796593	0.49999997	10.99963951	5.49981976	178194.11

Appendix 9 Reliability analysis results: Differentiated according to voltage levels.

420kV

Test case	H [1/year]	Q [min/year]	T [h]	L [MVA/year]	E [MVAh/year]	K [NOK/year]
1	0.21114582	48.65437928	3.84050369	16.36361694	62.84452820	2036162.75
2	0.21114603	48.65440222	3.84050179	25.35016060	97.35732269	3154377.25
3	0.21114582	48.65437928	3.84050369	25.35011482	97.35723114	3154374.25

132kV

Test case	H [1/year]	Q [min/year]	T [h]	L [MVA/year]	E [MVAh/year]	K [NOK/year]
1	0.71133037	106.05619232	2.40198873	12.41208647	30.22797683	979387.44
2	0.71173128	106.14867327	2.40356358	12.86142777	31.44929235	1018956.75
3	0.72713472	110.73237320	2.45595128	16.20116998	44.45441218	1440323.16

Appendix 10 Reliability analysis results: Differentiated according to substations.

Test case 1

Substation	H [1/year]	Q [min/year]	T [h]	L [MVA/year]	E [MVAh/year]	K [NOK/year]
Nyhamna	0.21114582	48.65437928	3.84050369	16.36361694	62.84452820	2036162.75
Hustad	0.06091687	10.64657390	2.91286945	3.40076637	9.91038513	321096.41
Eidseter	0.32273164	38.43885783	1.98507845	4.43960571	8.81297207	285540.28
Bolli	0.11052679	30.81890004	4.64727449	0.85199952	3.95948124	128287.20
Moldeli	0.04410311	7.24350645	2.73733759	1.05200076	2.88003206	93313.60

Test case 2

Substation	**H [1/year]**	**Q [min/year]**	**T [h]**	**L [MVA/year]**	**E [MVAh/year]**	**K [NOK/year]**
Nyhamna	0.21114603	48.65440222	3.84050179	25.35016060	97.35732269	3154377.25
Hustad	0.06093353	10.65270034	2.91374922	3.66695070	10.68969250	346346.19
Eidseter	0.32283089	38.44188281	1.98462439	4.52462435	8.97966766	290941.00
Bolli	0.11052700	30.81892490	4.64726925	0.86802167	4.03392220	130699.09
Moldeli	0.04429225	7.29862144	2.74638748	1.07582223	2.95332551	95687.38

Test case 3

Substation	**H [1/year]**	**Q [min/year]**	**T [h]**	**L [MVA/year]**	**E [MVAh/year]**	**K [NOK/year]**
Nyhamna	0.21114582	48.65437928	3.84050369	25.35011482	97.35723114	3154374.25
Hustad	0.07413208	14.58275091	3.27855134	6.48729706	22.27178764	721606.38
Eidseter	0.32283068	38.44185604	1.98462439	4.73446560	9.39614677	304434.84
Bolli	0.11052679	30.81889813	4.64727402	0.90819722	4.22064447	136748.89
Moldeli	0.04560446	7.68775971	2.80957866	1.16370106	3.27798295	106206.45

Appendix 11 Reliability analysis results Components involved in failure combinations with the highest share of frequency of supply interruptions.

Test case 1

Component	Name	Voltage level	Failure mode	H [1/year]	T [h]	K [NOK/year]
Overhead line	Eidseter-Årødal	132kV	UN	0.1193802953	9.56	26604.23
Overhead line	Nyhamna-Fræna	420kV	UN	0.0951477289	5.26	1256236.63
Overhead line	Istad-Eidseter	132kV	UN	0.0580463931	12.89	12935.80
Overhead line	Nyhamna-Fræna	420kV	SP	0.0254400000	0.50	31939.57
Busbar	Hustad	132kV	SP	0.0231919996	0.50	20966.20

Test case 2

Component	Name	Voltage level	Failure mode	H [1/year]	T [h]	K [NOK/year]
Overhead line	Nyhamna-Fræna	420kV	UN	0.0951477289	5.26	1946131.75
Transformer	Bolli	132kV	UN	0.0119521208	28.49	86633.39
Transformer	Eidseter A	132kV	UN	0.0117828008	28.89	154569.28
Busbar	Nyhamna	420kV	UN	0.0194969997	9.43	715191.00
Busbar	Hustad	132kV	UN	0.0061476682	19.57	234513.39

Test case 3

Component	Name	Voltage level	Failure mode	H [1/year]	T [h]	K [NOK/year]
Overhead line	Nyhamna-Fræna	420kV	UN	0.0951477289	5.26	1946131.75
Transformer	Bolli	132kV	UN	0.0119521208	28.49	90643.64
Transformer	Eidseter A	132kV	UN	0.0117828008	28.89	161738.33
Busbar	Nyhamna	420kV	UN	0.01949700	9.43	715191.00
Busbar	Hustad	132kV	UN	0.0061476682	19.57	309782.94

Appendix 12 Reliability analysis results: Components involved in failure combinations with the highest share of CENS.

Test case 3						
Component	**Name**	**Voltage level**	**Failure mode**	**H [1/year]**	**T [h]**	**K [NOK/year]**
Overhead line	Nyhamna-Fræna	420kV	UN	0.0951477289	5.26	1946131.75
Busbar	Nyhamna	420kV	UN	0.01949700	9.43	715191.00
Busbar	Nyhamna	132kV	UN	0.0049580000	16.15	311407.19
Busbar	Hustad	132kV	UN	0.0061476682	19.57	309782.94
Overhead line	Årødal-Moldeli	132kV	CM	0.0105750002	9.64	167966.86

Appendix 13 Reliability analysis results: Components involved in failure combinations with the longest average duration of supply interruption.

Test case 1-3

Component	Name	Voltage level	Test case	Failure mode	T [h]
Transformer	Hustad T1	132kV	3	UN	29.02
Transformer	Hustad T3	132kV	3	UN	29.02
Transformer	Hustad T2	132kV	3	UN	29.02
Transformer	Moldeli T2	132kV	3	UN	28.89
Transformer	Eidseter	132kV	3	UN	28.89

Appendix 14 Reliability analysis results: IEEE 1366 standard indices.

Test case 1	
Index	**Base area**
SAIFI [1/year]	0.079
SAIDI [min/a]	11.784

Test case 2	
Index	**Base area**
SAIFI [1/year]	0.079
SAIDI [min/a]	11.794

Test case 3	
Index	**Base area**
SAIFI [1/year]	0.081
SAIDI [min/a]	12.304