NTNU
Norwegian University of
Science and Technology

# Reliability Analysis of the Nordic44 Model and modelling of corrective Actions in OPAL

**Sindre Winsnes Nordhagen**

Master of Energy and Environmental Engineering
Submission date: January 2017
Supervisor: Gerd Kjølle, IEL
Co-supervisor: Sigurd Hofsmo Jakobsen, ELKRAFT
Iver Bakken Sperstad, ELKRAFT

Norwegian University of Science and Technology
Department of Electric Power Engineering

# Problem definition

In power system planning and operation a comprehensive and consistent methodology for security of electricity supply analysis is desired. The SAMREL methodology developed at SINTEF Energy Research is such a methodology, which combines, in its current version, an integration of the power market simulator (EMPS) and a methodology for reliability and interruption cost assessment (OPAL) with power flow models to do so.

In this thesis, a new method for integrating power market data is to be implemented in SAMREL, thus substituting EMPS. The new concept will extract specific market data from the Nord Pool Spot, which in turn will populate an aggregated model of the Nordic power system, abbreviated Nordic44. The populated model will at this time be a snapshot of the power system defined by consumption and generation, and will together with statistical reliability data for the Nordic44 eventually be inputs for the consequence and reliability analysis in OPAL. This thesis will further investigate the Nordic44 suitability for reliability analysis through OPAL, in four steps:

1. Finding suitable operating states for the reliability analysis.
2. Modify the OPAL methodology and the Nordic44 model to be able to perform reliability studies of Nordic44.
3. Preforming reliability analysis using different strategies of corrective actions in the consequence analysis.
4. Test and further develop the corrective action by reactive power compensation.

Obtaining a more comprehensive and realistic test system for the SAMREL methodology is of interest for future development of the SAMREL methodology and for other research projects. As the outputs from the analysis might be comparable to real behaviors in the Nordic power system.

Supervisor: Gerd Kjølle

Co-supervisor: Sigurd Hofsmo Jakobsen and Iver Bakken Sperstad.

# Acknowledgment

This thesis is the final work of the integrated Master programme in Electrical Power Engineering at the Norwegian University of Science and Technology (NTNU). The supervisor for this thesis has been Gerd Kjølle, chief scientist at SINTEF Energy Research and Professor at NTNU. Co-supervisors has been Phd candidate Sigurd Hofsmo Jakobsen at NTNU and scientist Iver Bakken Sperstad at SINTEF Energy Research. The thesis is given by SINTEF Energy Research.

I would like to thank Gerd Kjølle for guidance and for a providing such an interesting problem definition for my thesis. Also co-supervisor Sigurd Hofsmo Jakobsen deserves a great thank you, for the help understanding the OPAL methodology and discussions regarding the Nordic44 model. His patience and support has been very valuable for the end results.

I will also thank Fredrik Storås and Jon Lytskjold for support on proofreading and motivation.

Trondheim, January 2017

Sindre Winsnes Nordhagen

Sindre Winsnes Nordhagen

# Abstract

The power systems primary function is to supply electrical energy to costumers in a cost-effective way with satisfactory quality and continuity. Today's society is demanding continuously available electrical energy, which pushes the power system towards its limit. Continuous availability is not possible to accomplish, as the power system will experience component failures outside the control of the operators. As a result, the system designers, planners and operators will be fronted with a dilemma; how to best invest their money to operate the system within economic, reliability and operational constraints.

This thesis will look into the reliability analysis of power systems; an analysis which uses probabilistic techniques to evaluate the severity of a state of which the power system might exist. Thus obtaining a prediction of the power systems likely future behavior, which can point out unreliable parts of the system where investments are needed. In this thesis a reliability assessment of the Nordic44 model is implemented, which is an aggregated model of the Nordic power system. The reliability analysis is carried out using the OPAL methodology, developed at SINTEF Energy Research. The methodology consists of a consequence analysis where the severity of different system states is assessed, pursued by the accumulation of reliability indices, which can be used in decision-making processes for long-term planning purposes. The results revealed that the Nordic44 model was an unreliable model, with several issues providing adequate supply.

In the consequence analysis, the system operators may apply different strategies, as to minimize customers load shedding. These strategies can be disconnection of transmission lines, generator rescheduling or reactive compensation. Correct modelling of these strategies is important in the methodology used, and they should be implemented as close to the corrective actions used in real power system operation. This thesis will further develop the corrective action by reactive compensation. Finally, the benefits of activating different corrective action options in the consequence analysis will be considered for the Nordic44 model under different system states, and their performance will be compared to foregoing studies. Results affirmed the corrective actions applicability for larger power systems, and that reactive compensation is beneficial for adequate supply when assessing reliability of the Nordic44.

# Sammendrag

Kraftsystemets hovedrolle er å levere energi til kundene på en mest kostnadseffektiv måte, med tilfredsstillende kvalitet og kontinuitet. Dagens samfunn har utviklet seg til å forvente kontinuerlig tilgjengelig elektrisk energi, noe som presser kraftsystemet mot grensene når det kommer til overføringskapasitet. En slik trend er ikke mulig å opprettholde på grunn av tilfeldige utfall av kraftsystemkomponenter, som vil være utenfor systemoperatørenes kontroll. På grunn av slike utfall må kraftsystemoperatørene, planleggerne og designere gjøre vanskelige investeringsbeslutninger innenfor økonomi, pålitelighet og operasjonelle grenser.

Denne rapporten vil se på pålitelighetsanalysen i kraftsystemet. En analyse som benytter seg av sannsynlighetsberegninger til å evaluere alvorlighetsgraden til kraftsystemet i en gitt tilstand. Resultatet fra analysen vil kunne gi en indikasjon på svake deler av kraftsystemet hvor investeringer trengs. Videre i rapporten vil en pålitelighetsvurdering bli gjennomført på en forenklet modell av det nordiske kraftsystemet, forkortet Nordic44. For å gjennomføre analysene blir OPAL metodikken brukt, en metodikk utviklet av SINTEF Energy AS bestående av en konsekvensanalyse etterfulgt av en akkumulering av pålitelighetsindekser basert på resultatet av konsekvensanalysen. Pålitelighetsindeksene kan videre bli brukt i kraftsystemplanlegging. Fra resultatene viste Nordic44 modellen seg å være ett upålitelig system med lav forsyningssikkerhet.

I konsekvensanalysen kan operatørene gjennomføre forskjellige korrektive tiltak, for å redusere kutt av last. Korrektive tiltak kan for eksempel være uttak av kraftlinjer, regulering av generert effekt på generatorer eller reaktiv kompensasjon. Presis modellering av korrektive tiltakene er viktig i metodologien brukt og burde derfor være tilnærmet lik tiltakene gjort i reelle kraftsystemer. Rapporten vil videre utvikle de korrektive tiltakene forbundet med reaktiv kompensasjon. Til slutt vil forskjellige korrektive tiltakskombinasjoner bli brukt til å beregne pålitelighetsindekser for modellen, før sammenligning med hverandre og tidligere studier. De korrektive tiltakene viste seg å være anvendbare på større kraftsystemer. Korrektive tiltak ved bruk av reaktiv kompensasjon viste seg også å være viktig for forsyningssikkerheten i pålitelighetsanalysen av Nordic44.

# Contents

# List of Figures

# List of Tables

# 1. Introduction

This thesis describes the work carried out on modelling of reactive compensation as a corrective action in OPAL, the work associated with preparing the Nordic44 model for reliability analysis and the results obtained from reliability analysis using different corrective actions in the consequence analysis. The background for the thesis is based on further work in *Modelling of corrective actions in reliability analysis* [3], where it was recommended that the performance of the corrective action options modelled in OPAL should be tested on larger and more complex power systems. The work on reactive compensation builds on previous work from *Implementing reactive compensation as a corrective action in OPAL* [13]. All in all the work is part of the methodology for security of electricity supply (SAMREL) developed at SINTEF Energy Research.

The main objective in reliability analysis is to determine reliability of supply indices for delivery points, such as energy not supplied and interruption frequency and duration. Interruptions of supply can occur after failures of primary components in the power system. The OPAL methodology is designed for these purposes, and will consider different outages and assess the severity of the outages through reliability indices. Outages in the power system might breach operational constraints for the system, such as voltage limits or overloading of transmission lines. Consequently, the operators will try to remove the violating constraint by applying corrective actions. Corrective actions is in this work defined as an action taken in the power system in response to a contingency [3]. In the consequence analysis in OPAL, such corrective actions are applied with the objective to minimize load shedding. A consequence analysis will involve power flow calculations to estimate the systems capability of supplying the delivery points and detect which system limits breached, so that the correct strategy is applied. A strategy is defined as a combination of several corrective actions options. The strategies used in the consequence analysis can be ranked between two extremes in terms of resulting energy not supplied; from the simplest trip-next models, which gives a pessimistic estimate of systems reliability, to more sophisticated optimal power flow models, which might give an overly optimistic estimate of systems reliability. The actual reliability for the system can therefore be found within this gap.

The implementation of reactive compensation as a corrective action in OPAL is based on using typical compensation components installed in the power systems, each with its pros and cons. The corrective actions by reactive compensation will respond to contingencies breaching voltage limits, generator reactive power limits or overloading of transmission lines. The needed compensation is calculated using power flow algorithms and by using simple heuristics. Preparing the Nordic44 model for the OPAL methodology involved finding fault statistics, defining analysis extent and how to handle internal and external HVDC exchanges correctly.

## 1.1 Scope

The results obtained from the reliability analysis using the corrective actions implemented in the consequence analysis is not used for short-time network operation, but rather as decision support tool for long-term network planning. Dynamic phenomena in power systems is ignored, this implies that the corrective actions modelled will neglect interruptions with short durations (from seconds and possibly up to a few minutes). Corrective action options based on optimal power flow (OPF) algorithms is not used in this thesis, because setting up constraints for the OPF algorithm so that the Nord Pool Spot exchanges remain the same is a comprehensive task in itself. There is neither done changes in the Nordic44 model to be able to make it a true and accurate model of the Nordic power system, nor trying to improve the models instabilities in several normal operation states. The limitations and aggregations in the Nordic44 model will affect the accuracy of the results from the reliability analysis; consequently, the results are non-comparable to the actual Nordic power systems adequacy.

## 1.2 Definitions and abbreviations

This thesis consists of a several terms and abbreviations which are used throughout, some already used without any further introduction. Definitions of terms and abbreviations can be found in appendices A.2 and A.2.2 respectively.

## 1.3 Thesis outline

The thesis is structured as follows. Chapter 2 describes the theoretical background for reliability analysis of power systems, the integrated methodology for security of supply analysis, which the OPAL methodology is part off and an introduction to reactive compensation in power systems. Chapter 3 describes the methodology used to solve the problem definition. Thus presenting the Nordic44 model, the states chosen for the case studies and the modelling of reactive compensation. Chapter 4 present the results from the case studies and discusses it briefly. Chapter 5 compares the results from the case studies with previous work on corrective actions performance in OPAL and an overall discussion on performance. Chapter 6 will draw a final conclusion and present some thoughts and recommendations for further work.

# 2. Theory

## 2.1 Reliability analysis of power systems

Reliability has a wide range of interpretations, and is therefore not associated with a specific definition. When the term is related to power systems, reliability is usually defined as the ability of the system to perform it's function [14]. When assessing the power systems reliability, reliability is divided into *adequacy* and *security*. Adequacy relates to the power systems ability to satisfy the consumer load demand or system operational constraints, and is by this considered a static condition [25]. A static condition can also be seen as a steady state where generation and transfer capabilities determine if the load demand is met. The term *security* is related to the systems ability to respond to transient or dynamic disturbances arising within the system [14]. Reliability assessments are mostly considering the adequacy domain, which results in a limiting ability to evaluate security.

The reliability analysis considers outages caused by failures of the components in the system analysed [1]. Outages is in reliability analysis defined as failures of one or several components in the system. When assessing the reliability, the consequences of such outages is found. The consequences of an outage can result in interruption of electricity supply for delivery points. Thus giving an impression of the power systems adequacy by looking at several indices providing information about the different delivery points in the system. The reliability indices can then be used in power system planning and operation, and e.g. for investment measures. This chapter will try to describe the theory behind reliability analysis, by presenting the most common reliability models and the principle of occurrence of interruptions, and the main reliability indices provided by the OPAL methodology.

### 2.1.1 Reliability analysis method

There are several methods and tools developed to evaluate reliability indices. The main approaches used are either analytical techniques or Monte Carlo simulations, with the essential difference in how to select system state scenarios to be evaluated [14]. The OPAL methodology is an analytical approach, which is based on the Markov model. The Markov model claims that a component exist in two possible states; either state 1 (activated) or state 0 (disabled). The frequency for the component to switch state is given by its fault rate ($\lambda$) and repair rate ($\mu$). The model is illustrated in figure 2.1.

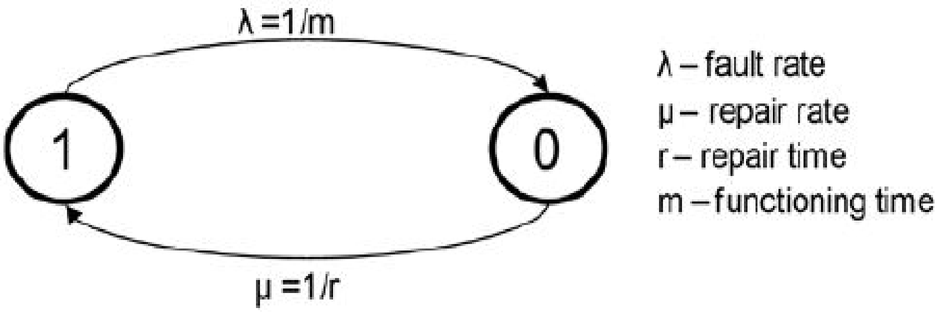

Figure 2.1: Two state Markov model with failure and repair process [1]

A system consist of many components creating chains of components in parallel or series structures. For a series system, both components must be in state 1, whereas for parallel structures only one component must be in state 1 to function.

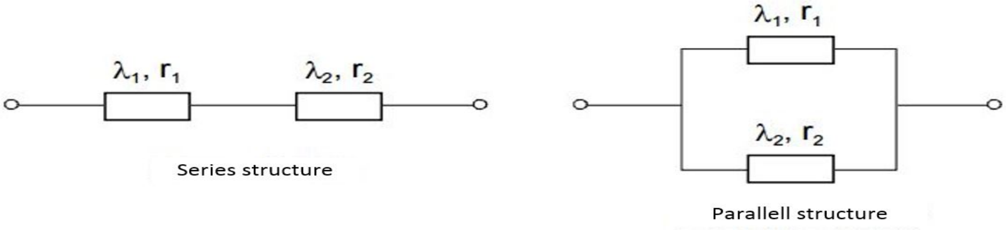

Figure 2.2: System structures [19]

The equivalent fail rates ($\lambda_s$), average repair time ($r_s$) and yearly repair time ($U_s$) for the system (S) in 2.2, can be calculated as follows:

**Series system**

Fault rate for the system:

$$\lambda_s = \lambda_1 + \lambda_2 = \sum_{i=1}^{2} \lambda_i$$

Repair time for the system:

$$r_s = \frac{\lambda_1 r_1 + \lambda_2 r_2 + \lambda_1 \lambda_2 r_1 r_2}{\lambda_1 \lambda_2} \simeq \frac{\lambda_1 r_1 + \lambda_2 r_2}{\lambda_1 + \lambda_2} = \frac{\sum_{i=1}^{2} \lambda_i r_i}{\sum_{i=1}^{2} \lambda_i}$$

The simplification is based on that: $\lambda_1 \lambda_2 r_1 r_2 \lambda_1 \lambda_2 \ll \lambda_2 r_2$ and $\lambda_1 r_1$ in most cases.

The yearly outage time for the system is then:

$$U_s = f_s r_s \simeq \lambda_s r_s$$

**Parallel system**

Fault rate for the system:

$$\lambda_s = \frac{\lambda_1 \lambda_2 (r_1 r_2)}{1 + \lambda_1 r_1 + \lambda_2 r_2} \simeq \lambda_1 \lambda_2 (r_1 r_2)$$

$\lambda_1 r_1$ and $\lambda_2 r_2$ is usually $\ll 1$.

Repair time for the system:

$$r_s = \frac{r_1 r_2}{r_1 + r_2}$$

The yearly outage time for the system is then:

$$U_s \simeq \lambda_s r_s$$

### Minimal cut set method

Figure 2.3 illustrates a general reliability model, which links the power system supply chain to the method for calculating reliability indices for a system. The lower part in the figure can be seen as a *minimal cut set* structure. Minimal cut sets are combinations of power system components, that if disabled causes interruption of load at a delivery points. The minimal cuts consists of faults leading to component outages and other incidents in the system (system constraints violated) [1], and may represent single component faults or multiple independent/dependent faults.

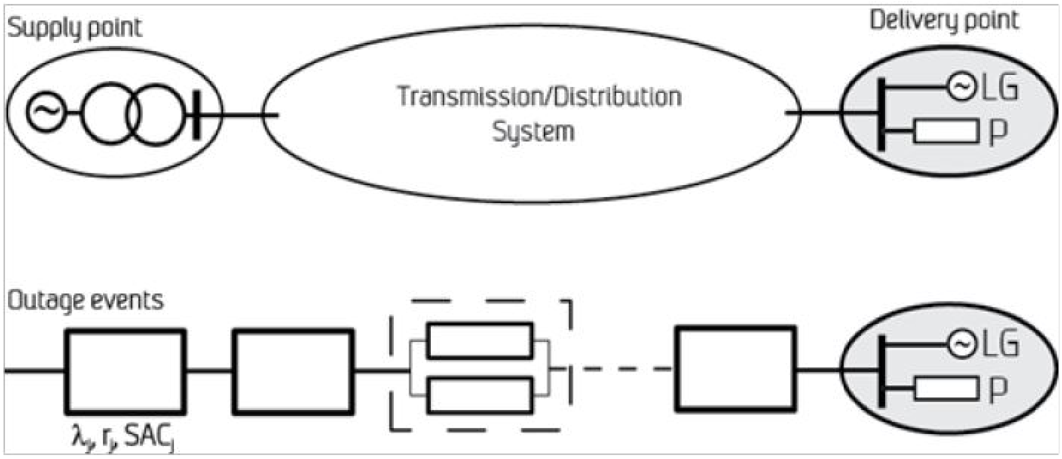

Figure 2.3: Reliability model for a delivery point using minimal cut sets [1]

The minimal cut sets method is based on components in a minimal cut set forming parallel structures, implying that supply interruption only occurs if all components in the cut set fails. A system consists of several minimal cut sets, which together forms a series structure of minimal cut sets. The equivalent fault rate and repair time for the series can be calculated using the formula's for series and parallel structures (2.1.1, 2.1.1). To obtain the equivalent fault rates and repair time for delivery points, a summation of all the minimal cut sets contributing to load interruptions at the delivery points are done. The fault rate and repair time for the delivery points can then be used to calculate reliability indices, such as energy not supplied (ENS), for the delivery points and even for the whole system.

## 2.2 Integrated methodology for security of supply analysis

An integrated methodology for security of supply (SoS) analysis is developed at SINTEF Energy Research referred to as the SAMREL project [2]. SoS is here defined as the ability of an electricity system to supply final customers with electricity, and is composed of energy availability, power capacity and reliability, with long term (system adequacy) and short-term (security) perspectives [1]. The project consists of three modules, which together can generate an output describing the reliability of supply indices for delivery points in the system analysed. The first module is the security constrained power market analysis, which will generate operating states as input to the contingency enumeration approach analysis. An operating state (OS) is defined as a system state valid for a time period characterized by load and generation as well as import/export to neighboring areas [1]. The contingency enumeration approach consists of a consequence analysis of contingencies pursued by the reliability assessment and accumulation of reliability indices. The two last steps is what together forms the integrated OPAL methodology. Figure 2.4 illustrates the different modules.

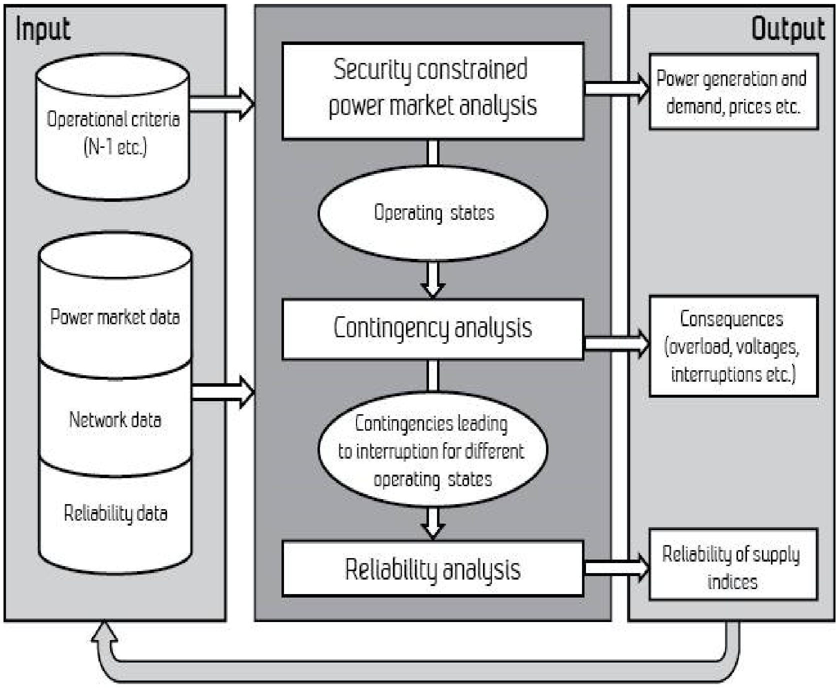

Figure 2.4: Illustration of the different modules in the integrated SoS analysis [1]

### 2.2.1 The OPAL methodology

Electric power systems are generally large and complex infrastructures, consisting of many components. The number of possible states correlate directly to the number of components, and increases exponentially by $2^n$ for a system of $n$ components [1]. Assessing the adequacy for every possible state is therefore a time consuming and demanding computational task. To reduce the number of states to analyse, OPAL uses the contingency enumeration approach, which focuses on the critical contingencies; those likely to cause delivery point interruption. The approach can be divided into four steps:

1. Definition of analysis.
2. Selection of contingencies.
3. Consequence analysis of contingencies.
4. Reliability assessment and accumulation of reliaiblity indices.

A more comprehensive structure of the contingency enumeration approach is illustrated in 2.5.

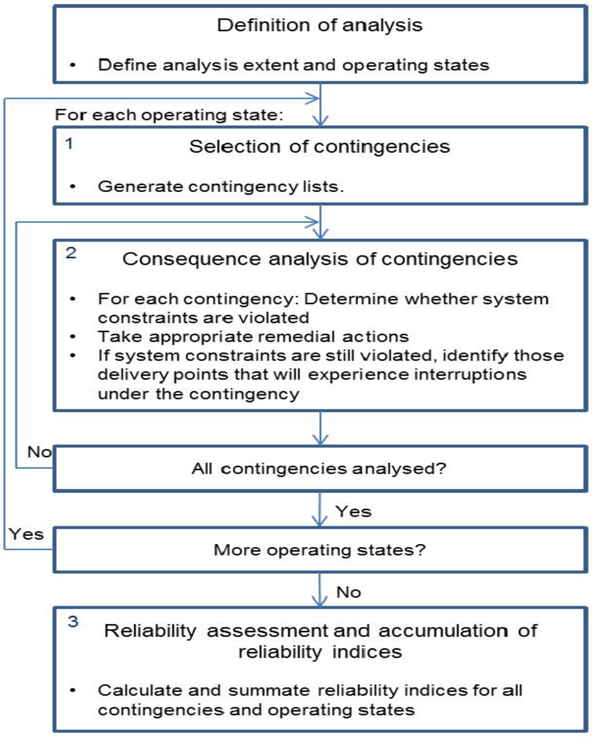

Figure 2.5: Contingency enumeration approach in OPAL [1].

**1. Definition of analysis**

The first step in the OPAL methodology is to define the extent of the analysis. This includes deciding which part of the network to analyse, which delivery points to include in the reliability assessment, choosing the depth of contingencies to be analysed (single, double or higher order combinations of outages), specifying which components that shall be included in the outage list (transformer, generator and overheaded lines etc.) and defining the operating states to analyse. The selection of operating states for the analysis is dependent on the intention of the reliability assessment. Often the high load operating state is chosen as it's most likely to include contingencies that may lead to load interruptions at delivery points and is therefore dimensional for the power systems reliability.

**2. Selection of contingencies**

The objective of this section is to reduce the number of contingencies, which is sent to the consequence analysis. The contingencies selected are those who causes violation of system operational constraints, potentially leading to interruptions of load at delivery points [1]. The selection of contingencies will directly correlate to the depth of contingencies analysed. High voltage systems is dimensioned under the N-1 criteria, thus able to withstand single outages of any component. It's therefore convenient to assess outages of higher order to reveal contingencies leading to interruptions. A typical analysis depth is to include all first and second order independent/dependent outages. Higher order outages than second is often neglected as it's computational demanding due to the increased number of contingencies and due to the low probability of the contingency to occur.

**3. Consequence analysis of contingencies**

The reduced list of contingencies is now input to the consequence analysis in OPAL. The goal is to identify which delivery points that will experience interruptions. Interruptions can arise in consequence of the system being outside its operating limits. Whether the system is outside its limits is revealed using power flow analysis. The violations can be over and under voltages, overloading of transmission branches or generator exceeds production limits. To minimize the consequences of such violations, corrective actions are applied in the consequence analysis to bring the system back within operating limits. In OPAL, several corrective action options are added, such as generator rescheduling, distributing slack and reactive compensation[1]. If these actions comes short in bringing the system back within limits, load shedding is necessary. Load shedding will result in partially or total interruption of supply for some delivery points in the system, meaning that the total available capacity after the contingency is unable to match the load at the delivery point [1]. This can be expressed by the inequality:

$$P > SAC + LG$$ [2]

The outputs from the consequence analysis are lists of the delivery points experiencing interruptions by the analysed contingencies and the $SAC_{j,n}$ matrices, giving information about the systems available capacity for delivery point $n$ due to contingency $j$. The results are used as inputs to the last module in the OPAL methodology; reliability assessment and accumulation of reliability indices

**4. Reliability assessment and accumulation of reliability indices**

The objective of the reliability analysis is to estimate the reliability indices for the delivery points in the system. The $SAC_{j,n}$ matrices and minimal cut sets interrupting the load supply are used to calculate the equivalent fault rate and repair time for the delivery points, using the formulas for series and parallel structures (2.1.1, 2.1.1). For a delivery point ($DP$) the fault rate ($\lambda_{DP}$), repair rate ($r_{DP}$) and annual interruption duration ($U_{DP}$) is given in equations as follows:

---

[1] The different corrective actions in OPAL is presented and defined further in A.2.1.

[2] P = load, SAC = System Available Capacity, LG = Local generation

$$\lambda_{DP} = \sum_{j=1}^{J} \lambda_j \qquad \text{[interruption/year]}$$

$$U_{DP} = \sum_{j=1}^{J} \lambda_j r_j \qquad \text{[hours/year]}$$

$$r_{DP} = \frac{\sum_{j=1}^{J} \lambda_j r_j}{\sum_{j=1}^{J} \lambda_j} \qquad \text{[interruption/year]}$$

Where $J$ equals the number of minimal cuts. The basic reliability indices fault rate ($\lambda_j$) and repair rate ($r_j$) can in turn be used to calculate expected consequences in terms of interrupted power ($P_{interr,j}$), energy not supplied ($ENS_j$) and interruption costs ($IC_j$) for each minimal cut $j$ as follows:

$$P_{interr,j} = P - SAC_j - LG \qquad \text{[MW/interruption]}$$

$$ENS_j = r_j P_{interr,j} \qquad \text{[MWh/interruption]}$$

$$IC_j = c(r_j) ENS_j \qquad \text{[NOK/interruption]}$$

These indices for the minimal cut set can then be annualized (per annum *a*) as follows:

$$P_{interr,j,a} = \lambda_j P_{interr,j} \qquad \text{[MW/year]}$$

$$ENS_{j,a} = \lambda_j ENS_j \qquad \text{[MWh/year]}$$

$$IC_{j,a} = c(r_j) \lambda_j ENS_j \qquad \text{[NOK/year]}$$

The interrupted power ($P_{inter,DP,a}$), energy not supplied ($ENS_{DP,a}$) and interruption costs ($IC_{DP,a}$) for the delivery points are found by summation of the contribution from the minimal cut sets as follows:

$$P_{interr,DP,a} = \sum_{j=1}^{J} \lambda_j P_{interr,j} \qquad \text{[MW/year]}$$

$$ENS_{DP,a} = \sum_{j=1}^{J} \lambda_j ENS_j \qquad \text{[MWh/year]}$$

$$IC_{DP,a} = \sum_{j=1}^{J} c(r_j) \lambda_j ENS_j \qquad \text{[NOK/year]}$$

## 2.3 Reactive compensation in power systems

Proper reactive power and voltage control is crucial in electric power systems for reliable and efficient operation. Reactive power is generated and consumed in almost every component in the system from generators to transmission lines and eventually by the loads [15]. The different states the power system might exist in can cause situation where reactive power is required to operate the system within its operational constraints. This can be solved by adequate control of reactive power, by utilizing components supplying reactive power. Adequate and optimized control is obtained if the reactive compensation components fulfil the following objectives:

**Voltage support:** Maintaining the voltages in the system within acceptable limits.

**Stability:** Reactive compensation can relieve reactive power flow on transmission lines such that the active power transmitted in the system is maximized. This will improve the stability of the power system.

**Losses:** Compensating buses with reactive power can increase the power factor of the system, which reduces the active power losses as the current through the components are reduced.

By achieving these objectives, reactive compensation can maintain a flat voltage profile in the system, control steady state and temporary overvoltage and even prevent blackouts [17]. Reactive power is generally regarded a local quantity, as it is poorly transmitted through long transmission lines [16]. Consequently, reactive compensation components should be installed at strategic locations where reactive compensation might be needed. The location and components needed for adequate compensation can be found using detailed power flow studies and stability studies. The most common components used for reactive compensation are series and shunt VAR compensation, synchronous condensers, static VAR compensator's (SVCs) and flexible ac transmission systems (FACTS).

### 2.3.1 Series and shunt VAR compensation

Series and shunt VAR compensation is regarded as *passive* components, meaning that there is no integrated controller that calculates the compensation needed, therefore they are either connected to the system with their specified ratings or disconnected. *Passive* components are used to modify the characteristics of the electrical network, and by this controlling the reactive power flowing through the system [17]. Shunt compensation will change the loads impedance, while series compensation will change the transmission lines parameters. Compensation through *passive* components is considered economical as they are generally cheap and easy to operate. But has operational disadvantages in system states with large voltage deviation from the nominal voltage, as their output is directly proportionate to the square of the bus voltage.

### 2.3.2 Synchronous condenser and Static variable compensator (SVC)

Synchronous condensers and SVCs are components providing *active* compensation, thus automatically supplying the exact amount of reactive power needed to maintain the nominal voltage. Synchronous condensers are rotating synchronous generator without any active power output, and has benefit's over *passive* components in low voltage situations, as they can efficiently supply reactive power by increasing the current to supply reactive power. A disadvantage is the high operational and purchase costs.Consequently, synchronous condensers has been replaced by SVCs in many applications. SVCs are also generally faster and more reliable in operation than synchronous condensers. SVCs are composed of thyristor controlled reactors (TCRs) and thyristor switched capacitors (TSCs), and supplies the needed reactive power by controlling/switching the *passive* components using power electronics.

### 2.3.3 Reactive compensation schemes in real-life power system operation

Modelling of reactive compensation as a corrective action in OPAL should be as close to the schemes of the national Transmission System Operators (TSO). An interview with a domain expert from Statnett SF (TSO in Norway) provided information about installation locations, component types installed and the prioritized order of corrective actions [20]. The information given can be summarized as follows:

**Install locations:**

- Large intakes/withdrawals of reactive power, e.g. in conjunction with long transmission lines.
- HVDC plants.
- Stations with loads dependant on voltage stability.

**Component types:**

- Capacitor banks (usually manually coupled in by the TSO, but some are automatic coupled in at a specified voltage).
- Static VAR compensators (SVCs).
- Synchronous condensers.
- Reactors (usually manually coupled in by the TSO).
- HVDC cables with voltage source converters.

**Prioritized order:** The prioritized order for which components to activate first in contingencies causing over and under voltages in Statnett SF is attached in appendix A.3.

The modelling of reactive compensation as a corrective action is in this thesis based on the information provided from the domain expert in Statnett SF and the previous work done in *Implementing Reactive Compensation as a Corrective Action in OPAL* [13].

# 3. Method

This chapter present the Nordic44 model, the methodology used to obtain suitable case studies and assessment of reliability indices for the case studies. Finally, the modelling of reactive compensation as a corrective action is presented. The operating states analysed is based on the Nord Pool Spot market data from 2015 [11].

## 3.1 The Nordic44 model

The Nordic44 model developed by iTesla, is an aggregated model of the Nordic power system, where the raw and processed data files corresponding to the model are available as an open data set and documented in [4]. The first appearance of the model is found in [5]. The countries included in the model is Norway, Sweden and Finland. The system consists of 44 buses, 28 loads, 80 generators and 79 branches (12 transformator branches and 67 overheaded transmission line branches). There are 33 generators in Norway, 26 in Sweden and 18 in Finland. The swing bus is located in eastern part of Sweden, in Oskarshamn (3300).

The Nordic44 model is trying to match a simplified equivalent model of the Nordic power system with historical electricity market data from Nord Pool Spot. Thus real consumption, production and exchanges are fed into the model. The equivalent single line diagram of the model is depicted in figure 3.1. The different market price areas are also indicated in the figure, given by the Nord Pool Spot price areas [11]. There are 10 price areas in the model, whereas 5 in Norway, 4 in Sweden and 1 in Finland. The generation and consumption data for 2015 is given in table 3.2. Table 3.1 present the maximum production capacity and maximum consumption at highest load operating state in 2015 distributed on the Nord Pool Spot areas. The highest consumptions are in area SE3, NO1 and FI, while the largest production capacity are in N02, SE3 and FI.

Table 3.1: Distribution of production and consumption in the Nord Pool Spot areas.

| NordPoolSpot area | Maximum capacity (MWh/h) | Consumption at high load sceneario (MWh/h) | Number of generators |
|---|---|---|---|
| **SE1** | 5000 | 1522 | 5 |
| **SE2** | 10690 | 2870 | 9 |
| **SE3** | 16803 | 15082 | 15 |
| **SE4** | 7098 | 5469 | 6 |
| **NO1** | 5860 | 7235 | 6 |
| **NO2** | 12280 | 7872 | 13 |
| **NO5** | 6450 | 3452 | 6 |
| **NO3** | 4000 | 2698 | 4 |
| **NO4** | 4200 | 2698 | 4 |
| **FI** | 13203 | 12131 | 12 |

Table 3.2: Production and consumption data for 2015 for the Nordic44 model. After power flow in PSS/E.

| **Total annually production** | 370,46 TWh |
|---|---|
| Annually Norway | 144,97 TWh |
| Annually Sweden | 160,11 TWh |
| Annually Finland | 65,37 TWh |
| **Total annually consumption** | 365,84 TWh |
| **Maximum consumption (MWh/h)** | Hour 10, 23.01.2015<br>62229 MWh/h |
| **Minimum consumption (MWh/h)** | Hour 5, 26.07.2015<br>24413 MWh/h |

Also included in the Nordic44 model are 7 external and 1 internal HVDC cable as well as an internal exchange from N04 to Finland and Russia. The HVDC cables and the internal exchange are modelled as loads; negative load implies import, while positive implies export at the bus. Table 3.3 present the different HVDC buses, the corresponding bus number, their ratings and the annual import/export in 2015.

Table 3.3: Mapping of HVDC cables in Nordic44. Annual import amd export is found using the code in appendix A.5.2. The HVDC cables ratings was found in [24].

| Cable | Corresponds to bus | Connection | Power rating (MW) | Annual export 2015 (GWh) | Annual import 2015 (GWh) |
|---|---|---|---|---|---|
| NorNed | 5620 | NO2 - NE | 700 | 5980 | 11 |
| Skagerak (1-4) | 5610 | NO2 - DK1 | 1700 | 6606 | 1610 |
| Konti-Skan | 3360 | SE3 - DK1 | 550 | 1407 | 1783 |
| Baltic cable | 8600 | SE4 - DE | 600 | 148 | 1914 |
| SwePol | 8700 | SE4 - PL | 600 | 3547 | 20 |
| FennoScan | 3020 to 7030 | SE3 - FI | 1200 | 8721 | 22 |
| Estlink | 7020 | FI - EE | 350 | 5008 | 28 |
| Vyborg | 7010 | FI - RU | 1420 | 24 | 3924 |

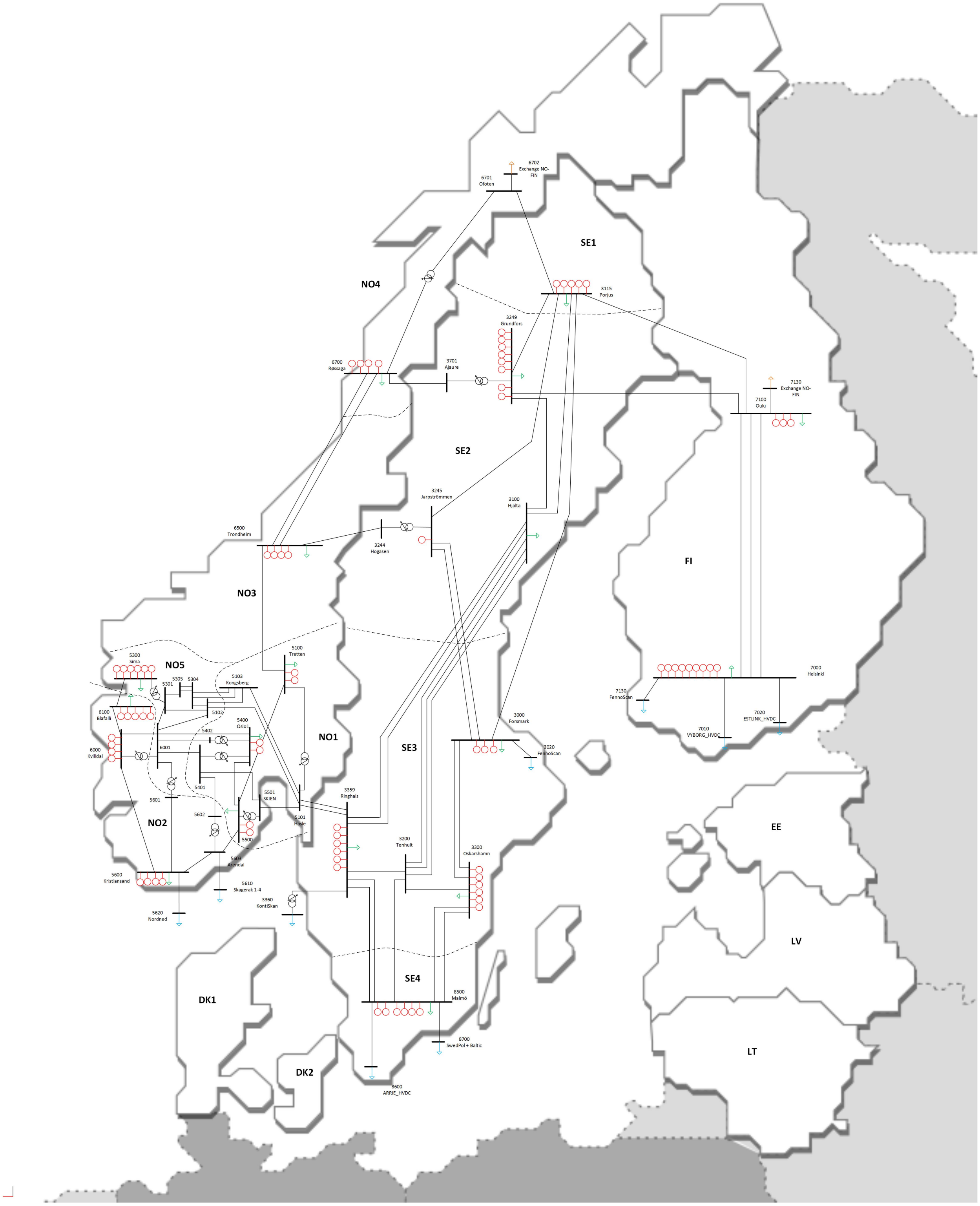

Figure 3.1: Single line diagram of the Nordic44 model with geographical bus location.

## 3.2 Tools

The tools used to perform a reliability analysis on the Nordic44 model are:

**Python:** A python script developed by SmartTS lab [22], has been made to automate the process of matching historical Nord Pool data with the Nordic44 model. The operate states are saved as a PSS/E file [1].

**Matlab:** The OPAL methodology is implemented in the MATLAB environment, thus all data processing was performed in MATLAB [21]. The PSS/E file, representing the operating state, is converted to the MATLAB environment for analysis.

**MATPOWER:** Package in MATLAB for solving of power flow and optimal power flow problems [23], used in the consequence analysis in OPAL.

**Excel:** Used to set the analysis extent, corrective actions settings and storage of system data.

## 3.3 Limitations

When performing a reliability analysis of a system, ideally all possible operating states should be considered to correctly reflect the systems adequacy. Unfortunately the Nordic44 model cannot match every scenario of historical data from Nord Pool Spot for 2015. The problem is mentioned in [10], where it's stated that no further modifications of the model has been applied to handle the discrepancies.

By iterating through the operating states in 2015, 4977 out of 8760 operating states was proven unfit for the OPAL methodology, due to system operational limits exceeded for the initial power flow. This result in a limited pool of operating states for the case studies presented in section 3.5[2]. The operating states outside operational limits after initial power flow in 2015 are

---

[1] Load flow simulation program developed by Siemens [4]

[2] The operating states could probably be initialised by optimal power flow, but this would change the power flow between the areas, and results in a model not matching the data from Nord Pool Spot. Consequently, a reliability analysis using OPF would result in reliability indices reflecting something else than the Nordic power system.

given in table 3.4.

Table 3.4: Operating states outside operational limit's after initial power flow for 2015. Found using the script *OS_finder*, see appendix A.5.2.

| **Limits exceeded** | **Location** | **Number of operating states** |
|---|---|---|
| Branch current exceeded | Hjälta - Grundfors (3100-3249) | 1801 |
| Branch current exceeded | Hjälta - Ringhals (3100-3359) | 988 |
| Branch current exceeded | Kaggefoss - Hagafoss (5402-6001) | 977 |
| Generator active power constraints violated for generator | Oskarshamn (3300) | 478 |
| Branch current exceeded | Helsinki - Estlink_HVDC (7000-7020) | 214 |
| Generator active power constraints violated for generator | Sima (5600) | 155 |
| Generator reactive power constraints violated for generator | Oulu (7100) | 103 |
| Branch current exceeded | Kvilldal - Hagafoss (6000-6001) | 48 |
| Branch current exceeded | Sima - Aurland (5300-5301) | 41 |
| Miscellaneous | | 172 |
| **SUM** | | 4977 |

### Computational time

The OPAL methodology is a time consuming algorithm in its current version. The algorithm does not support parallel loop iteration, and therefore each operating state must be analysed in subsequent order. Analysing one operating state takes from 50 to 400 seconds (dependent on processor power and combination of corrective action options enabled). To scale this up, a year analysis will lie in the interval 122 - 970 hours. With this in mind, its more practical to analyse a few operating states which together will represent the year. Approximately 85 % of the time consumption comes from *contanalysis.m*, the script which execute the consequence analysis. The consequence analysis in OPAL relies heavily on the Newton-Raphson algorithm to solve the power flow, which limits the computational time for the integrated methodology.

### Voltage limits

The operational constraints for voltages is set very spacious in the Nordic44 model. The acceptable voltage magnitude interval is $\pm 10\%$ the nominal voltage. The limit is probably set due to voltage instabilities when matching the Nord Pool Spot market data with the model. Consequently, there will be fewer contingencies causing voltage breaches in the consequence analysis.

## 3.4 Fault statistics

When performing an reliability analysis it's evident that the accuracy of the results is dependent of the quality of the fault statistics. To allocate correct fault statistics for the Nordic44 model, historical statistics for the power system components is gathered from *Nordic and Baltic Grid Disturbance and Fault Statistics 2014* [7] and *Årsstatistikk 2005 33-420 kV nettet* [8]. The fault statistics are based on historical statistics from 1996-2005 for the Statnett reference, and from 2005-2014 for the ENTSOE reference.

Table 3.5: Fault rate ($\lambda$) and repair time (r) for components.

| | $\lambda$ (no/yr) | **r** (h/interr) |
|---|---|---|
| **Overhead lines (420 kv)** | 0,044 (1/km) [7] | 28,32[8] |
| **Overhead lines (300 kV)** | 0,064 (1/km)[7] | 61,58 [8] |
| **Transformator (300 - 420 kV)** | 0,0229 [7] | 536,48 [8] |
| **Generator (300-420 kV)** | 0,5665 [8] | 20,8833 [8] |

The lengths for the overheaded lines are not specified in the Nordic44 model, which is needed to calculate the number of interruption per year ($\lambda$ (no/yr)). Two procedures can either approximate the lengths of the lines; by looking at the geographical distances or by calculating backwards from the models specified line resistance and reactance. Since the geographical bus locations in the model are approximate, the backward calculation method is used. The *Planleggingsbok for kraftnett* is used, which has specific transmission line data for over headed lines in $\Omega$/km [6]. The transmission line lengths are then calculated using the algorithm in A.4. The estimations done for $\lambda$ (no/yr) for transmission lines are not satisfactory for an exact reliability analysis, and is therefore added to further work in chapter 6.

## 3.5 Case studies

Ideally, all the operating states in a year should be used to assess the adequacy of the Nordic44 model for 2015. Unfortunately, 4977 of the operating states is unsuitable for reliability analysis (table 3.4). Consequently, a few operating states are used instead to represent the year. Manually finding the operating states needed to do so is time consuming. Therefore, two iterative scripts was written to automate the process of finding operating states and to evaluate the average reliability indices: *OS_finder* (attached in appendix A.5.2) and *main_all_OS* (attached in appendix A.5.1).

| | |
|---|---|
| *OS_finder*: | Used to search through all operating states in a year to find specific operating states for the case studies (e.g. finding high load cases and low load cases). |
| *main_all_OS*: | Used to run the consequence and reliability analysis for the cases chosen, and print the average reliability indices for this period. The code structure is presented in flow chart 3.2. |

After selection four case studies were chosen for further analyses. Two high load scenarios in December and March, one day representing the annual average load situation in April, a minimum load situation in June and the special operating state "Vårknipa" in March. The next sections will present the case studies.

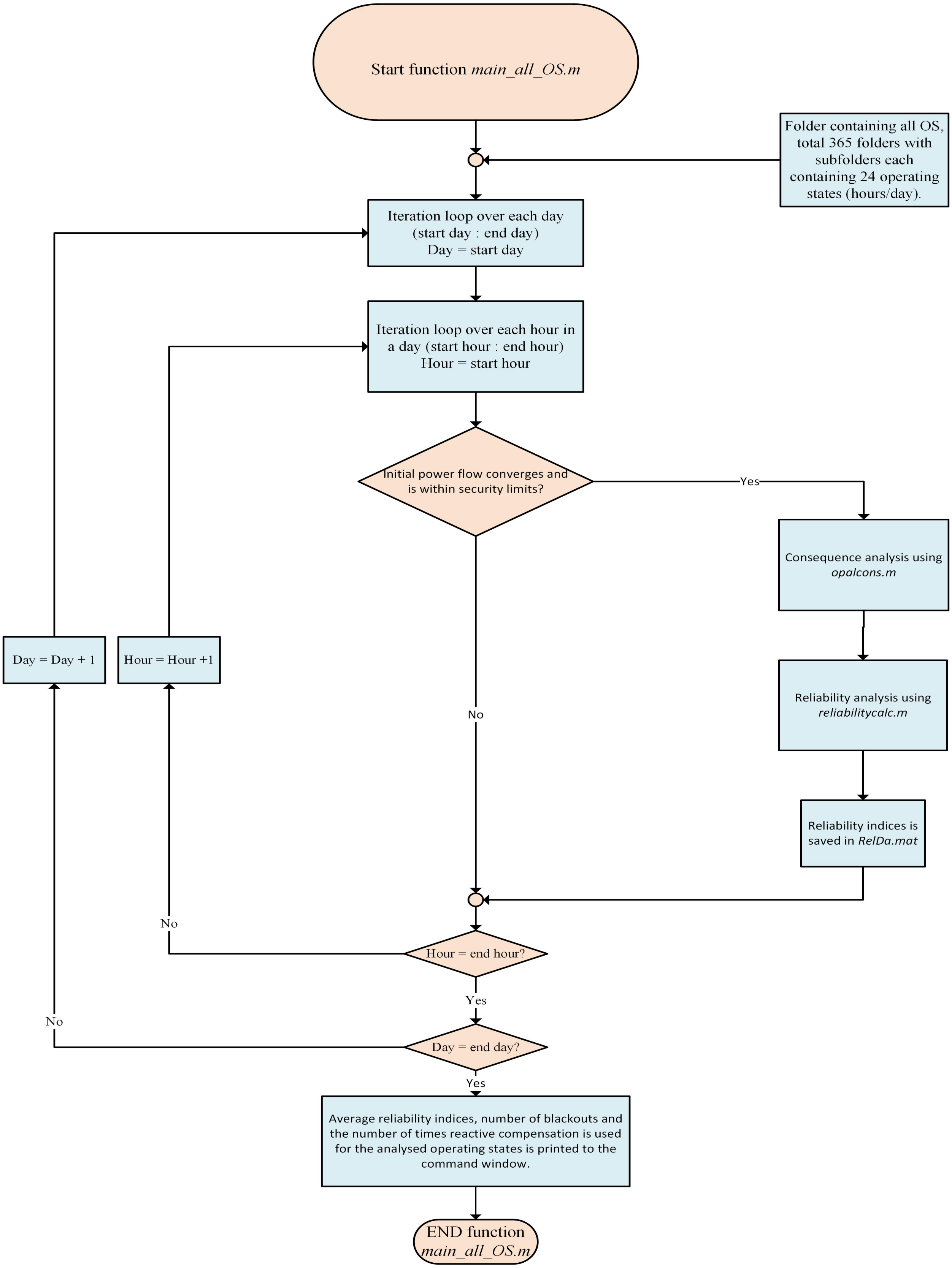

Figure 3.2: Flow chart for *main_all_OS.m*.

### 3.5.1 High load operating state

The maximum consumption operating state (23.01.15 hour 10) is unfit for the OPAL methodology due to generator active power constraints violated for generators at Oskarshamn (3000), Sima (5300) and Røssaga (6700). Therefore, another operating state representing the highest possible consumption that converges for the initial power flow within the security limits is found using the script in A.5.2. Two operating states is chosen to represent the high load operating state:

**Time:** 04.12.2015 hour 11:00:00 and 03.03.2015 hour 11:00:00.

**System data:** Load = 50030 and 49294 MWh/h
Generation = 50532 and 49773 MWh/h

**Computational time:** ~ 12 minutes.

### 3.5.2 Annual average load operating state

To represent the average annual load, a whole day is chosen so that the effect of changes in consumption, generation and exchanges throughout the day is captured in the consequence analysis. By iterating the whole year using the attached script in appendix A.5.2, the day closest to the annual average load in 2015 was found [3]:

**Day:** 01.04.2015, hour 1 - 24.

**Description:** 21 of 24 operating states converges for the initial power flow within security limits.

**System data:** Average load: 42174 MWh/h.

**Computational time:** 1 hour.

---

[3] A condition was set in *OS_finder*, which stated that more than 20 operating states must converge for the chosen day within the operational security limits, to represent the annual average load operating state.

### 3.5.3 Low load operating state

The minimum load OS was found using the script attached A.5.2.

**Time:** 26.07.2015 hour 04:00:00

**System data:** Load = 24436 MWh/h
Generation = 24536 MWh/h

**Computational time:** ~50 seconds.

### 3.5.4 "Vårknipa" operating state

The "Vårknipa" situation is an operating state that occurs in Norway when the consumption in Norway is larger than available generation capacity due to late snow melting in the spring. Norway is then dependent of import from Europe and Sweden to fulfil the demand. The exchanges relevant to "Vårknipa" is depicted in figure 3.3. NO3 is the most critical area in Norway, where the demand exceeds the available generation capacity [4].

**Time:** 01.03.2015 hour 6:00:00

**System data:** Load = 36150 MWh/h
Generation = 36334 MWh/h
Import HVDC (Skagerak 1-4 and NorNed) = 1939 MWh/h
Import Sweden = 2862 MWh/h

**Computational time:** ~70 seconds.

---

[4] $P_{demand,NO3}$= 2425 MWh/h, $P_{generation,NO3}$= 986 MWh/h

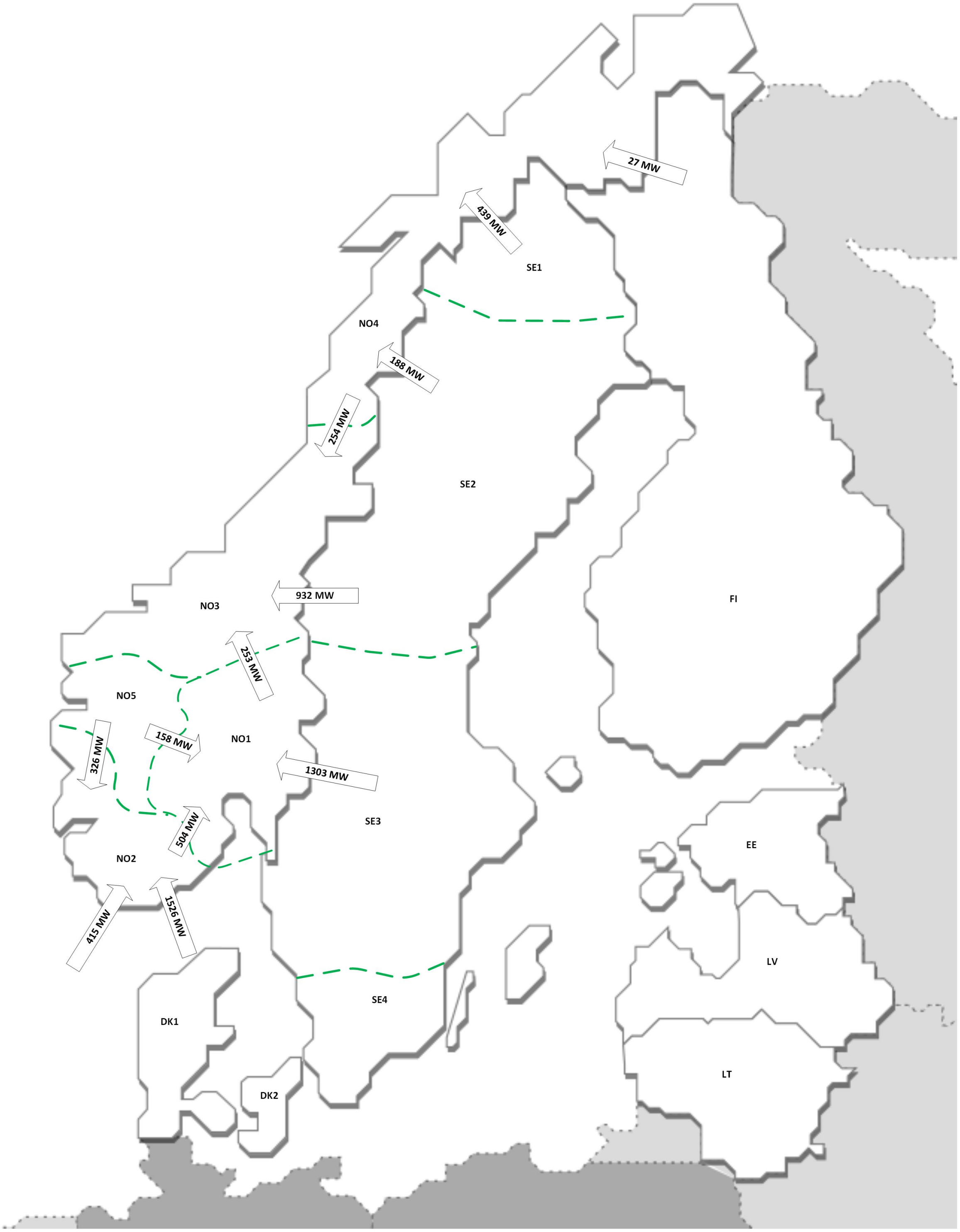

Figure 3.3: The power flow between Nord Pool Spot areas in Norway, and import to Norway during the OS "Vårknipa".

## 3.6 Analysis extent and default settings

Some settings are default in the OPAL methodology to define the extent of the analysis for the case studies. The settings are saved in an Excel spreadsheet where options for corrective actions, input system data and analysis settings are stored.

- Defining which delivery points that should be included in the reliability assessment. The HVDC buses and internal exchange buses from N04 to Russia/Finland are not included in the reliability assessment of the Nordic44 model.
- The Nordic44 is a meshed network where it's expected that few first order contingencies causes interruptions for the delivery points. Therefore, the depth of contingencies analysed is set to second order branch outages and first order generator outages. By defining this extent of the analysis, the contingency enumeration approach in OPAL generates 3177 contingencies to be analysed for each operating state in the case studies. Higher order than second outages is not considered, as the probability to enter such a state is minimal, thus contributing minimal to ENS.
- In reality the operator has a limited time to solve the problem, therefore there has been specified a maximum number of iterations allowed in the corrective action script. For this thesis its set to 10 iterations [3].

## 3.7 Modifications in the OPAL methodology and Nordic44 model

Modifications has been done in the OPAL methodology and the Nordic44 model to do contingency and reliability analysis. The changes are associated with the inclusion of HVDC cables and the internal exchanges and minor changes in modelling of outage-list (i.e contingency list) and corrective actions.

### 3.7.1 Changes in the Nordic44 model

The changes in the Nordic44 model are associated with the internal exchanges, which includes the buses in connection with the FennoScan HVDC and the transfer between N04 and Finland/Russia. For the corrective action options to properly work on these buses, three theoretical transmission lines and two buses has been added to the model.

For the FennoScan HVDC this results in adding a bus at the Finland side of the cable, named bus 7030. A transmission line is added to connect this bus to its origin Helsinki (bus 7000). For the exchange from N04 to Finland/Russia two new load buses are added, bus 6702 in N04 and bus 7130 in Finland. Two transmission lines are added to connect them to Ofoten (6701) and Oulu (7100) respectively. The new transmission lines are not included in the outage list for the consequence analysis, and are added as very short transmission lines [5], which minimizes their contribution to transmission losses in the system. All changes are added in figure 3.1.

The logic behind these changes can be understood by looking on how corrective actions are modelled in OPAL. If load shedding is done at bus 3020, this must also result in load shedding at the opposite side at bus 7030 and vice versa. This will include the corrective action option partially load shedding.

---

[5] Transmission line impedance for branch 7000-7030, 6701-6702, 7100-7130 is set to X = 0,00001 Ω

### 3.7.2 Changes in the OPAL methodology

For outages of branch 1 (Forsmark (3000) to FennoScan (3020)) and branch 34 (Hasle (5101) to Skien (5501)) there is added conditions in the consequence analysis (*contanalysis.m*). For branch 1 the condition states that an outage of this branch will disable the transmission line between Helsinki (7000) and FennoScan (7130). Due to prevent injecting/withdrawal of void power flow into/out of the system (code line 16 in A.5.5). For branch 34, which is a submarine power cable over the Oslo fjord, the condition states that if the cable is disabled, the reactive power compensating the cable is set to zero, thus preventing injecting/withdrawal of void reactive power flow into/out of the system (line 25-28 in A.5.5).

#### Remodelling of *reducecont.m*

The outage-list (i.e. contingency list) is modified so that it only contains relevant component outages, thus excluding the extra branches added associated with the internal HVDC cables and internal exchanges in the outage-list. The script which reduces the contingency list (*reducecont.m*) has been rewritten using logical indexing with the component type as conditions[6]. An advantage using logical indexing is that *reducecont.m* can handle several branches between two buses and several generators at the same bus, which often occurs in larger power systems like the Nordic power system, which the Nordic44 model represent.

## 3.8 Reactive compensation as a corrective action

The Nordic44 model is a larger and more complex power system than the test networks in *Implementing reactive compensation as a corrective action in OPAL* [13]. Consequently, the scripts associated with corrective actions by reactive compensation needed a few modifications and extensions to function properly. The new features in such actions is the possibility of reactive compensation at buses without load, reactive compensation at generation buses which exceeds their reactive generation limits and the inclusion of static VAR compensator (SVC) as a compensation device. All features are inspired further work in [13]. A prototype for reactive power

---

[6] Component types: 1 = overhead line, 2 = bus, 3 = generator, 5 = transformer

rescheduling has also been implemented, which can be used to remove overloading of transmission lines by compensation reactive power.

### Corrective actions script

The *corrective_action.m* script has been remodeled for better strategies in contingencies requiring reactive power compensation in the consequence analysis. The new code structure is presented in the figure 3.4. A script named *ReactiveCompensation.m* (attached in A.5.4), is used to calculate the reactive compensation needed to bring the system back within limits. The script will consider inputs from the Excel spreadsheet about available compensation components, ratings and which reactive compensation actions enabled as corrective actions. The order for which compensation component to activate first is inspired by Statnett SF strategy schemes during under and over voltages shown in appendix A.3 [20]. Generally *shunt_compensation* is tried first, before resorting to *SVCs* followed by *synchronous_condenser*. If there is no devices available at *worstcase* or if its insufficient capacity to bring the system back within limits, the worstcase load/bus will be shedded/disconnected.

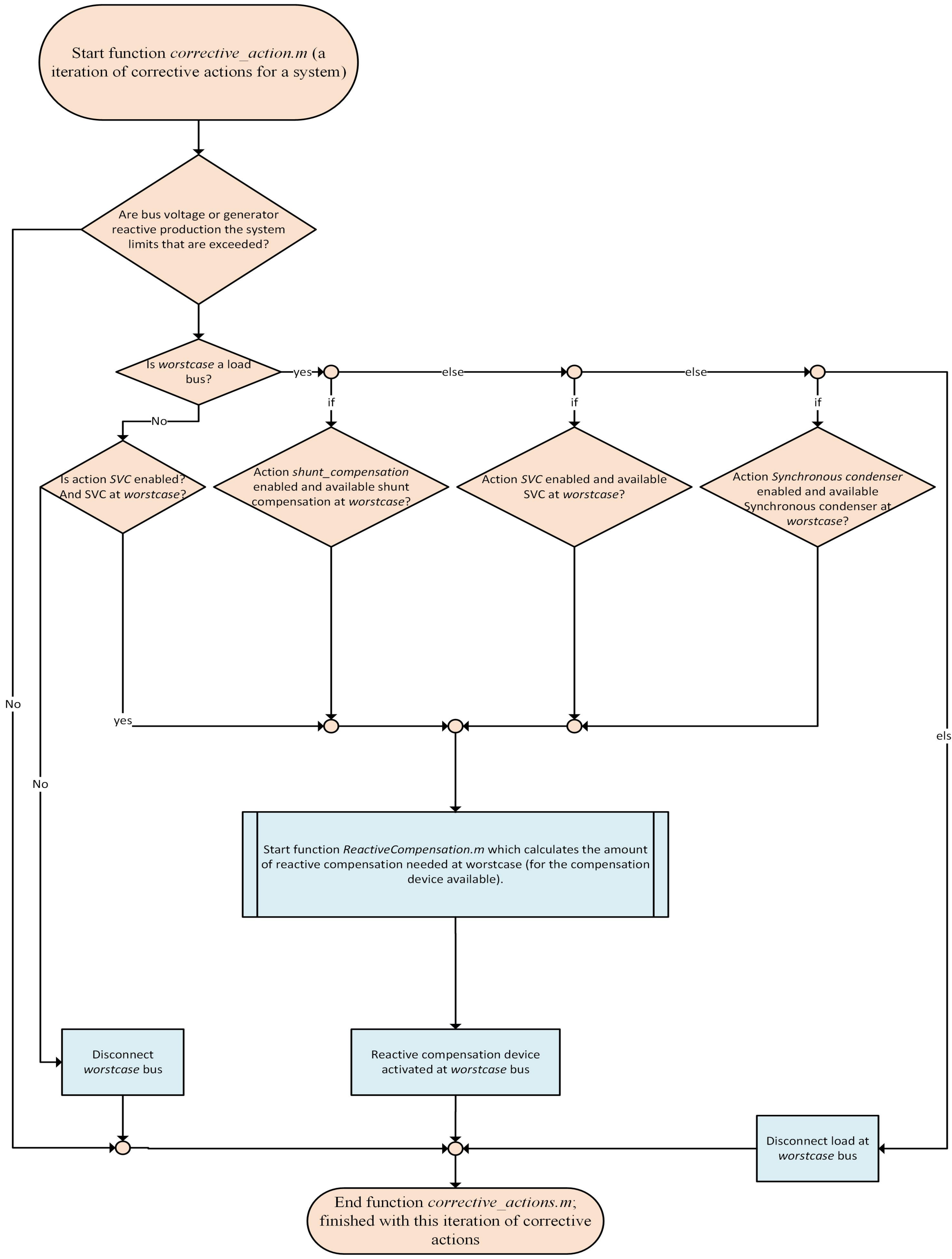

Figure 3.4: Script structure for reactive compensation in *corrective_actions.m.*

### SVC compensation

The new corrective action option static VAR compensator (SVC) is modelled as a generator with $P_{out} = 0$. A SVC is added to a bus as follows:

1. Add the SVC to the spreadsheet *SVC* with given ratings.
2. Add the SVC to the *generator* spreadsheet with same ratings but turned off.
3. Enable corrective action option *SVC* in the spreadsheet *actions*.

The corrective action option *SVC* will respond to either voltage or reactive power limits exceeded at the *worstcase* bus. Given that there is an available SVC at the bus and enabled *shunt_compensation* or *SVC* as a corrective action.

### Shunt compensation and Synchronous condenser

Definitions of the corrective action options *shunt_compensation* and *synchronous_condenser* can be found in *Implementing reactive compensation as a corrective action in OPAL* [13]. In short *shunt_compensation* is a corrective action that tries to activate reactive compensation components in a prioritized order; first by shunt compensation, secondly by SVCs, and finally by synchronous condensers (line 23 - 108 in *ReactiveCompensation.m* A.5.4). Corrective action option *synchronous_condenser* will only considers available synchronous condensers at the *worstcase* bus.

### Reactive rescheduling prototype

The corrective action option *reactive_rescheduling* has been added as an option in the consequence analysis. The preliminary implementation of the corrective action is by having shunt compensation available at PQ buses in the system, with goal to reduce the reactive power flow in transmission lines. If a contingency causes overloading of lines, the first action is to reschedule active generation at both ends of the transmission line. If that's not enough to bring the system within operational limits, rescheduling by reactive rescheduling using heuristics is done as illustrated in figure 3.5. Reactive rescheduling is tested and explained further for the high load operating state in section 4.1.

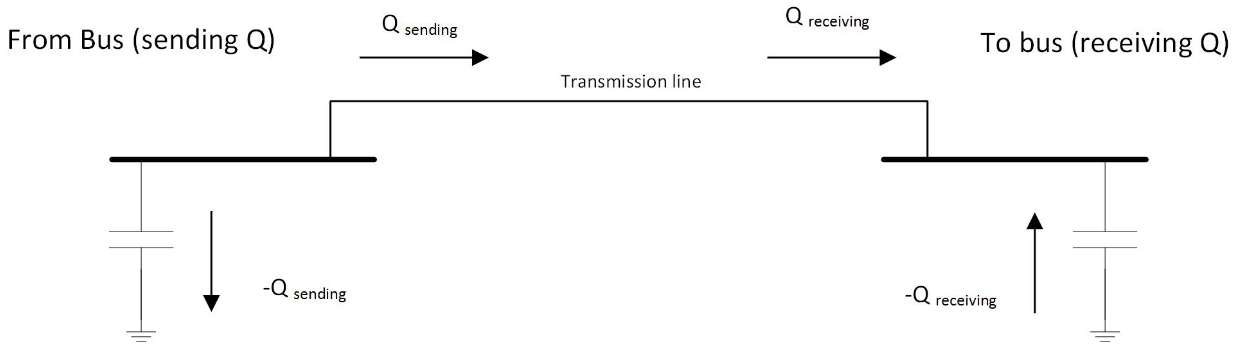

Figure 3.5: Reactive rescheduling which relieves overloading of transmission lines by compensating reactive power at the transmission line ends.

### 3.8.1 Compensation devices in the Nordic power system

To be able to perform correct and realistic reactive compensation after contingencies leading to either voltage or generator reactive production limits being exceeded, correct ratings and geographical location of the components must be included in the model. There is little information available regarding location and ratings for such components. Some information was found in the report *Nordic and Baltic grid disturbance statistic* [7]. The number of compensation units available in the Nordic power system is given in table 3.6 [7].

Table 3.6: Available compensation devices in 2014 in the Nordic countries [7].

| **Country** | **Shunt capacitor** | **SVC** | **Series capacitor** | **Reactor** |
|---|---|---|---|---|
| **Norway** | 194 | 15 | 36 | 3 |
| **Sweden** | 186 | 3 | 77 | 12 |
| **Finland** | 42 | 5 | 70 | 9 |

Finding correct ratings and location of every compensation device in the Nordic power system is a comprehensive task, and is beyond the scope of this thesis.

Nevertheless, correct reactive compensation for the case studies is important. After looking briefly at the consequence analysis for the case studies, two areas in the model had contingencies needing reactive compensation. These were Oulu (7100) and Skien (5501).

The violation at Skien (5501) is caused by over voltages in the consequence analysis. Therefore a SVC is added at the bus rated for ± 250 MVAr to try absorb reactive power with goal to reduce the bus voltage within operational limits. The ratings for the SVC added is based on typically ratings of SVCs in Norway [12]. The violation at Oulu (7100) is caused by generators exceeding their reactive power limits. To compensate the bus with reactive power, thus relieving the generators reactive power production, two shunt capacitors is added to the bus with ratings ±200 MVAr each, typical ratings where found in [9].

The compensation installed in the model is a simplified way of representing the reactive compensation available at these buses, but for testing the effect of reactive compensation in the OPAL methodology, its acceptable.

# 4. Results

The results is presented in the order of the case studies from section 3.5. In the consequence analysis, different strategies can be used to reduce the consequences of contingencies. The strategies are combinations of corrective action options from the work in *Modelling of corrective actions in reliability analysis* [3]. Different strategies are tried in the consequence analysis, so that a comparison between adequacy is possible. The strategies tested, which are composed by combination of corrective action options are:

| | | Corrective action options | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | trip_next | allow_islanding | distr_slack | distr_by_max_cap | load_shedding | partial_shedding | reschedule_gen | shunt_compensation | SVC | synchronous_condenser |
| STRATEGIES | **trip_next** | x | x | x | x | | | | | | |
| | **shed_load** | x | x | x | x | x | | | | | |
| | **shed_load_partial** | x | x | x | x | x | x | | | | |
| | **shed_load_reschedule_manual** | x | x | x | x | x | | x | | | |
| | **shed_load_reschedule_manual_reactivecomp** | x | x | x | x | x | | x | x | x | |

Table 4.1: Strategies for corrective actions in the consequence analysis.

Further definition of the different corrective action options which the strategies are composed of is given in A.2.1. The default corrective action options enabled is given in table A.2.3.

## 4.1 High load operating state

Figure 4.1 displays the summation of ENS contributed by the delivery points from different strategies for the high load operating state, beneath is the distribution of ENS on the delivery points in percentage.

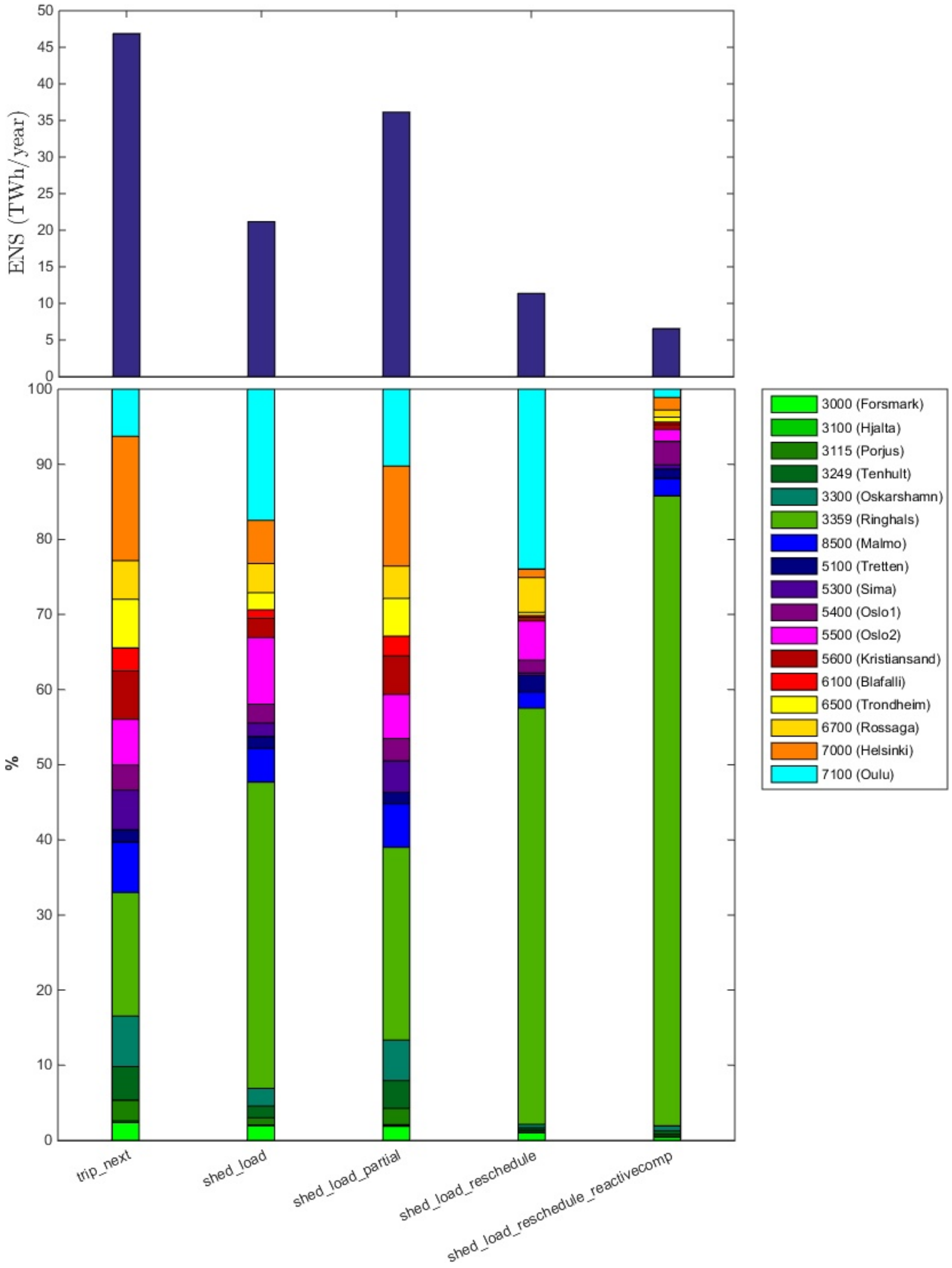

Figure 4.1: ENS for different strategies and their distribution on the DPs for high load case.

Main results:

- The desired strategy in terms of ENS is *shed_load_reschedule_reactivecomp*, with a total of 6,54 TWh/yr.
- The least desired strategy in terms of ENS is *trip_next*, with total of 46,86 TWh/yr.
- It is better to shed all load than partially shed it as a corrective action.
- For all the strategies the contribution to ENS is largest from Ringhals (3359).
- 72 of the 3184 contingencies led to blackout (i.e. system failure) for the desired strategy, 1 of them was due to a first order branch outage caused by failure of the transformator on branch 5300 - 5301.

The ENS for the different strategies is mostly affected by first order branch outages, thus explaining the large values of ENS. In a meshed network, which the Nordic44 represent, you would not expect first order branch outages to influence the reliability indices, due to the N-1 criteria [1]. The desired strategy (*shed_load_reschedule_reactivecomp*) has 44 first order outages that leads to load interruptions at the delivery points, whereas 17 was caused by generator outages and 27 due to branch outages. The interruptions were caused by overloading of transmission lines and non-convergence of power flow, thus contributing 6,42 TWh/yr to the annual ENS, i.e. first order outages counts for 98,16 % of the total annual ENS.

Another way to show the results is ENS sensitivities by changing different corrective action options for a base case strategy. Figure 4.2 illustrates the relative impact of enabling/disabling different corrective action options for the base case *trip_next* and *shed_load*. The figure can be used to compare how the corrective actions modelled perform on the Nordic44 model, compared to previous test networks analysed in *Modelling of corrective actions in reliability analysis* [3]. First *trip_next* is used as base case. Disabling distribute slack by max capacity and islanding turns out to be almost insignificant for the ENS of the system, while disabling distribute slack increases the total ENS by a considerable amount. Secondly *shed_load* is used as base case,

---

[1] A system withstanding any single major contingency is termed N-1 secure [18], withstand is defined as no load interruption or violating any security limits in the system after the outage.

disabling distribute slack and distribute slack by maximum capacity has now greater ENS sensitivity than for the *trip_next* base case. An interesting observation is that disabling distribute by max capacity decreases the total ENS.

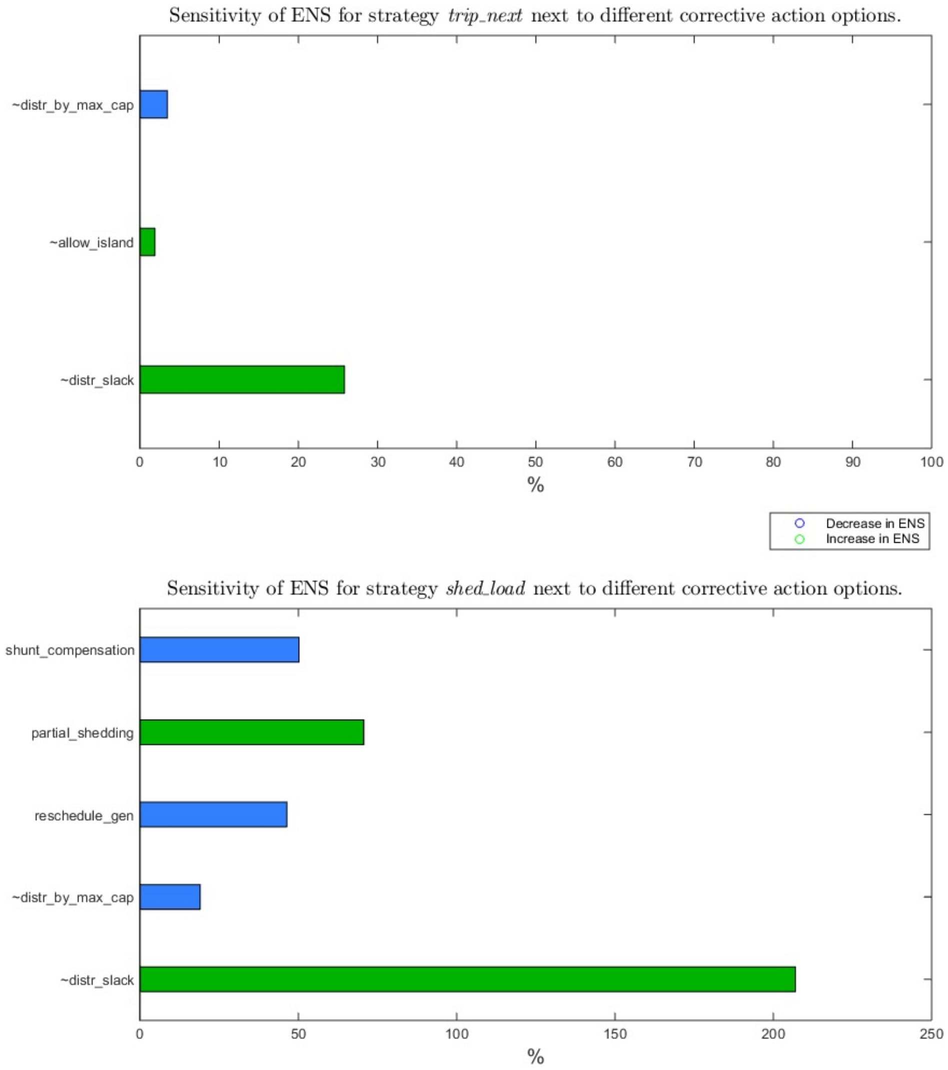

Figure 4.2: Sensitivity of ENS for base case strategies to other corrective action options for the high load case.

## Disabling distribute by max capacity for desired strategy

Disabling *distribute_by_max_capacity* will also affect the desired strategy in terms of ENS, a comparison is presented in table 4.2.

Table 4.2: Comparison of reliability indices for strategy *shed_load_reschedule_reactivecomp* with/without corrective action option *distribute_by_max_capacity*.

| **Strategy** | $\lambda_{s,a}$ **(interr/yr)** | $r_{s,a}$ **(hours/interr)** | $ENS_{s,a}$ **(TWh/yr)** | ***calls shunt_compensation*** | ***calls: SVC*** | **Blackouts** |
|---|---|---|---|---|---|---|
| *shed_load_reschedule_reactivecomp* | 36,36 | 33,60 | 6,54 | 2004 | 77 | 72 |
| *shed_load_reschedule_reactivecomp ~distr_max_cap* | 33,07 | 37,50 | 6,38 | 2001 | 78,5 | 90 |

By disabling distribute by max capacity there is a 2,38 % reduction in total energy not supplied, even if the number of blackouts is increased by 18. This contradicts the results from [3], where modelling of distribute slack was proven negligible in terms of ENS.

### Load shedding

There is vast differences comparing adequacy for strategy *shed_load* and *shed_load_partial*. The difference in energy not supplied is 15 TWh/year, and is a result of strategy *shed_load_partial* having 431,7 interruptions per year against 220,4 interruptions per year for *shed_load*. Considering repair time, it's a little less for *shed_load_partial* than *shed_load*; 27,23 versus 28,07 hours per interruption. Partially shedding seems to move the consequences of contingencies from one delivery point to others, resulting in failure to restore operational limits. On the other hand shedding the entire load will successfully restore operational limits, thus reduce the number of interruptions.

### Reactive compensation for the high load operating state

A comparison of reliability indices for strategy *shed_load_reschedule_reactivecomp* versus *shed_load_reschedule* is presented in table 4.3

Table 4.3: Comparison of reliability indices for strategy *shed_load_reschedule_reactivecomp* and *shed_load_reschedule*.

| **Strategy** | $\lambda_{s,a}$ **(interr/yr)** | $r_{s,a}$ **(hours/interr)** | $ENS_{s,a}$ **(TWh/yr)** | ***calls shunt_compensation*** | ***calls: SVC*** | **Blackouts** |
|---|---|---|---|---|---|---|
| *shed_load_reschedule* | 97,78 | 31,46 | 11,36 | 0 | 0 | 102 |
| *shed_load_reschedule_reactivecomp* | 36,36 | 33,58 | 6,54 | 2004 | 77 | 72 |

For the strategy *shed_load_reschedule_reactivecomp*, there is 2081 calls for reactive compensation in the consequence analysis, due to generator reactive power generation exceeded at

Oulu (bus 7100) and bus over voltage at Skien (5501). The corrective action option *shunt_compensation* is called 2004 times at Oulu (7100). Corrective actions is applied by activating the shunt capacitors and SVC installed. The shunt capacitors are compensating 400 MVAr for all the contingencies, while the SVCs are activated in two contingencies, as the shunt capacitor alone was insufficient [2]. The compensation scheme at Oulu is able to remove the problem, thus reducing load shedding. Having the possibility to compensate at Oulu reduces the energy not supplied by 42,42% compared to the strategy *shed_load_reschedule*.

There are 75 contingencies causing over voltages at Skien (5501). The installed SVC, rated for ±250 MVAr, absorbs -250 MVAr for these contingencies, but it's not enough to remove the over voltage problem at the bus. Activating the SVC for these contingencies has therefore no influence on the reliability indices. To obtain an acceptable voltage level at the bus there has to be at least 1200 MVAr inductive reactive compensation at Skien. If say, there were enough reactive compensation available at the bus, this would reduce the total ENS by 20820 MWh/year. The amount of reduction in ENS is almost negligible in comparison to the total amount of ENS, but it would be important if the Nordic44 model were N-1 secure.

Reactive compensation is most effective reducing the number of interruption per year, but not so much in regard of repair rate. The reduced number of blackouts also emphasize the effectiveness of reactive compensation. Looking at figure 4.2, reactive compensation is also effective when combined with the strategy *load_shedding*. The results implies the importance of reactive compensation as a corrective action to improve the systems relative adequacy for a high load operating state.

### Reactive rescheduling prototype testing

The corrective action option, *reactive_rescheduling* has not been used in the strategies; as it is still a prototype and should be tested further to make sure it behaves correctly in the consequence analysis. Nevertheless, the prototype is tested on the high load operating state as to

---

[2] Using *ReactiveCompensation.m* (appendix A.5.4), the calculated amount of compensation needed is between 337 and 504 MVAr for the contingencies. Thus 400 MVAr is a satisfactory compensation size at Oulu (7100), optimized for most of the contingencies.

present the thoughts and motivate for further development. The possibility for shunt compensation is added to all PQ buses in the Nordic44 model. Compensation is not added to PV buses, as the characteristics of PV buses are to adjust reactive power as to maintain a constant voltage magnitude, injecting/absorbing reactive power will therefore have no effect on the loading on the transmission line, as long as the bus generators are within their reactive generation limits. The simple heuristics of *reactive_rescheduling* absorbs/injects reactive power at the sending/receiving end as to relive the loading of the transmission line. There is no calculation of the optimized amount of absorption/injection, the heuristics will only check which side is receiving/sending, and compensate the amount of reactive power transmitted on the transmission line. Three modelling choices were tested, and then compared to reliability indices for strategy *shed_load_reschedule_reactivecomp*. Modelling choices:

1) Absorbing at sending end, injecting at receiving end (as illustrated in figure 3.5).

2) Only injecting at receiving end (capacitive shunt compensation).

3) Only absorbing at sending end (inductive shunt compensation).

The reliability indices for the modelling choices are presented in table 4.4. The results indicate that modelling choice 1) is most beneficial for the systems adequacy.

Table 4.4: Reliability indices for different modelling choices for reschedule reactive.

| **Modelling choice** | **$\lambda$ (interr/year)** | **r (h/interr)** | **ENS (TWh/year)** | **Decrease in ENS compared to shed_load_reschedule_reactivecomp** |
|---|---|---|---|---|
| 1) | 31,43 | 34,55 | 6357077 | 2,79 % |
| 2) | 31,81 | 34,39 | 6371331 | 2,57 % |
| 3) | 32,25 | 34,39 | 6376070 | 2,50 % |

## 4.2 Annual average load operating state

Figure 4.3 displays the summation of ENS contributed by the delivery points from different strategies for the annual average load operting state, beneath is the distribution of ENS on the delivery points in percentage.

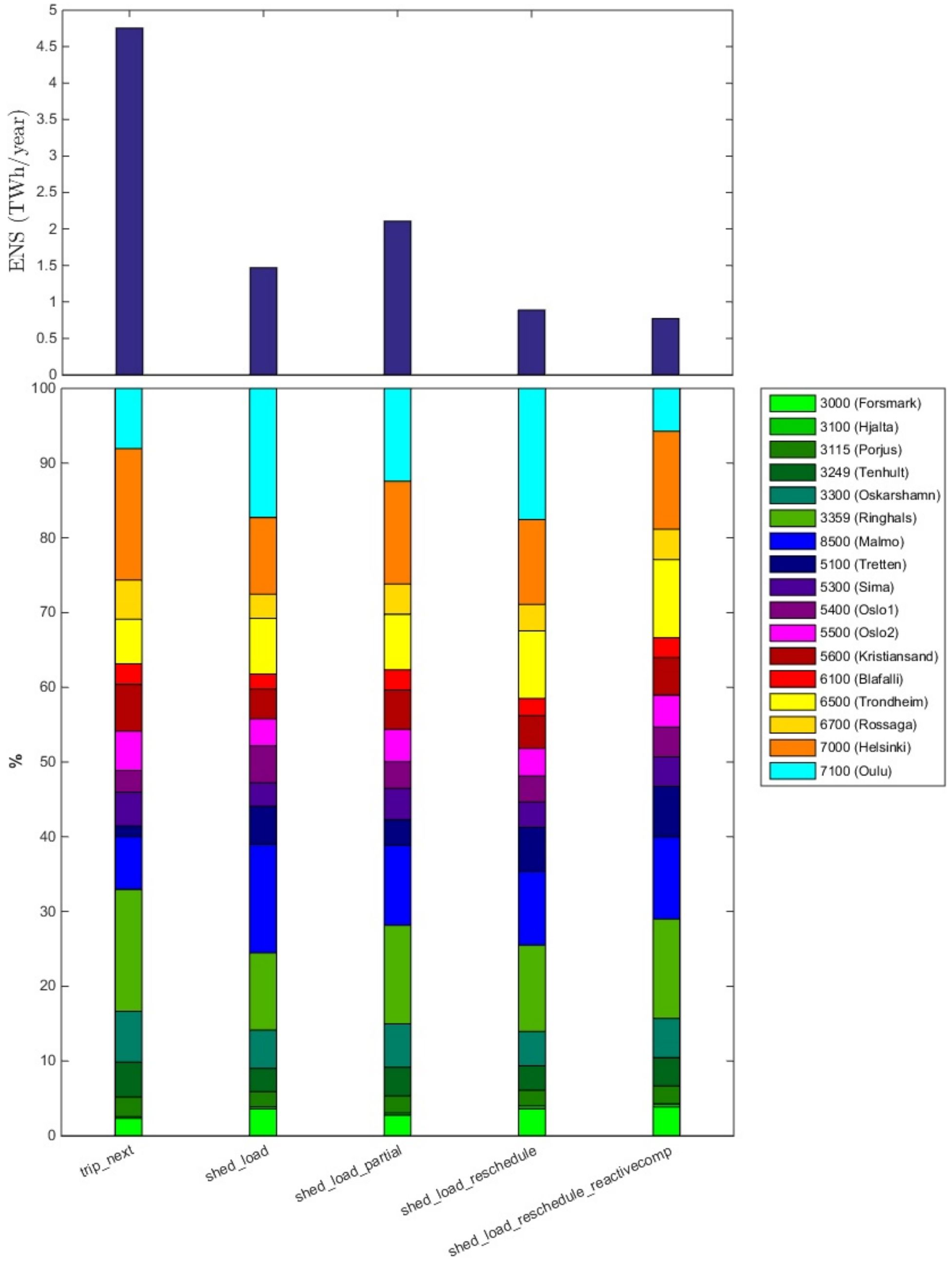

Figure 4.3: ENS for different strategies and their distribution on the DPs for average annual load case.

Main results:

- *shed_load_reschedule_reactivecomp* is the desired strategy with ENS of 0,77 TWh/year. The least desired is *trip_next* with 4,75 TWh/year.
- The distribution of ENS is evenly distributed on the delivery points.
- Reactive compensation is activated at average 153 times in the consequence analysis, 76 times at Oulu (7100) and 77 times at Skien (5501). The SVC in Skien is still insufficient to remove the over voltage, and has therefore no influence on the reliability indices. On the other hand compensation at Oulu (7100) reduces the total ENS by 13,27 %, especially the adequacy at Oulu (7100) is improved when enabling *shunt_compensation*, as the ENS is reduced by 71,5% at the bus.
- For the desired strategy, there were an average of 33 contingencies leading to blackout. Some of the operating states representing the case had blackouts caused by first order branch outage of transformator on branch 5300 - 5301. At average there were 9 interruptions of load due to first order outages in the consequence analysis, contributing a total of 0,74 TWh/year to the ENS. Consequently the contribution to ENS from first order outages counts for 96 % of the total ENS.

The sensitivity figure 4.2 is also made for the annual average load operating state, depicted in figure 4.4. The result points out the same trends when disabling/enabling the corrective actions options as for the high load operating state, which indicate the effectiveness and robustness for the corrective action options under different operating states. The annual average load operating state seems to be more ENS sensitive for disabling distribute slack than for the high load operating state. Reactive compensation is a less important corrective action option for this case, due to less loaded transmission lines, which reduces the reactive power absorbed from the system.

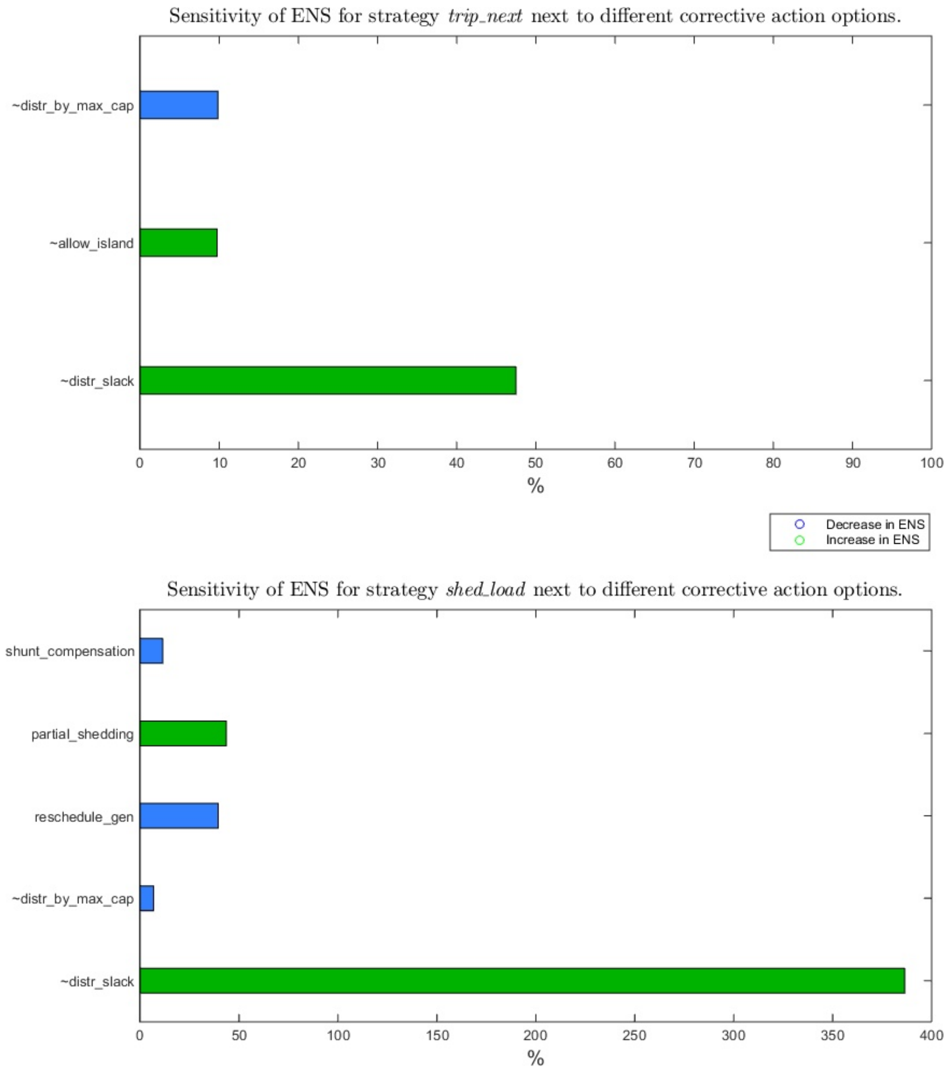

Figure 4.4: Sensitivity of ENS for base case strategies to other corrective action options for the average annual load case.

## 4.3 Low load operating state

Figure 4.3 displays the summation of ENS contributed by the delivery points from different strategies for the low load operating state, beneath is the distribution of ENS on the delivery points in percentage.

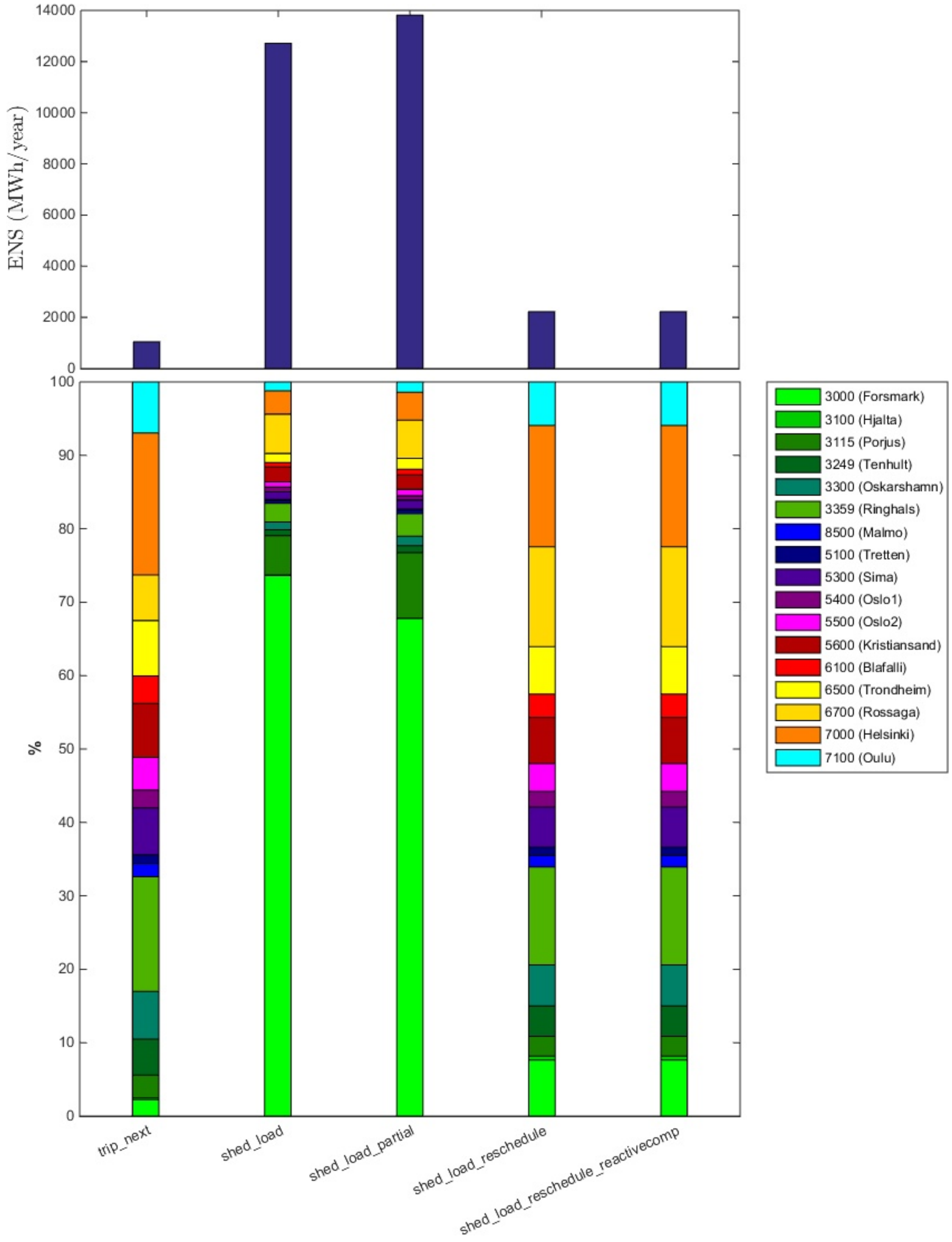

Figure 4.5: ENS for different strategies and their distribution on the DPs for low load case.

Main results:

- *trip_next* is the desired strategy in terms of ENS with 1048 MWh/year. The least desired strategy is *shed_load_partial* with 13816 MWh/year.
- The system is N-1 secure for the low load operating state. There were only 2 contingencies causing interruption of load for the desired strategy, both due to double branch outages.
- Yet there is over voltage issues at Skien (5501), reactive compensation from the SVC is not improving the systems adequacy.

To investigate why *trip_next* was better off than *shed_load_reschedule* in the consequence analysis, the sequence in the consequence analysis for the strategies was followed. A typical contingency requiring corrective actions were overloading of transmission lines in southern Sweden. Strategy *trip_next* corrective action is to disconnect the overloaded transmission line, which successfully brings the system back within operational limits. Strategy *shed_load_reschedule* attempts rescheduling of generation at both ends of the overloaded line. It turns out that the amount of generation moved to the other side of the overloaded branch is insufficient to remove the overload. Consequently, the strategy turns to load shedding to resolve the problem. This sequence repeats until the overload is removed at the branch. The heuristics in the code for rescheduling generation might be to passively modelled, and might be rewritten so that load shedding is only considered as a last resort for low load operating states.

## 4.4 "Vårknipa" operating state

Figure 4.3 displays the summation of ENS contributed by the delivery points from the different strategies for the "Vårknipa" operating state, beneath is the distribution of ENS on the delivery points in percentage.

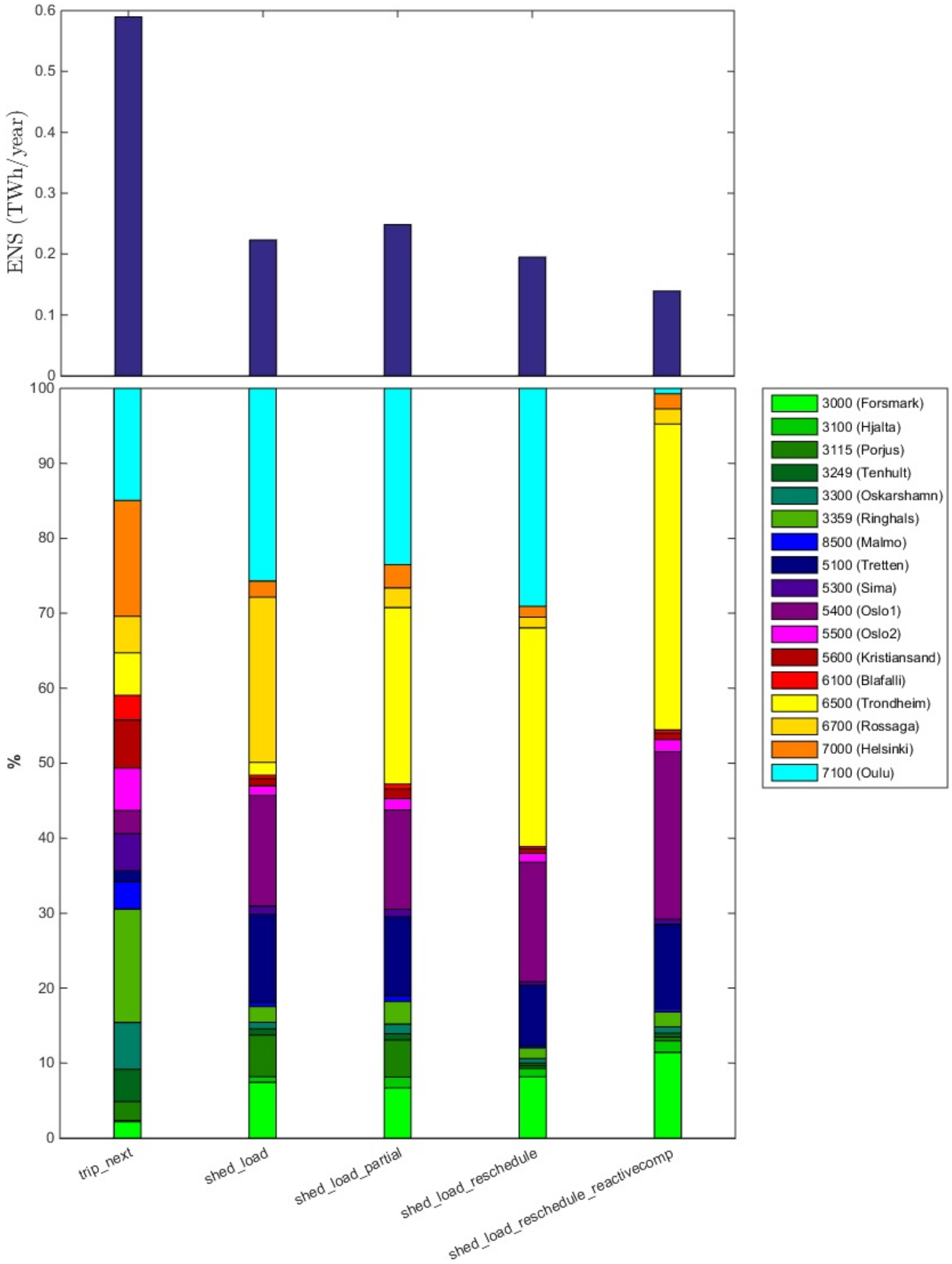

Figure 4.6: ENS for different strategies and their distribution on the DPs for "Vårknipa" case.

Main results:

- The desired strategy in terms of ENS is *shed_load_reschedule_reactivecomp*, with a total of 139333 MWh/yr.
- The least desired strategy in terms of ENS is *trip_next*, with total of 589848 MWh/yr.
- For the desired strategies the contribution to ENS is largest from Trondheim (6500) and Oslo1 (5400). This makes sense due to the pressured situation in the area for this operating state.
- Reactive compensation is needed 77 times in Skien (5501) and 2 times in Oulu (7100). The SVC at Skien (5501) is still insufficient to influence the reliability indices. On the other hand compensation at Oulu (7100) reduces the systems ENS by 28,5%.
- 5 of the 3184 contingencies led to blackout (i.e. system failure) for the desired strategy, all by second order branch outages. There were 5 first order branch outages causing load interruptions, consequently contributing 14% to the total ENS.

# 5. Discussion

## 5.1 The Nordic44 model

From the case studies, it is evident that assessing the Nordic power systems adequacy based on the Nordic44 model is incorrect. The Nordic power systems real ENS in 2014 was approximately 5500 MWh/year [7]. For the annual average load the ENS for the desired strategy was 770000 MWh/year, their magnitudes are not even comparable. The results implies that the model is not N-1 secure in its current version as there is too many first order outages causing load interruptions. The operating states representing 2015 indicated that the problem with reliability comes from the models capability to match the market data from Nord Pool Spot. Consequently, the system is already pushed to its limits even before contingencies occurs in the consequence analysis. The corrective actions applied will therefore have issues bringing the system back within operational limits, thus resulting in load shedding and blackouts. Most of the operational limits breached, both in normal operation and in contingency states, relates to overloading of transmission lines and generator active generation exceeded (table 3.4). Also first order outages of the transformator on branch 5301-5300 contributes a lot to the systems energy not supplied.

## 5.2 Corrective actions performance

Although the reliability indices are unrealistic, the relative differences of the strategies performance is comparable. The strategies tested can be ranked in terms of ENS, based on the trends from the case studies as follows:

Table 5.1: Ranking of strategies in terms of energy not supplied (ENS).

| **Ranking:** | **Strategy:** |
|---|---|
| Highest ENS | *trip_next ~ distr_slack* |
| $2^{nd}$ highest ENS | *trip_next* |
| $3^{nd}$.. | *trip_next ~ distr_by_max_cap* |
| ... | *shed_load_partial* |
| ... | *shed_load* |
| ... | *shed_load + shunt_compensation* |
| ... | *shed_load_reschedule* |
| $2^{nd}$ lowest ENS | *shed_load_reschedule_reactivecomp* |
| Lowest ENS | *shed_load_reschedule_reactivecomp*<br>*~ distr_by_max_cap* |

The ranking of corrective action options has many similarities with the results in *Modelling of corrective actions in reliability analyses* [3], which implies that the modelling of corrective actions in OPAL is applicability for larger power systems.

Main findings:

- Allowing partially load shedding is worse off than shedding all load.
- Allowing reactive compensation is crucial for systems adequacy during high and annual average load operating states. Compensation is mostly done at Oulu (7100).
- The strategies applied by the operator will depend on the operating state analysed. For the low load operating state strategy *trip_next* was most effective.
- Modelling choice of distribution of slack on generators has some influence on the adequacy.
- Allowing operation in island operation is insignificant for the adequacy, as the probability to get islands in the consequence analysis is minimal for large meshed power systems, which the Nordic44 model represent.

### 5.2.1 Distributed slack

Having possibility to distribute slack on all the generators, and not only at the swing bus, was proven important in the case studies. Especially the annual load operating state was very ENS sensitive to distributed slack. The results indicated also some benefits of distributing over- or underproduction at generators by their maximum capacity (*distr_by_max_cap*), instead of distribution according to the remaining generator capacity (*distr_slack*). Using distribute by max capacity reduced the ENS by reducing the number of load interruptions, but increased the number of blackouts. The use of distribute slack by their maximum capacity seems to cause less overloading of nearby transmission lines in the consequence analysis, resulting in improved adequacy.

### 5.2.2 Load shedding

Full or partially load shedding is generally improving the adequacy for the system, except for low load operating states. Corrective actions by load shedding is therefore an effective way to improve systems reliability. In *Modelling of corrective actions in reliability analyses* [3], which analysed smaller power systems, the results indicated that partially load shedding is better off than shedding all load in terms of ENS for a delivery point. The results from the case studies contradict these results. In the case studies, partially load shedding was not able to restore operational limits where full load shedding is. Consequently, partially shedding the load will move the consequences of contingencies, which initially concerned one delivery point, to concern several. This results in a vast increase in number of load interruptions and reduced adequacy.

### 5.2.3 Reactive compensation

The reactive compensation strategies implemented in OPAL has proven to be important in improving systems adequacy. The need for reactive compensation in the consequence analysis is highest during high load operating states, where the reactive consumption is high due to the heavy loading of transmission lines. The most used corrective action option is *shunt_compensation*, which is used to relieve the generators reactive power production at Oulu (7100), by injecting reactive power through shunt capacitors and SVCs. Corrective action option *SVC* was frequently called for several operating states due to over voltages at Skien (5501). Lowering the voltage was difficult within reasonable amount of compensation. Regardless, having the required amount of compensation would not influence the reliability indices considerably, due to the large contribution of ENS from first order outages. For the high load operating state 2/3 of the contingencies analysed experienced issues with reactive power, which emphasize that the Nordic44 model is sensitive to reactive power limits. The reactive compensation strategies mostly reduced the number of interruptions per year, i.e. reducing the number of minimal cuts that causes load interruptions.

The prototype by rescheduling reactive power to remove transmission line overloads seems to be beneficial for systems adequacy. The simple heuristics is effective, without any optimisation techniques. The implementation of reactive rescheduling should therefore be developed further. Questions that should be asked in doing so are; is it optimal to have the possibility to use reactive rescheduling at all PQ buses? How should the heuristic guess the optimal amount of compensation? How can reactive rescheduling be implemented at PV buses? The characteristics of PV buses neglect the affect off reactive compensation, as their goal is to maintain voltage magnitude at the expense of reactive power. An solution is to make a temporary PQ bus in short proximity to the PV bus and do the compensation there.

### 5.2.4 Limitations

Some limitations constrained the accuracy and analysis extent for the case studies; the main limitations are listed underneath.

- The Nordic44 models issues matching real generation, consumption and exchanges from Nord Pool Spot has been a general limitation to the results in thesis. Both in obtaining suitable operating states for modelling of corrective actions, as well as not having the possibility to assess all operating states in 2015.
- Computational time has also been limiting the analysis extent, ideally, several different strategies for numerous operating states should be analysed, but this causes a very high

computational time. Not being able to assess several operating states (e.g. weeks) in the consequence analysis will consequently influence the credibility of the results.

- None of the strategies has included corrective action options by optimal power flow (OPF) algorithms. It is not used, as it is a comprehensive task to be able to set constraints for the OPF model to match the flows from Nord Pool Spot. As a start, the OPF model should include the area spot prices from Nord Pool Spot.
- The voltage limits set in the Nordic44 model will reduce the need for reactive compensation in voltage limits exceeded contingencies. Only a few contingencies caused voltage limits exceeded in the case studies, this might be different under a stricter operational limit (i.e. under a more realistic voltage operational limit).
- The number of first order outages affecting the reliability indices will hide some behaviors of the corrective action options, e.g. compensation at Skien (5501) (if adequate) would actually be an important corrective action if there was only second order outages causing load interruptions.

# 6. Conclusion and further work

The results in this thesis confirms that the Nordic44 model is an unreliable power system. It is evident that the model is not optimized for reliability studies. Consequently, the reliability indices will not be accurate in assessing the Nordic power systems adequacy in 2015. The fact that 57 % of the operating states in 2015 are unfit for the OPAL methodology implies the extent of the issue. Nevertheless, the performance of the corrective actions in case studies emphasize a common trend with previous analysis, which indicates that the modelling of corrective actions are generally robust, and not particular given to one test network. The implemented modelling of reactive compensation as a corrective action proves to be very beneficial for adequacy for the high load situations, and is essential to reduce load shedding and blackouts in the consequence analysis for these operating states. For the more low load operating states there are little to none benefits from reactive compensation.

This thesis has implemented several new features for the OPAL methodology. It has made it possible to run reliability analysis in OPAL on large power systems, consisting of internal/external HVDC cables and internal exchanges. A script was written to extract desired operating states for reliability analysis, as well as an automatic script to calculate average reliability indices for the operating states in analysis. The automatic script can be used to run a full year analysis, or even several years, but is limited by the computational time of OPAL. The corrective actions by reactive compensation has been further developed and adapted for larger systems, including the new corrective action options *SVC* and *reschedule_reactive*. To motivate for further work on modelling of corrective actions in OPAL and further development of the Nordic44 model, a few bullet points has been added underneath to highlight the most important areas to look into:

- Making the Nordic44 model N-1 secure should be most prioritized in further work. This will include reworking of transmission line capacities in the model and improving steady-state voltage stability.

- Adding outages of HVDC cables in the outage list. To do so obtaining fault statistics for HVDC cables, and rewrite the script *reducecont.m* to be able to handle bus outages.

- Further development of the corrective action *reschedule_reactive*. Suggestions for further work: determine location for compensation, test different compensation amounts in the heuristics and include the feature of reactive rescheduling at PV buses by adding temporary PQ bus in short proximity to the PV bus.

- Finding exact reactive compensation in the network. For now, there has only been done a brief survey on available compensation regarding SVCs and shunt compensation. This would be especially useful for further development of *reschedule_reactive*. Also for the other corrective actions assuming the limitations with the Nordic44 model are dealt with.

- A mistake was done in finding fault statistics for the Nordic44 model for the 300 kV part of the network. The mistake was not seen before all the results were obtained. It is therefore recommended for further analysis of the Nordic44 model to redo the fault statistics. A redo is only necessary if the issues with the Nordic44 model are fixed, as the accuracy of fault statistics is only important when the system is N-1 secure, and thus comparable to the real Nordic power system adequacy.

- Having the possibility to use corrective actions by optimal power flow should also be looked into. The OPFs constraints should than include the Nord Pool Spot price areas.

# References

[1] G.H. Kjølle, O. Gjerde *The OPAL methodology for reliability analysis of power systems* SINTEF Energy Research, Trondheim TR A7175, 2012

[2] G.H. Kjølle, O. Gjerde, http://www.sintef.no/globalassets/upload/energi/nyhetsbrev/security-of-electricity-supply---analysis-tools.pdf

[3] I. B. Sperstad, S. H. Jakobsen, A. Oftebro *Modelling of corrective actions in reliability analyses* SINTEF Energy Reasearch, Trondheim AN 14.12.74, 2014

[4] L. Vanfretti, S.H. Olsen, V. S. Narasimham Arava, G. Laera, A. Bibadafar, T. Rabuzin, J. Lavenius, and M. Baudette, *"An Open Data Repository and a Data Processing Toolset of an Equivalent Nordic Grid Model Matched to Historical Power Flow Data,"* submitted for publication, Data in Brief, 2016.

[5] L. Vanfretti, T. Rabuzin, M. Baudette, M. Murad, *iTesla Power Systems Library (iPSL): A Modelica library for phasor time-domain simulations*, SoftwareX, Available online 18 May 2016, ISSN 2352-7110,http://dx.doi.org/10.1016/j.softx.2016.05.001.

[6] SINTEF Energi AS *Tekniske data, from Planleggingsbok for kraftnett* 2010

[7] REGIONAL GROUP NORDIC *Nordic and baltic grid disturbance statistics 2014* European Network of Transmission System Operators for Electricity

[8] Avdeling for vern og feilanalyse *Årsstatistikk for 20015 33-420 kV nettet* Statnett SF

[9] *http://new.abb.com/docs/librariesprovider78/chile-documentos/jornadas-tecnicas-2013—presentaciones/4-jos%C3%A9-matias—reactive-power-compensation.pdf?sfvrsn=2* Lest 27.11.2016

[10] L. Vanfretti, N. Arava, T. Rabuzin *Updates on Statnett-A Use-Case* SmarTS Lab

[11] *http://www.nordpoolspot.com/How-does-it-work/Bidding-areas/* Lest 10.01.2017

[12] K. Uhlen, 18.11.2016, talk on SVCs in Norway.

[13] S. Nordhagen *Implementing reactive compensation as a corrective action in OPAL* Project Work, Autumn 2015.

[14] R. Billington, W. Li *Reliability Assessment of Electric Power Systems Using Monte Carlo Methods* New York: Plenum, 1994

[15] L. Grigsby *Electric Power Generation, Transmission, and Distribution, 3rd Edition* CRC Press, 2012.

[16] G. Andersson *Dynamics and Control of Electric Power Systems* EEH - Power Systems Laboratory, ETH Zürich, February 2012, pp. 93-98

[17] J. Dixon, L. Moran, J. Rodriguez, R. Domke *Reactive Power Compensation Technologies: State-of-the-Art-Review* IEEE, Vol: 93 Issue: 12. Dec. 2005.

[18] J. Glover, M. Sarma, T. Overbye *Power system analysis and design fifth edition* CENGAGE Learning, 2010.

[19] SINTEF Energi AS *Leveringspålitelighet from Planleggingsbok for kraftnett* 2010

[20] F. Trengereid, Statnett *Email correspondence*November, 2015.

[21] All data processing was performed using a commercial software package (MATLAB R2014B, 1994-2017 The MathWorks, Inc.).https://se.mathworks.com/products/matlab.html

[22] SmartTS lab, Research group leader: Luigi Vanfretti http://www.eps.ee.kth.se/personal/vanfretti/Luigi_Vanfrettis_Website/SmarTS_Lab.html

[23] Ray D. Zimmerman, Carlos E. Murillo-Sánchez others http://www.pserc.cornell.edu/matpower/ 1997-2016 PSERC

[24] *http://new.abb.com/systems/hvdc/references/norned*
*http://new.abb.com/systems/hvdc/references/skagerrak*
*http://new.abb.com/systems/hvdc/references/konti-skan*
*https://en.wikipedia.org/wiki/Baltic_Cable*
*http://new.abb.com/systems/hvdc/references/swepol-link*
*http://new.abb.com/systems/hvdc/references/estlink*
*https://en.wikipedia.org/wiki/Vyborg_HVDC_scheme*
*http://new.abb.com/systems/hvdc/references/fenno-skan*
Lest: 05.12.2016

[25] S.A. Solheim *Probabilistic Reliability: A State of the Art Study* Masther thesis, January 2009.

# A. Appendices

## A.1 Numerical results from the case studies

The numerical results from the case studies are found in the digital attachments of this thesis. Inside sub-folder *01.Results*.

## A.2 Terms, definition and list of abbreviations

### A.2.1 Terms and definitions

**Corrective action options**

Most of the definitions are obtained from *Modelling of corrective actions in reliability analysis* [3].

| | |
|---|---|
| *iterate* | The number of corrective actions iterations allowed [3]. |
| *shunt_compensation* | Compensation by shunt capacitors or shunt reactors in the consequence analysis. If not available shunt at the worstcase bus, the corrective action option next searches for available SVC at *worstcase* before synchronous condensers. |
| *SVC* | Compensation by SVC in response to either voltage or reactive power limits exceeded at the *worstcase* bus. |
| *synchronous_condenser* | Compensation by synchronous condenser in response to either voltage or reactive power limits exceeded at the *worstcase* bus. |

| | |
|---|---|
| *reschedule_reactive* | Option to try reactive power rescheduling before considering other corrective actions (as line tripping or load shedding). |
| *reschedule_gen* | Option to try generator rescheduling before considering other corrective actions (as line tripping or load shedding) [3]. |
| *load_shedding* | Option to allow load shedding as a corrective action. If activated shedding all load at a delivery point, by choosing the set of load poitns supplied by the overloaded line or generator that gives the smallest loss of load [3]. |
| *allow_islanding* | Wheter one should allow island operation of a subsystem not including the original swing bus of the system. If false all load for subsystem is lost [3]. |
| *distr_slack* | If true, the over- or underproduction (slack) due to contingencies is distributed on all generators and not just the swing bus [3]. |
| *distr_by_max_cap* | If true, trying to distribute any over- or underproduction by maximum capacity of the generator, thus limiting the generation to their max and min limits [3]. |
| *bfk* | Disconnection of load according to agreements [3]. |
| *trip_next* | If true, tripping the most overloaded line. Alternative is blackout [3]. |
| *opf* | Using optimal power flow algorithms as corrective actions. Using load, generation, voltage magnitude and angles as optimisation variables. Generation cost and interruption cost is also included in the objective function. Not releveant for Nordic44 model as it will change the flow between areas (you must include price areas in the opf to do so correctly) [3]. |
| *all_pot_swing_bus* | Whether all generation buses should be allowed to function as swing buses if necessary [3]. |

| | |
|---|---|
| *partial_shedding* | If true, only the necessary load to remove the overload is shed at the delivery points. Only activated if shed_load is true [3]. |
| *shed_closest* | If true, atempt to shed load closest to the overloaded line or generator outside its limits [3]. |
| *shedding_also_gen* | If true, atempt to reduce generation if shed_load is true due to line overload. Its better to try to shed generation at closest generators instead of shedding load to bring the system back within limits [3]. |
| *reschedule_gen_opf* | If true, generation rescheduling is done using optimal power flow [3]. |
| *pfk* | Disconnection of generators according to agreements [3]. |

## General definitions

Most of the following general definitions are obtained from *The OPAL methodology for reliability analysis of power systems* [1], for references look Appendix A.1.1 Terms and definitions in [1].

| | |
|---|---|
| *Strategy* | A strategy is combinations of corrective action options A.2.1. Can be defined as an operators set of corrective actions that can be used to restore normal operation after a contingency. |
| *worstcase* | The power system component (branch or bus) which breaches operational constraints in the consequence analysis. The breaches can be: generation is less than load, branch flows are out of bounds, generator active or reactive power limits are out of bounds or bus voltages are out of bounds. |
| *Transmission branch* | A component, either a transmission line or transformator, where electric power is transmitted. |
| *PQ bus* | Load bus. P and Q are specified. |
| *PV bus* | Generator bus. P and V are specified. Voltage magnitude is kept at its given magnitude by adjusting reactive power, Q. |

| | |
|---|---|
| *Component* | A *component* is a device which performs a major operating function and which is regarded as an entity for purposes of recording an analysing data on outage occurrences. Examples: line sections, transformers, shunt capacitors or reactors and SVC [1]. |
| *Contingency (outage event)* | A *contingency* is an unplanned *outage* of one or more primary equipment components, i.e. one ore more primary components are in the outage state [1]. |
| *Delivery point* | A *delivery point* is a point in the network where electrical energy is exchanged [1]. |
| *Energy not supplied (ENS)* | The estimated amount of energy that would have been supplied to the end-user if the supply *fault* did not occur [1]. |
| *Failure, fault* | A *failure* is the termination of the ability of an item to perform a required function. After failure, the item has a *fault* [1]. |
| *Fault rate* | The *fault rate* is the number of faults of a continuously required function (of a component), pr unit of time exposed to such faults = number of faults of a particular type pr unit exposure time. The fault rate is usually expressed in faults per year [1] [1]. |
| *Interruption* | A condition characterized by missing or reduced supply of electric energy to one or more end users [1]. |
| *Minimal cut set* | A set of components that, if removed from the system, results in loss of continuety to the delivery point being investigated and does not contain as a subset any set of components that is itself a cutset of the system [1]. |

---

[1] Fault rate is usually measured as an average over several years in adequacy studies and long term planning purposes

| | |
|---|---|
| *Operating state* | A system state valid for a period of time, characterized by load and generation composition including the electrical topological state and import/export to neighbouring areas [1]. |
| *Outage* | A state of a component or system when its not available to properly perform its intended function due to an event [1]. |
| *Outage state* | Is when the component or unit is not in the in-service state. Either partially or fully isolated from the system [1]. |
| *Outage time* | The accumulated time in which one or more components or units are in the outage state during the reporting period. In OPAL outage time represents the repair time for a single component or the equivalent outage time for a minimal cut set [1]. |
| *Reliability of a power system* | *Reliability* is the degree to which the performance of the elements of that system results in power being delivered at consumers within accepted standards and the amount demanded. The degree of reliabiliy can be measured by frequency, duration and magnitude of adverse effects on the consumer service. Reliability may be divided into *power system security* and *power system adequacy* [1]. |
| *Power system adequacy* | The ability of the system to supply the aggregate electric power and energy requirements of the customers at all times, taking into account scheduled and unscheduled outages of the system components [1]. |
| *Repair time* | The mean time to repair or replace a failed component. The most common unit for repair time is hours. Administrative delay is not included [1]. |

| | |
|---|---|
| *Security of electricity supply (SoS)* | The abilitity of an electricity system to supply final customers with electricity. Can be divided into long-term and short-term security of supply [1]. |
| *System available capacity (SAC)* | The available capacity to supply a certain load after the occurrence of specific contingency [1]. |

### A.2.2 List of abbreviations and symbols

| | |
|---|---|
| $\lambda$ | Number of faults per year for components. |
| r | Repair/outage time for components, in hours pr fault. |
| | Or average interruption duration for delivery points, in hours pr interruption. |
| U | Annual interruption duration for delivery points, in hours pr year. |
| ENS | Energy not supplied, in MWh or TWh. |
| $P_{interr}$ | Interrupted power, in MW. |
| IC | Interruption cost, in NOK. |
| $c_{DP}(r)$ | Specific interruption cost as a function of duration r, in NOK/kWh. |
| APC | Available power capacity, in MW. |
| SAC | System available capacity, in MW. |
| LG | Local generation, in MW. |
| DP | Delivery points |
| OS | Operating state |
| P | Load, in MW. |
| SVC | Static Var Compensator |
| OS | Operating state |

### A.2.3 Default values for corrective action options

Table A.1: Corrective action options in the consequence analysis

| | **Default value** | |
|---|---|---|
| **Corrective action option** | **Enabled/true** | **Disabled/false** |
| *trip_next* | x | |
| *allow_islanding* | x | |
| *distr_slack* | x | |
| *distr_by_max_cap* | x | |
| *load_shedding* | | x |
| *partial_shedding* | | x |
| *shed_closest* | | x |
| *shedding_also_gen* | | x |
| *reschedule_gen* | | x |
| *reschedule_gen_opf* | | x |
| *opf* | | x |
| *all_pot_swing_bus* | x | |
| *bfk* | | x |
| *pfk* | | x |

## A.3 Statnett strategy scheme for over and under voltages

Table (A.2) and Table (A.3) shows the prioritised order of corrective actions for under and over voltages at Statnett, from [13].

Table A.2: Actions are ranked from the preferred one (1) to the last resource (12) [13].

| **Over-voltages** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Device / Action** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| Line Reactors | | | | | | | | | | | | x |
| Changing Transformer taps | | | | | x | | | | | | | |
| Connection of lines | | | | | | | | | | | | x |
| Disconnection of lines | | | | | | x | | | | | | |
| Serial Capacitors | | | | | | | | | | | | x |
| Disconnection of open ended lines | x | | | | | | | | | | | |
| Shunt capacitors & reactors | | x | | | | | | | | | | |
| SVC´s | | | x | | | | | | | | | |
| Using Synchronous Groups(*) | | | | | | | | | | | | |
| Moving PV nodes to Synchronous Groups | | | | | | | | | | | | x |
| Changing generator´s set-points | | | | x | | | | | | | | |
| Lowering Active Power transmission | | | | | | | | | | | | x |

Table A.3: Actions are ranked from the preferred one (1) to the last resource (12) [13].

| **Under-voltages** | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Device / Action** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| Shunt Capacitors & Reactors | x | | | | | | | | | | | |
| Line Reactors | | | | | | | | | | | | x |
| Connection of Transformers | | | | | | | | | | | x | |
| Changing Transformer Taps | | | | x | | | | | | | | |
| Connection of lines | | | | | | x | | | | | | |
| Connection of open ended lines | | | | | | | x | | | | | |
| Load shedding | | | | | | | | x | | | | |
| SVC´s | | x | | | | | | | | | | |
| Using Synchronous Groups | | | | | | | | | | | | x |
| Moving PV nodes to Synchronous Groups | | | | | | | | | | | | x |
| Changing generator´s set-points | | | x | | | | | | | | | |
| Lowering Active Power transmission | | | | | x | | | | | | | |

## A.4 Calculation of number of interruption per year for overheaded lines

Example calculation for branch 1 and 2 when calculating fault rate, $\lambda$ (no/yr). The calculations are approximations, as the transmission line type (duplex, simplex etc.) has great influence on the resulting length. The line data for a common duplex is used from [6].

Branch 1: Forsmark (3000) to FennoScan (3020)

$$R_{420kV,duplex} = 0,32\ \Omega/km,\ Z_{pu} = \frac{420\,kV^2}{1000\,MVA},\ X_{branch\,1,pu} = 0,1$$

$$length_{branch\,1} = \frac{X_{branch\,1,pu} * Z_{pu}}{X_{420kV,duplex}}$$

$$length_{branch\,1} = \qquad 5,51\ km$$

$$\lambda_{branch\,1} = \qquad 5,51 * 0,0044\ \frac{no}{yr * km} * km$$

$$\lambda_{branch\,1} = \qquad 0,0025\ \frac{no}{yr}$$

Branch 2: Forsmark (3000) to Porjus (3115)

$$R_{420kV,duplex} = 0,02\ \Omega/km,\ Z_{pu} = \frac{420\,kV^2}{1000\,MVA},\ R_{branch\,1,pu} = 0,075$$

$$length_{branch\,1} = \frac{X_{branch\,1,pu} * Z_{pu}}{X_{420kV,duplex}}$$

$$length_{branch\,1} = \qquad 5,51\ km$$

$$\lambda_{branch\,1} = \qquad 661,5 * 0,0044\ \frac{no}{yr * km} * km$$

$$\lambda_{branch\,1} = \qquad 2,91\ \frac{no}{yr}$$

## A.5 Matlab code

### A.5.1 *main_all_OS.m*

```
%====================================================================================
%To run this script you must:
%   1. Specify the path of the folder containing the
%      operating states (myFolder = "folder containing operating states").
%   2. Specify which days and hours you would like to analyse:
%       *Day is specified like: k = Start Day : End day
%           If Start day = 1, its the first folder in myFolder etc.
%       *Hour is specified like: i = Start hour : End hour.
%   3. Run the script, and the average reliability indices for the
%      operating states choosen to analyze is printed on the screen.
%====================================================================================
%   - To set which corrective actions that should be active, open n44x.xls and
%     go to the sheet "actions" (0 = disabled, 1 = enabled).
%
%   - Also default settings, etc. debth of contingencies, is found in sheet "general"
%     in n44x.xls.
%
%   - Activating reactive compensation as a corrective action is done in
%     sheet "actions". To add new reactive compensation device:
%           * If add shunt compensator:
%                1. Got to sheet "shunts". Enable shunt compensation possible at the
%                   bus you want compensation. And set the ratings for the component.
%           * If add SVC or SC:
%                1. Go to sheet "SVC" or "Synchronous condenser". Enable compensation
%                   at the bus in question and set ratings.
%                2. At the end of "gen" and "gencost" sheet add a disabled
%                   generator with same ratings as the SVC/Synchronous
%                   condenser.
%====================================================================================
% Specify the folder where the operating states are:
```

```
myFolder = 'c:\users\sindrewn\desktop\Masterfiler\PSSE_Resources'; %Set path here.

RelDa; %Emptying the temporary storage of the results.

if ~isdir(myFolder)
    errorMessage = sprintf('Error: The following folder does not exist:\n%s', myFolder);
    uiwait(warndlg(errorMessage));
    return;
end

subdirs = dir(myFolder);
subdirs(~[subdirs.isdir]) = [];
tf = ismember( {subdirs.name}, {'.', '..'});
subdirs(tf) = [];
numberOfFolders = length(subdirs);
%=====================================================================================
for k = 1:numberOfFolders
    %High load case: set k = [62,338], hour = 12:12
    %Low load case: set k = 207:207, hour = 5:5
    %Annual average case: set k = 91:91, hour = 1:length(theHours)
    %"V rknipa" case: set k = 60:60, hour = 7:7
    %A year: set k = 1:numberOfFolders, hour = 1:length(theHours)
    %Voltage problems skien: k = 194:194 i = 8:8

    baseFileName = subdirs(k).name;
    fullFileName = fullfile(myFolder, baseFileName);
    fprintf(1, 'Now reading %s\n', fullFileName);

    filePattern = fullfile(fullFileName, 'h**_after_PF.raw');
    %Extracting the operating state after power flow for the 24 h day.
    theHours = dir(filePattern); %This is not sorted from hour 0 to 23.
    names = {theHours.name};
    stripped_names = strrep(names,'h','');
    stripped_names = strrep(stripped_names,'_after_PF.raw','');
    [~,idx] =     sort(str2double(stripped_names));
    NewHours = theHours(idx); %Sorted.
```

```

    for i = 1:length(theHours)
        FullStiTime = fullfile(fullFileName,NewHours(i).name); %Path
        %for the file to convert.
        mpc = psse2mpc(FullStiTime); %Convert from psse .raw to mpc.

        x = runpf(mpc);
        [l,type,worstcase] = pf_checklims(x.bus,x.branch,x.gen);
        if any(l)
            continue;
        end

        branchExchangeintern = [7000 7030 0 0.00001 0 1500 1800...
        2100 0 0 1 -360 360;
            7100 7130 0 0.00001 0 1200 3000 3500 0 0 1 -360 360;
            6701 6702 0 0.00001 0 1200 3000 3500 0 0 1 -360 360];
        mpc.branch = [mpc.branch;branchExchangeintern];
        busExchangeintern = [7030 1 -mpc.bus(2,3) -mpc.bus(2,4) 0 0 31...
        1 mpc.bus(38,9)
            420 1 1.1 0.9;
            7130 1 -mpc.bus(37,3) -mpc.bus(37,4) 0 0 31 1 mpc.bus(41,9)...
            420 1 1.1 0.9;
            6702 1 mpc.bus(37,3) mpc.bus(37,4) 0 0 14 mpc.bus(37,8)...
            mpc.bus(37,9) 420 1 1.1 0.9];
        mpc.bus = [mpc.bus;busExchangeintern];

        mpc.bus(38,3) = mpc.bus(38,3) - busExchangeintern(1,3);
        mpc.bus(38,4) = mpc.bus(38,4) - busExchangeintern(1,4);
        mpc.bus(41,3) = mpc.bus(41,3) - busExchangeintern(2,3);
        mpc.bus(41,4) = mpc.bus(41,4) - busExchangeintern(2,4);
        mpc.bus(37,3) = mpc.bus(37,3) - busExchangeintern(3,3);
        mpc.bus(37,4) = mpc.bus(37,4) - busExchangeintern(3,4);

%====================================================================================
        % Set "Calculate Reliability indices?" to zero for HVDC
        %and internal exchanges.
```

```

        indexReliability = ones(length(mpc.bus),1);
        no_dp = [3360;5610;5620;7010;7020;8600;8700;3020;7030;7130;6702];%11 DPs.
        [busnum1,busidx1] = intersect(mpc.bus(:,1),no_dp);

        for j = 1 : numel(busidx1)
            indexReliability(busidx1(j))=0;
        end
        filename = 'n44x.xls';
        xlswrite(filename,indexReliability,3,'E4'); %List of dps not included in
        %"calculate reliability indices".
%=====================================================================================
        %EXPORTING TO EXCEL FILE:
%=====================================================================================
        xlswrite(filename,mpc.bus,8,'B3'); %Writing bus data.
        xlswrite(filename,mpc.gen,9,'B3'); %Writing gen data.
        xlswrite(filename,mpc.branch,10,'B3'); %Writing branch data.
        xlswrite(filename,mpc.gen(:,2),4,'C4'); %Writing to gendata.
        xlswrite(filename,mpc.bus(:,3),3,'F4'); %Writing to loaddata.

        %RUNNING OPAL METHODOLOGY:
%=====================================================================================
        opal = opalData(filename,false,'', true); %Set up the opal sys.
        cont_res = opalcons(opal,false,[],[],true); %Contingency analysis.

        [aggres,cutres]=reliabilitycalc(opal,false,false); %Reliability calc.


    end

end
%Printing results to screen.
load('RelDa.mat')
Relindices_avg = RelData;
Relindices_avg(:,2:end) = RelData(:,2:end)/Antall_OS;
indices = find(Relindices_avg(:,end)==0);
```

```
Relindices_avg(indices,:)=[];
Relindices_avg(:,5)=Relindices_avg(:,4)./Relindices_avg(:,3);
fprintf('\n');
fprintf('\n================================================================================
fprintf('\n|     Reliability indices for delivery points %2d . Bus %6d
fprintf('\n================================================================================
fprintf('\n  Bus     |  Lambda      U           r       Pinterr     ENS        IC');
fprintf('\n              (No/yr)   (h/yr)   (h/interr)   (MW/yr)   (MWh/yr)   (kNOK/yr)');
fprintf('\n-------   --  -------   ------   ----------   -------   --------   ---------');
fprintf('\n--------------------------------------------------------------------------------
fprintf('\n%7d   %1d   %7.3f   %6.3f   %10.1f   %7.1f   %7.1f   %9.0f',...
    Relindices_avg(:,[1,2,3,4,5,6,7,8])');
fprintf('\n--------------------------------------------------------------------------------
fprintf('\nSUM           %7.3f   %6.3f   %10.1f   %7.1f   %7.1f   %9.0f\n\n' ,...
    sum(Relindices_avg(:,3)),...
    sum(Relindices_avg(:,4)),sum(Relindices_avg(:,4))./sum(Relindices_avg(:,3)),...
    sum(Relindices_avg(:,6)),sum(Relindices_avg(:,7)),sum(Relindices_avg(:,8)));

load('Counter.mat')
load('SCcomp.mat')
load('SVCcomp.mat')
fprintf('\n--------------------------------------------------------------------------------
fprintf('\n--------------------------------------------------------------------------------
fprintf('\nNumber of blackouts (#/OS):           %7.3f \n\n' ,Counter/Antall_OS);
fprintf('\n Avg. shunt compensation activated (#/OS):...
%7.3f   %6.3f   %10.1f   %7.1f   %7.1f   %9.0f\n\n' ,SCn/Antall_OS);
fprintf('\n Avg. SVCs activated (#/OS):...
%7.3f   %6.3f   %10.1f   %7.1f   %7.1f   %9.0f\n\n' ,SVCn/Antall_OS);

fprintf('\n--------------------------------------------------------------------------------
```

### A.5.2 *OS_finder.m*

```
%==========================================================================================
%OS_finder.m.
```

```
%   *Script used for finding operating states for the OPAL methodology, i.e
%    high load.
%Must be modified for each operating state you would like to extract, in
%this example file script for average annual OS, high load, low load and
%"Vaarknipa" is presented.
%==========================================================================================
myFolder = 'c:\users\sindrewn\desktop\Masterfiler\PSSE_Resources';%Set path here.

if ~isdir(myFolder)
  errorMessage = sprintf('Error: The following folder does not exist:\n%s', myFolder);
  uiwait(warndlg(errorMessage));
  return;
end

subdirs = dir(myFolder);
subdirs(~[subdirs.isdir]) = [];
tf = ismember( {subdirs.name}, {'.', '..'});
subdirs(tf) = [];
numberOfFolders = length(subdirs);

maxgen = 0;
maxlast = 0;
mingen = 40000;
minlast = 40000;
generationSUM = 0;
consumptionSUM = 0;
largestVaarknipa = 0;
maxlasti = 0;
MedianBest = 0;
MedianSUM = 0;
generationNO = 0;
generationSWE = 0;
generationFI = 0;
loadNO = 0;
loadSWE = 0;
loadFI = 0;
```

```
counterAntallOS = 0;
counter = 0;

for k = 1:numberOfFolders %k = start day :  end day.
  baseFileName = subdirs(k).name;
  fullFileName = fullfile(myFolder, baseFileName);
  fprintf(1, 'Now reading %s\n', fullFileName);

  filePattern = fullfile(fullFileName, 'h**_after_PF.raw');
  theHours = dir(filePattern); %This is not sorted from hour 0 to 23.
  names = {theHours.name};
  stripped_names = strrep(names,'h','');
  stripped_names = strrep(stripped_names,'_after_PF.raw','');
  [~,idx] = sort(str2double(stripped_names));
  NewHours = theHours(idx); %Sorted list from 0 - 23 hours.

%====================================Annual average day OS===========================
  if counter > 20
      if MedianSUM/counter > 41000 && MedianSUM/counter < 42300
          dag = fullFileName;
          antallOSok = counter;
          MedianBest = MedianSUM/counter;
          load('Counter.mat')
          counter = 0;
          save('Counter.mat','counter')
          MedianSUM = 0;
      else
          load('Counter.mat')
          counter = 0;
          MedianSUM = 0;
          save('Counter.mat','counter')
      end
  else
      load('Counter.mat');
      counter = 0;
      MedianSUM = 0;
```

```
      save('Counter.mat','counter')
  end
%====================================================================================
  for i = 1 : length(theHours) %Iterating through each hour in a day.
      FullStiTime = fullfile(fullFileName,NewHours(i).name);
      mpc = psse2mpc(FullStiTime); %Convert from psse .raw to mpc.

      counterAntallOS = counterAntallOS + 1;
      generationSUM = generationSUM + sum(mpc.gen(:,2)); %total generation year.
      consumptionSUM = consumptionSUM + sum(mpc.bus(:,3)); %total consumption year.
      generationNO = generationNO + sum(mpc.gen(30:62,2)); %gen nor.
      generationSWE = generationSWE + sum(mpc.gen(1:29,2)) + sum( mpc.gen(75:80,2));
      %gen swe.
      generationFI = generationFI + sum(mpc.gen(63:74,2)); %gen fi.
%====================================================================================
      x = runpf(mpc);
      [ls,types,worstcases] = pf_checklims(x.bus,x.branch,x.gen);
      if any(ls) %This checks if the OS is within system limits...
      %after initial power flow.
          load('Counter2.mat')
          counter2 = counter2 + 1;
          types_breach = [types_breach;types];
          save('Counter2.mat','counter2','types_breach')
          continue;
      end

      MedianSUM = MedianSUM + sum(mpc.bus(:,3)); %Sum of all consumption in a day.
      load('Counter.mat')
      counter = counter + 1;
      save('Counter.mat','counter')
%============================Max/min consumption and generation======================

      counterAntallOS = counterAntallOS + 1;

      generation = sum(mpc.gen(:,2)); %hour generation.
      last = sum(mpc.bus(:,3));
```

```

      if generation > maxgen
          maxgen = generation;
          currentfolderMAXGEN = FullStiTime;
      end

      if generation < mingen
          mingen = generation;
          currentfolderMINGEN = FullStiTime;
      end

      if last > maxlast
          maxlast = last;
          currentfolderMAXLAST = FullStiTime;
      end

      if last < minlast
          minlast = last;
          currentfolderMINLAST = FullStiTime;
      end
%====================================="VAARKNIPA"======================================

      genNor = sum(mpc.gen(30:62,2));
      loadNord = sum(mpc.bus(13:37,3)) - mpc.bus(37,3) - mpc.bus(31,3) - mpc.bus(30,3);

      diff = loadNord-genNor;
      if diff>0
          if diff > largestVaarknipa
              largestVaarknipa = diff;
              currentfolderVaarknipa = FullStiTime;
          end
      end
%====================================================================================


  end
```

```

end
```

### A.5.3 *corrective_actions.m*

```
%====================================================================================
%corrective_actions.m
%This is a code snippet from line 277 to 439.
%====================================================================================

if limits_exceeded == 5 || limits_exceeded == 4
    load('voltagedata.mat'); %Counter for breaches linked to reactive compensation.
    NumberVoltageBreach = NumberVoltageBreach + 1;
    BusWorstcase = [BusWorstcase;[worstcase limits_exceeded]];
    save('voltagedata.mat','NumberVoltageBreach','BusWorstcase')
    if limits_exceeded == 4
        bus_name = geno(worstcase,1);
        [bus_name, worstcase_bus] = intersect(sys.bus(:,1),bus_name);
    else
        [bus_name, worstcase_bus] = intersect(sys.bus(:,1),worstcase);
    end
    % For voltage limits exceeded or generator reactive power
    bus_num = worstcase_bus;
    bus_idx = sys.bus(:,1) == bus_name;

%====================================================================================
%Delivery point
    if sys.bus(bus_idx,3) > 0 %Worstcase is a load bus.
        if actions.shunt_compensation %The order which corrective actions reactive
            %compensation is #1 shunt #2 SVC #3 Synchronous condenser.

            [shunt_comp,svc_comp,gen_comp,no_comp] = ReactiveCompensation(sys,...
                bus_num,bus_name,bus_idx,worstcase_bus,shunts,SVC,...
                synchronous_condenser,actions,mpopt,limits_exceeded);

```

```
        if any(shunt_comp)
            if length(shunt_comp) == 1 %Activating at worstcase bus.

                load('SCcomp.mat') %Counter
                SCn = SCn + 1 ;
                SCon = [SCon;[bus_name limits_exceeded shunt_comp]];
                save('SCcomp.mat','SCon','SCn');

                sys.bus(bus_idx,6) = shunt_comp; %Inserting value into the sys.bus.
                disp(['Shunt at: ' num2str(bus_name)...
                    '  is switched on with value: ' num2str(shunt_comp) '  MVAr'])
            else %Neighbouring buses of worstcase only if voltage problem.
                sys.bus(shunt_comp(2),6) = shunt_comp(1);
                disp(['Shunt at: ' num2str(shunt_comp(3))...
                    ' is switched on with value: ' num2str(shunt_comp(1)) ' MVAr'])
            end

        elseif any(svc_comp)
            if size(svc_comp,1) == 1
                load('SVCcomp.mat') %Counter
                SVCn = SVCn + 1;
                SVCon = [SVCon;[bus_name limits_exceeded svc_comp(2)]];
                save('SVCcomp.mat','SVCn','SVCon');

                sys.gen(svc_comp(1),3) = svc_comp(2);
                sys.gen(svc_comp(1),8) = 1;
                disp(['SVC at: ' num2str(bus_name)...
                    '  is switched on with value: ' num2str(svc_comp(2)) ' MVAr'])
            end

        elseif any(gen_comp)
            if size(gen_comp,1) == 1
                sys.gen(gen_comp(1),3) = gen_comp(2);
                sys.gen(gen_comp(1),8) = 1;
                disp(['Synchronous condenser at: ' num2str(bus_name)...
                    '  is switched on: ' num2str(gen_comp(2)) ' MVAr'])
```

```
            end
        elseif any(no_comp)
            disp(['Disconnecting load at bus ' num2str(bus_name)...
                ': ' num2str(sys.bus(bus_idx,3))])
            sys.bus(bus_idx,3) = 0;
        end
    elseif actions.SVC

        [shunt_comp,svc_comp,gen_comp,no_comp] = ReactiveCompensation(sys,...
            bus_num,bus_name,bus_idx,worstcase,shunts,SVC,...
            synchronous_condenser,actions,mpopt);

        if any(svc_comp)
            if size(svc_comp,1) == 1

                load('SVCcomp.mat') %Counter
                SVCn = SVCn + 1;
                SVCon = [SVCon;[bus_name limits_exceeded svc_comp(2)]];
                save('SVCcomp.mat','SVCn','SVCon');

                sys.gen(svc_comp(1),3) = svc_comp(2);
                sys.gen(svc_comp(1),8) = 1;
                disp(['SVC at: ' num2str(bus_name)...
                    '  is switched on with value: ' num2str(svc_comp(2)) ' MVAr'])
            end
        elseif any(gen_comp)
            if size(gen_comp,1) == 1
                sys.gen(gen_comp(1),3) = gen_comp(2);
                sys.gen(gen_comp(1),8) = 1;
                disp(['Synchronous condenser at: ' num2str(bus_name)...
                    '  is switched on: ' num2str(gen_comp(2)) ' MVAr'])
            end
        elseif any(no_comp)
            sys.bus(bus_idx,3) = 0;
        end

```

```
        elseif actions.synchronous_condenser

            [shunt_comp,svc_comp,gen_comp,no_comp] = ReactiveCompensation(sys,...
                bus_num,bus_name,bus_idx,worstcase,shunts,SVC,...
                synchronous_condenser,actions,mpopt);

            if any(gen_comp)
                if size(gen_comp,1) == 1
                    sys.gen(gen_comp(1),3) = gen_comp(2);
                    sys.gen(gen_comp(1),8) = 1;
                    disp(['Synchronous condenser at: ' num2str(bus_num)...
                        '  is switched on: ' num2str(gen_comp(2)) ' MVAr'])
                end
            else
                sys.bus(bus_idx,3) = 0;
            end

        else
            % Disconnecting load, no reactive compensation actions
            % available.
            disp(['Disconnecting load at bus ' num2str(bus_num)...
                ': ' num2str(sys.bus(bus_idx,3))])
            sys.bus(bus_idx,3) = 0;
            return;
        end
    %====================================================================================
    %Not delivery point
    else
        %If no load at the bus with problems, try SVC before disconnect the
        %entire bus.
        if actions.SVC
            [shunt_comp,svc_comp,gen_comp,no_comp] = ReactiveCompensation(sys,...
                bus_num,bus_name,bus_idx,worstcase,shunts,SVC,...
                synchronous_condenser,actions,mpopt);
            if any(svc_comp)
                if size(svc_comp,1) == 1
```

```

                load('SVCcomp.mat') %Counter
                SVCn = SVCn + 1;
                SVCon = [SVCon;[bus_name limits_exceeded svc_comp(2)]];
                save('SVCcomp.mat','SVCn','SVCon');

                sys.gen(svc_comp(1),3) = svc_comp(2);
                sys.gen(svc_comp(1),8) = 1;
                disp(['SVC at: ' num2str(bus_name)...
                    '  is switched on with value: ' num2str(svc_comp(2)) ' MVAr'])
            end
        elseif any(no_comp)
            bus_num = worstcase;
            disp(['Disconnecting bus: ' num2str(bus_num)])
            branch_idx = sys.branch(:,1) == bus_num | sys.branch(:,2) == bus_num;
            sys.branch(branch_idx,11) = 0;
            return;
        end
    else

        bus_num = worstcase;
        disp(['Disconnecting bus: ' num2str(bus_num)])
        branch_idx = sys.branch(:,1) == bus_num | sys.branch(:,2) == bus_num;
        sys.branch(branch_idx,11) = 0;
        return;

    end
end
%============CHECK FOR LIMS AND UPD.======================

[baseMVAo, buso, geno, brancho, success] = runpf(sys, mpopt);
[limits_exceeded,limtype,worstcase] = pf_checklims(buso,brancho,geno,ignore);
if limits_exceeded == 0
    sys.bus = buso;
    sys.branch = brancho;
    sys.gen = geno;
```

```
        within_limits = true;
        more_actions = false;
        return;
    else
        sys.bus = buso;
        sys.branch(:,14:17) = brancho(:,14:17);
        sys.gen(:,2) = geno(:,2);
    end
    return;
end
```

### A.5.4 *ReactiveCompensation.m*

```
%=====================================================================================
function [shunt_comp,svc_comp,gen_comp,no_comp] = ReactiveCompensation...
    (sys,bus_num,...
    bus_name,bus_idx,worstcase_bus,shunts,...
    SVC,synchronous_condenser,actions,mpopt,limits_exceeded)

shunt_comp = 0;
svc_comp = zeros(1,2);
gen_comp = zeros(1,2);
no_comp = 0;
SVCwc_bus = find((bus_name == SVC(:,1))); %Is there SVC at worstcase?
SCwc_bus = find((bus_name == synchronous_condenser(:,1))); %Is there
%sync.c. at wostcase?
sysN = runpf(sys,mpopt);
SVCidx = find(ismember(sysN.gen(:,1:7),SVC(SVCwc_bus,1:7),'rows')); %Find
%SVC turned off in sys.gen.
SCidx = find(ismember(sysN.gen(:,1:7),...
    synchronous_condenser(SCwc_bus,1:7),'rows')); %Find sync.c. turned
%off in sys.gen

if sys.bus(bus_idx,3) > 0 %Worstcase a loadbus?
    if actions.shunt_compensation % Tries shunt_compensation, by order:
```

```
        %1. Activating shunt components
        %2. Activating SVC
        %3. Activating synchronous condenser.

        idx_shunts = find((bus_name == shunts(:,7)) == 1);
        if any(worstcase_bus == shunts(:,1)) && shunts(idx_shunts,2)...
                == 1 && sys.bus(bus_idx,6) == 0; %Checks if there is
            %shunt compensation disconnected at bus.

                shuntgen = zeros(1,length(sysN.gen(1,:)));
                shuntgen(1:10) = [shunts(idx_shunts,7) 0 0 ...
                    shunts(idx_shunts,4) shunts(idx_shunts,3)...
                    shunts(idx_shunts,5) shunts(idx_shunts,6)...
                    shunts(idx_shunts,2) 0 0];
                sysN.gen = [sysN.gen;shuntgen];
                sysN.gencost =[sys.gencost;[2 0 0 3 0 1 0]];
                sysN.bus(bus_idx,2) = 2; %Changed to PV bus.
                [baseMVAX, busX, genX, branchX, successX] =...
                    runpf(sysN,mpopt); %Power flow solution gives the
                %value of compensation needed.

                if genX(end,3) < sysN.gen(end,4) && genX(end,3) > sysN.gen(end,5)
                    if genX(end,3) > sysN.gen(end,5) && genX(end,3) > 0
                        shunt_comp  = sysN.gen(end,4); %Set to upper limi
                        %(shunt can only supply its ratings).
                    elseif genX(end,3) > sysN.gen(end,5) && genX(end,3) < 0
                        shunt_comp = sysN.gen(end,5); %Set to lower limit
                        %(shunt can only supply its ratings).
                    end
                elseif genX(end,3) < sysN.gen(end,5) %Value exceeds
                    %capability, set to lower limit.
                    shunt_comp = sysN.gen(end,5);

                elseif genX(end,3) > sysN.gen(end,4)
                    shunt_comp = sysN.gen(end,4); %Value exceeds
                    %capability, set to upper limit.
```

```

                end

        else
            if actions.SVC && any(SVCidx) %Connect SVC, no shunt available.
                if SVC(SVCwc_bus,8) == 1
                    svc_comp(1) = SVCidx;
                    svc = zeros(1,length(sysN.gen(1,:)));
                    svc(1:length(SVC(SVCwc_bus,1:10))) = SVC(SVCwc_bus,1:10);
                    sysN.gen = [sysN.gen;svc];
                    sysN.bus(bus_num,2) = 2;
                    sysN.gencost =[sys.gencost;[2 0 0 3 0 1 0]];
                    [baseMVAX, busX, genX, branchX, successX]...
                        = runpf(sysN,mpopt);
                    if genX(end,3) < sysN.gen(end,5)
                        svc_comp(2) = svc(5);
                    elseif genX(end,3) > sysN.gen(end,4)
                        svc_comp(2) = svc(4);
                    else
                        svc_comp(2) = genX(end,3);
                    end
                    return;
                end
            end
            if actions.synchronous_condenser && any(SCidx)
                    %Connect sync.c. no SVC available.
                if synchronous_condenser(SCwc_bus,8) == 1
                    gen_comp(1) = SCidx;
                    sc = zeros(1,length(sysN.gen(1,:)));
                    sc(1:length(synchronous_condenser(SCwc_bus,1:10)))...
                        = synchronous_condenser(SCwc_bus,1:10);
                    sysN.gen = [sysN.gen;sc];
                    sysN.bus(bus_num,2) = 2;
                    sysN.gencost = [sys.gencost;[2 0 0 3 0 1 0]];
                    [baseMVAX, busX, genX, branchX, successX]...
                        = runpf(sysN,mpopt);
```

```
                    if genX(end,3) < sysN.gen(end,5)
                        gen_comp(2) = sc(5);
                    elseif genX(end,3) > sysN.gen(end,4)
                        gen_comp(2) = sc(4);
                    else
                        gen_comp(2) = genX(end,3);
                    end
                    return;
                end
            end

            shuntidx = find(shunts(:,2) == 1); %Finds the available
            %shunts in the system.
            SVCidx = find(SVC(:,8) == 1);
            %Add for SVC+1 search. Find voltage problem fault.

            if isempty(shuntidx) && isempty(SVCidx) ||...
                    limits_exceeded == 4
                % It wont help activating neigbhouring bus for generator
                %reactive power breached.
                no_comp = 1;
                return;
            end
%==========After @ worstcase bus is checked for reactive compensation,
%the next step is to look to neighbouring buses but only for voltage
%problems at worstcase!===============

            shunt_idx = shuntidx';
            SVC_idx = SVCidx';

            for idx = shunt_idx %Iterating through the available shunts...
                %and checking if they are close to worstcase.
                x = 0;
                element = shunts(idx,7);
                if any(ismember(find(sysN.branch(:,1) ==...
                        element),find(sysN.branch(:,2) == bus_name)))
```

```
                    x = 1;
                end
                if any(ismember(find(sysN.branch(:,2) == ...
                        element),find(sysN.branch(:,1) == bus_name)))
                    x = 1;
                end
                try
                    sys.bus(idx,6); %Checking if the bus with shunt is
                    %in the system.
                catch
                    return;
                end

                if any(x) %If x exsists there is a shunt connected to...
                    %neighbor bus of worstcase.

                    if sys.bus(idx,6) == 0 %Checking if it's active.

                        shuntgen = zeros(1,length(sysN.gen(1,:)));
                        shuntgen(1:10) = [shunts(idx,7) 0 0 shunts(idx,4)...
                            shunts(idx,3) shunts(idx,5) shunts(idx,6)...
                            shunts(idx,2) 0 0];
                        sysN.gen = [sysN.gen;shuntgen];
                        sysN.gencost =[sys.gencost;[2 0 0 3 0 1 0]];


                        sysN.bus(idx,2) = 2; %Changed to PU bus.
                        [baseMVAX, busX, genX, branchX, successX]...
                            = runpf(sysN,mpopt); %Power flow solution gives
                        %the value of compensation needed.

                        if genX(end,3) < sysN.gen(end,4) && genX(end,3)...
                                > sysN.gen(end,5)
                            shunt_comp = [genX(end,3);idx;element];

                        elseif genX(end,3) < sysN.gen(end,5) %Value exceeds
```

```
                            %capability, set to lower limit.
                            shunt_comp = [sysN.gen(end,5);idx;element];

                        elseif genX(end,3) > sysN.gen(end,4) %Value exceeds
                            %capability, set to upper limit.
                            shunt_comp = [sysN.gen(end,4);idx;element];

                        end
                    end
                else
                    no_comp = 1;
                end
            end
        end

    elseif actions.SVC && any(SVCidx) %Shunt_compensation is not activated....
        %Checks if SVC is enabled, and activates SVC if at worstcase.
        if SVC(SVCwc_bus,8) == 1
            svc_comp(1) = SVCidx;
            svc = zeros(1,length(sysN.gen(1,:)));
            svc(1:length(SVC(SVCwc_bus,1:10))) = SVC(SVCwc_bus,1:10);
            sysN.gen = [sysN.gen;svc];
            sysN.bus(bus_num,2) = 2;
            sysN.gencost =[sys.gencost;[2 0 0 3 0 1 0]];
            [baseMVAX, busX, genX, branchX, successX] = runpf(sysN,mpopt);
            if genX(end,3) < sysN.gen(end,5)
                svc_comp(2) = svc(5);
            elseif genX(end,3) > sysN.gen(end,4)
                svc_comp(2) = svc(4);
            else
                svc_comp(2) = genX(end,3);
            end
        else
            no_comp = 1;
        end

```

```
    elseif actions.synchronous_condenser && any(SCidx) %Shunt_compensation...
        %and SVC is not activated. Checks if synchronous_condenser...
        %is enabled, and activates sync.c if at worstcase.
        if synchronous_condenser(SCwc_bus,8) == 1
            gen_comp(1) = SCidx;
            sc = zeros(1,length(sysN.gen(1,:)));
            sc(1:length(synchronous_condenser(SCwc_bus,1:10)))...
                = synchronous_condenser(SCwc_bus,1:10);
            sysN.gen = [sysN.gen;sc];
            sysN.bus(bus_num,2) = 2;
            sysN.gencost = [sys.gencost;[2 0 0 3 0 1 0]];
            [baseMVAX, busX, genX, branchX, successX] = runpf(sysN,mpopt);
            if genX(end,3) < sysN.gen(end,5)
                gen_comp(2) = sc(5);
            elseif genX(end,3) > sysN.gen(end,4)
                gen_comp(2) = sc(4);
            else
                gen_comp(2) = genX(end,3);
            end
        else
            no_comp = 1;
        end

    else
        % Disconnecting load, no reactive compensation actions
        % available.
        disp(['Disconnecting load (due to voltage problems) at bus '...
            num2str(bus_num) ': ' num2str(sys.bus(bus_idx,3))])
        no_comp = 1;

    end

%===================BUS IS NOT AN LOAD=====================================

else
    if actions.SVC && any(SVCidx) %Checks if SVC is enabled,...
```

```
        %and activates SVC if at worstcase.
        if SVC(SVCwc_bus,8) == 1
            svc_comp(1) = SVCidx;
            svc = zeros(1,length(sysN.gen(1,:)));
            svc(1:length(SVC(SVCwc_bus,1:10))) = SVC(SVCwc_bus,1:10);
            sysN.gen = [sysN.gen;svc];
            sysN.bus(bus_num,2) = 2;
            sysN.gencost =[sys.gencost;[2 0 0 3 0 1 0]];
            [baseMVAX, busX, genX, branchX, successX] = runpf(sysN,mpopt);
            if genX(end,3) < sysN.gen(end,5)
                svc_comp(2) = svc(5);
            elseif genX(end,3) > sysN.gen(end,4)
                svc_comp(2) = svc(4);
            else
                svc_comp(2) = genX(end,3);
            end
        else
            no_comp = 1;
        end
    else
        no_comp = 1;

    end
end
```

### A.5.5 *contanalysis.m*

```
%====================================================================================
%contanalysis.m
%Snippet line 374 - 400 in contanalysis.m
%====================================================================================
if ~isempty(branchout)
    for m = 1:length(branchout) %Iterates through the branchesout, and searches
        %for the internal exchanges or Oslo fjord connection.
        if ismember(branchout(m),[1;80;81;82;34])
```

```
            a = find(sys.branch(:,2)==7030);
            b = find(sys.branch(:,2) == 3020);
            c = find(sys.branch(:,2) == 7130);
            d = find(sys.branch(:,2) == 6702);
            e = find(sys.bus(:,1) == 5101);
            f = find(sys.bus(:,1) == 5501);
            if branchout(m) == 1
                sys.branch(a,11)=0;
            elseif branchout(m) == 80
                sys.branch(b,11)=0;
            elseif branchout(m) == 81
                sys.branch(d,11)=0;
            elseif branchout(m) == 82
                sys.branch(c,11)=0;
            elseif branchout(m) == 34 %Oslo fjord connection
                %Set reactive compensation to zero at recieving and giving end.
                sys.bus(e,5) = 0;
                sys.bus(e,6) = 0;
                sys.bus(f,5) = 0;
                sys.bus(f,6) = 0;
            end
        end
    end
end
```