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DEVELOPING A METHOD TO CALCULATE BORDER TRANSMISSION CA-  
PACITY

Master's thesis

Examiner: Professor Sami Repo  
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## ABSTRACT

**TIMO HALTTUNEN:** Developing a method to calculate border transmission capacity

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As European Union published the capacity allocation and congestion management guideline, the goal was to publish a guideline which would, among others, optimise the use of the power grid as well as the calculation and allocation of the cross border capacities. The guideline requires a coordinated manner to calculate the cross borders within transmission system operators as well as increase the frequency of the capacity calculation. Based on these objectives the currently in use capacity calculation methodology has to be developed to be in line with capacity allocation and congestion management guideline.

The calculation methodology developed in this thesis utilises the NTC-method, which is currently in use, as a theoretical base. In the future this methodology is required to calculate capacities hourly for the whole Nordic synchronous area. This sets a strict operational environment for the CNTC method, in which the methodology is meant to calculate secure values fast. CNTC method was developed to utilise a simulation environment, which is used in Fingrid's current capacity calculation. The method is divided into three main parts, which creates the base for the calculated technical maximum capacities. In the first stage the method collects all the necessary input data. Second phase is steady state analysis, where the N-1 principle is examined as well as the violation of thermal and voltage limits. As the greatest cross-border capacity in steady state is found, the dynamic analysis is run. Once a dynamically stable case is found, the capacity calculation is seen as completed.

The developed method was tested in case study calculating the capacity for the AC-border between Finland and Sweden. In order to conduct the case study the input data was collected from the relevant TSOs, which included grid models which comprised the whole Nordic synchronous system. With these calculations the developed CNTC method was proven to give capacities close to the ones that the current NTC methodology gives for the border.

In order to finalise the developed CNTC method into a capacity allocation and congestion management guideline compliant more work is needed. The topics for the further development include the implementation of the current capacity allocation methodolo-

gies and inclusion of remedial actions. The implementation of said additions require further testing in order to take the method to production use in the Nordic capacity calculation region.

## TIIVISTELMÄ

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Euroopan unioni julkaisi kapasiteetin allokointi ja pullonkaulojen hallinta -suuntaviivan, jonka osana päämääristä on optimoida verkon käyttö, rajasiirtokapasiteettien laskenta sekä allokointi. Suuntaviivassa vaadittiin rajasiirtokapasiteettien laskennan koordinoitua siirtoverkkoyhtiöiden kesken, sekä laskentataajuuden nostoa. Tämän pohjalta Suomessa käytössä olevaa rajasiirtokapasiteettilaskentamenetelmää on kehitettävä kohti suuntaviivan mukaista laskentamenetelmää.

Kehitetty menetelmä hyödyntää nykyisellään käytössä olevan NTC-menetelmän teoreettista taustaa. Tulevaisuudessa menetelmällä mahdollisesti lasketaan rajasiirtokapasiteetteja jopa tunneittain koko pohjoismaiselle synkronijärjestelmälle. Tämä asettaa CNTC-menetelmälle tarkan toimintaympäristön, missä menetelmän on kyettävä toimimaan turvallisesti ja nopeasti. CNTC-menetelmä kehitettiin Fingridissä käytössä olevaan simulointiympäristöön pohjautuvaksi. Menetelmä koostuu kolmesta pääosasta, joiden pohjalta tekniset maksimi-arvot rajasiirtokapasiteeteille määritetään. Aluksi menetelmä kokoaa käytettävissä olevat lähtötiedot ja käynnistää simulointiympäristön. Alkuvalmisteluiden jälkeen on vuorossa pysyvän tilan analyysi. Sen aikana menetelmä pyrkii maksimoimaan pysyvän tilan rajasiirtokapasiteetin. Saavutettuaan suurimman pysyvän tilan rajasiirtokapasiteetin menetelmä analysoi verkon tilaa dynaamisen stabiiliuden kannalta. Löydettyessä dynaamisesti stabiili tilanne, saadaan yhden rajan rajasiirtokapasiteetti.

Kehitettyä menetelmää testattiin Suomen ja Ruotsin välisellä rajalla. Tätä varten tarvittavat lähtötiedot kerättiin molemmilta kantaverkkoyhtiöiltä. Testauksen pohjana käytettiin olemassa olevia koko Pohjoismaisen synkronijärjestelmän kattavia verkkomalleja. Näiden avulla todettiin CNTC-menetelmän tuottavan vastaavia kapasiteetteja kuin nykyinen NTC-menetelmä.

Viimeistelläkseen CNTC-menetelmän suuntaviivan vaatimaan tilaan on menetelmää vielä jatkokehitettävä. Jatkokehityksaiheisiin kuuluu nykyisten kapasiteetin allokointimenetelmien integrointi menetelmään, sekä järjestelmän käyttöön liittyvien korjaavien toimenpiteiden implementointi. Näiden lisäkehitystarpeiden lisäksi menetelmä vaatii tarkempaa testausta, jotta menetelmä voitaisiin ottaa jatkuva-aikaiseen käyttöön Pohjoismaissa.



## **PREFACE**

This Master of Science thesis was done for the market integration and regulatory affairs team in Fingrid Oyj. Heini Ruohosenmaa from Fingrid Oyj was the advisor and Professor Sami Repo from Technical University of Tampere was the examiner of this thesis.

I'd like to express my gratitude towards Heini for the support and detailed comments she offered me throughout the process. Special thanks are also in place for Marcin Pohjanpalo, who trusted me and gave me support during the practical work of this thesis. Ritva Hirvonen and Sami Repo also gave me insightful comments, from which I'm grateful. I'd also like to thank everyone who is working in Fingrid, for making it a pleasure to come to work.

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Helsinki, 21st July 2017

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## LYHENTEET JA MERKINNÄT

CACM	Capacity Allocation and Congestion Management
CNTC	Coordinated Net Transfer Capacity
AC	Alternating Current
NTC	Net Transfer Capacity
ENTSO-E	European Network of Transmission System Operators for Electricity
TSO	Transmission System Operator
NEMO	Nominated Electricity Market Operator
GSK	Generation Shift Keys
CGM	Common Grid Model
IGM	Individual Grid Model
CNE	Critical Network Element
PTDF	Power Transfer Distribution Factor
TRM	Transmission Reliability Margin
API	Application Programming Interface
RAM	Remaining Available Margin
BDD	Behaviour-Driven Development

# 1. INTRODUCTION

The European Union has stated that the future direction of the European power system should be to unify the European power system and the power market. To promote this objective a guideline called capacity allocation and congestion management (CACM) was established. In the context of capacity calculation and this thesis, the main objective of the CACM guideline is to ensure the optimal utilisation of the grid and to optimise the capacity calculation and allocation. To fulfil these objectives, the guideline states that harmonised methodologies to calculate the cross-zonal capacities and allocation shall be developed and implemented in all capacity calculation regions in Europe. The CACM guideline came into force in August 2015.

Aim of this thesis is to find out how the current cross border capacity calculation can be further developed in order to comply with the guideline. To answer to this research question, first the requirements of the guideline are analysed and then the technical requirements of the capacity calculation are gathered. The guideline presents two different options for capacity calculation approach, flow-based and coordinated net transfer capacity. These options along with the current capacity calculation method, net transfer capacity approach, are presented in this thesis in order to create understanding of the strengths and the weaknesses of the methods. Along with the development of the CACM compliant capacity calculation method, this thesis discusses the transition from the current capacity calculation methodology to the coordinated guideline compliant capacity calculation methodology.

The main goal of this thesis was to develop the method to calculate maximum technical cross-border capacities, called hereafter coordinated net transfer capacity (CNTC) method and to demonstrate that the method can be applied to capacity calculation as it gives reasonable capacities.

CNTC method covers the first part of CNTC approach defined in CACM guideline, where maximum power exchange on a bidding zone border to both directions respecting operational security limits are calculated. To verify that the developed method is in working order, a case study is conducted, where the method is used in the calculation of the technical cross border transmission capacities. The chosen border for the case study is the alternating current (AC) connection between Sweden and Finland. The CNTC methods results are then compared to the current maximum cross-border transmission capacities.

This thesis is done as part of the implementation of the changes that arise from the CACM guideline. Along with the CNTC approach, in which the developed CNTC method is part of, the flow-based approach is currently being developed in Nordic countries.

## **1.1 Structure of the thesis**

The second chapter presents the current status of the Nordic synchronous system and power market. It focuses on the power market and the terminology used in the market discussion later. The effect of the transmission capacity on the electricity price is explained as this relates closely to the subject of this thesis.

The third chapter presents the capacity allocation and congestion management guideline. The focus is to collect the requirements that the guideline states to be related to the capacity calculation. Along with the requirements the main changes to the current procedures in the capacity calculation and allocation are explained.

The fourth chapter presents the technical reasons behind the operational security limits. These are an important part of the capacity calculation and therefore the phenomena behind these are valuable information.

The approaches for capacity calculation are explained in the fifth chapter. The current net transfer (NTC) method is presented first. This is done to understand the grade of changes that the two different methods given in the guideline propose. More focus in this chapter is given to the two new CACM compliant approaches, CNTC and flow-based.

The developed calculation software for CNTC method is presented in the sixth chapter. The design decisions are validated given the interest groups involved in the future of the software. After this the structure of the software is presented and the different sections of the software are presented. For each section a detailed explanation of the inner workings is given.

The case study and the discussion of the software are presented in chapters seven and eight. In the seventh chapter the premises and the results of the case study are presented. The eighth chapter holds the reasoning behind the deviations in the results as well as the further research that emerged from the results and discussions with interest groups. The thesis and the results are concluded in the ninth chapter.

## 2. NORDIC POWER SYSTEM AND MARKET

This chapter presents the Nordic power system and markets. This is done to understand the context where the capacity calculation methodology is designed. The power system includes the grid, the production, and the consumption of power. Today, Nord Pool operates the Nordic power market and the market operator holds a vital role in the application of the calculated capacities.

### 2.1 Nordic power system

The Nordic power system is a synchronised system, which means that every countries' subsystems are interconnected with AC transmission lines. The advantages of the synchronised system are improved system security and lower costs to the operating partners as well as to the customers. The need for reserves is reduced in the synchronous system as the power production is not tied to a single country, and in the event of a serious disturbance the helping of other parties is improved. [1]

The production portfolio varies between the Nordic countries. In Norway the main production type is hydropower.[2] In Denmark most of the production is done with thermal power and wind power.[3] Finland and Sweden have rather similar structure where the basis is formed with nuclear power and hydropower. However, the distribution of production methods is different; Sweden has more hydro-power than Finland. [4; 5] The hydropower in Finland and Sweden is located in the northern parts of the countries. The nuclear power plants on the other hand are in the southern parts of the countries. The varying production structure improves the system security, as the production does not rely on single production source.

The Nordic power system is connected to other synchronous systems with several direct current connections. Sweden is connected to western Denmark, Germany, Poland and Lithuania. Norway is connected also to the western Denmark and in addition to this there is a connection to Netherlands. Finland is connected to Russia and Estonia.[6] Inside the synchronous system there are AC and direct current connections. Finland is connected to Norway and Sweden with AC connections as well as with direct current connection to Sweden. Sweden and Norway are connected to each other with many AC connections throughout the border between the two countries.



**Figure 1. Nordic power grid [7]**

The structure of the Nordic power grid is shown in Figure 1, which presents the 200-400 kV transmission lines that exist in Nordic system. The most typical voltage level in the transmission grid of Norway is 300 kV as the typical voltage level in Sweden, Finland and eastern Denmark is 400 kV.



The Swedish and Finnish grid comprises long transmission lines connecting the northern hydropower to the majority of the consumption in south. A typical case in the Nordic power system is that the power is generated far away from the consumption. This holds especially for the hydropower generation in Finland and Sweden that is typically located in the northern parts of each country, whereas the consumption is in the southern parts of the countries.

## 2.2 Nordic power market

Currently in the Nordic countries the power market is a harmonised market for Finland, Sweden, Norway and Denmark. This collaborative market was established to create an environment for developing a functioning and effectively integrated power market to Nordic countries. The Nordic power market is also a part of the multi-regional coupling in Europe, which links the majority of the European power markets. The foundations of the Nordic power market were laid down in the Nordic Grid Code, which was done in cooperation of all relevant TSO's. This coordinated market is seen as a reasonable choice to balance out the production methods that vary throughout the Nordic countries. [1]

The day-ahead market offers a wholesale market for generators, traders and consumers to submit offers and bids in order to buy or sell energy for the next day. This market promotes competition, as offers and bids from the whole area are matched together in implicit auction. The area price is supposed not to vary through different bidding zones unless cross-border transmission capacity is a limiting factor. Intraday market gives an opportunity for the market participants to trade close to real time. This is enabled by the continuous market, which is open until one hour before the delivery. Closer to real time trading gives a possibility for the market participant to manage risks and compensate for the possible changes in conditions e.g. changes in the weather forecast. [8]

Along with the day-ahead and intraday markets there are also other markets. These markets serve the Nordic TSOs responsibility to maintain continuous power balance. First of the two is the balancing power market. In balancing power market, the participants submit bids to the market concerning their capacity that can be regulated. A balancing bid is used by the TSO that needs to manage its balance or maintain the systems' frequency.[9] Along with the balancing power market, the reserve market exists in order to maintain the systems' frequency. The reserve market is divided to three groups: frequency containment reserve, frequency restoration reserve and replacement reserve. The frequency containment reserve is constantly used to maintain the power systems' frequency. The frequency restoration reserves are used to return frequency to its normal range and to release the activated frequency containment reserves. Finally, the replacement reserves are used to release the frequency restoration reserves back to the state of readiness in preparation for new disturbances. [10]

### 2.2.1 Bidding zones

Bidding zone definition plays a vital role in creating successful day ahead and intraday markets. Bidding zone is defined to mean the largest geographical area for market participants to buy or sell energy without taking into account the possible limitations in the grid.



**Figure 2. Bidding zones in Baltic sea region[11]**

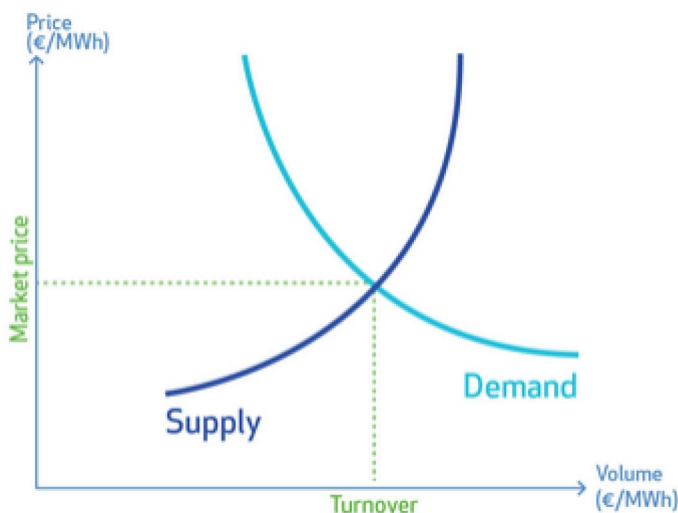
The Nordic area is divided into different bidding zones. The bidding zones are connected with cross-border power transmission lines, which all have a certain power transmission capacity. The bidding zones in Nordic grid are shown in Figure 2. A bidding zones sum of production and consumption, which comprises the cross-zonal power transmission as well, is called the net position of the bidding zone. In this sum, the consumption is seen as negative as it lowers the power balance for the bidding zone. If the power transmission from and to the bidding zone is zero, the net position would be balanced.

### 2.2.2 Price formation

The price for electricity is formed in the electricity market, which in Nordic countries is currently operated by Nord Pool, the nominated electricity market operator (NEMO). Nord Pool is a co-owned by Nordic TSO's and Nord Pool's function is to provide a stable and fair energy exchange environment for all members. Members are either sellers or buyers of electricity.

The price of electricity is based on the balance between supply and demand. Buyers send information of the volume they are willing to buy and the price they are willing to pay and sellers the price information at which they are willing to sell. Nord Pool uses an advanced algorithm to match the bids and determine the electricity price for different bidding zones using the information sent by the members. The target is to maximize the welfare of the market. For each bidding zone, an area price is calculated. First area price calculation takes into account supply and demand in each area. After this, transmission between the areas are iterated by increasing the power transmissions from higher price areas to the lower price areas as long as there is no more price difference between the areas or as long as the transmission capacity is fully utilised. In this situation, the flow of power will always go from the lower price area to the higher price area.

In Nordic region, system price is also calculated for each hour. The formulation of market solution and the system price is presented in Figure 1. The system price for each hour is determined by the intersection of the aggregate supply and demand curves, which represent all bids and offers for the entire Nordic region. The trading capacities between the bidding areas are not taken into account when the system price is calculated.



**Figure 3. System price formation [12]**

Congestion is a phenomenon where the cross-border transmission capacity limits the power transfer between two bidding zones. When the power transmission between bidding zones is limited the electricity market operator collects congestion income. This is due to the difference in the electricity price in surplus area and deficit area. The congestion income is forwarded to the TSOs responsible for the

limiting border. In Finland, Fingrid as a TSO is obligated to use the congestion income to increase the cross-border capacity.

From the previous, it is easy to understand the importance of cross-border transmission capacity calculation. Cross-border capacities have a major impact to the electricity prices and total welfare of the electricity market, and for this reason it is important to have as accurate cross-border capacities as possible. The current methods and the future options given in the capacity allocation and congestion management guideline for the transmission capacity calculation are further explained in chapter Methods used to calculate border transmission capacity.

### **3. NETWORK GUIDELINES REQUIREMENTS ON CROSS-BORDER TRANSMISSION CAPACITY CALCULATION**

European Network of Transmission System Operators for Electricity (ENTSO-E) drafted and later European Commission established a new guideline that set out to create a set of rules for cross-border electricity trading in Europe. CACM guideline came into force in August 2015. It enforces rules to capacity allocation and draws borders for the way capacity is calculated. These rules and outlines are applied to day-ahead and intra-day timeframes. [8] In this chapter, the focus is to describe what CACM guideline covers, focusing on the objectives defined in the guideline and explaining the requirements set for capacity calculation. In addition, existing practices are explained to better explain the scale of change introduced by CACM.

The objective of the one set of rules given in CACM guideline is to enable the Europe's electricity market to become the most competitive and largest in the world[8]. This rather large task is separated into smaller objectives in the CACM guideline. Firstly, regulation aims to promote effective competition for generating, trading and supplying electricity. Also, it sets out to ensure operational security and optimal use of the transmission infrastructure. Emphasis is given to create an open and non-discriminatory environment for transmission system operators (TSOs), NEMOs, the agency for the cooperation of energy regulators, national regulatory authorities and other market participants. This open and non-discriminatory market is specified in many of the objectives listed in the regulation. Finally, the cross-zonal capacity calculation and allocation is set to be optimized. [13]

As discussed a set of rules is created to achieve these objectives. This guideline is seen partly accomplish the vision known as the EU target model for electricity markets. EU target model is an electricity market, which comprises all of the EU countries. The proposed market design contains four main elements: day-ahead market, intraday market, bidding zone definition and coordinated capacity calculation. Each of the elements are to be implemented throughout Europe thus promoting cooperation of TSO's and confluence of existing rules.[8]

As the focus for this thesis is the capacity calculation part in CACM guideline, the requirements given for the capacity calculation and allocation are discussed in further detail. The guideline does not strictly limit how the calculation should be done, but rather defines the premises for the calculation and proposes two options for capacity calculation: flow-based approach and CNTC approach. First option for capacity calculation is flow-based approach, a method suitable for meshed grid. However, if TSOs can show that flow-based method does not currently work more efficiently than CNTC method would, the CNTC method can be applied [13].

### 3.1 Time scale of the calculation

First requirement mentioned in the guideline is the time scale of the calculation. The calculation time scale focuses on two different time frames, day-ahead and intraday. The day-ahead time frame means that the cross-border capacities are given to the relevant NEMOs one day before the delivery day, by 11:00 CET. For intraday time frame, the capacities shall be given to the NEMOs no later than 15 minutes before the intraday cross-zonal gate opening time.

The day-ahead calculation should not be done earlier than at 15:00 two days before the day of delivery. In intra-day, the guideline requires the recalculation to be done as the forecasts improve. Frequency for the recalculation is not specified. For both time frames, the calculation should be based on the latest available information. [13]

Currently the capacity calculation is done when necessary and every TSO is responsible for the decision to recalculate the capacities. This means that if the topology of the grid changes in such a way which might affect the cross border capacity the calculation is redone. This means that typically, the capacity stays constant as minor changes in the consumption or generation happens.

### 3.2 Input methodologies

The guideline requires the capacity calculation methodology to use the results of different input methodologies. The guideline gives rough definitions for the input methodologies. These input methodologies include methodologies to determine reliability margins, operational security limits, contingencies, generation shift keys and remedial actions. Every output of the proposed methodologies must be reviewed and updated yearly using the latest available information[13].

Reliability margin is the margin that is reduced from total transmission capacity in order to get transmission capacity that can be given to the market. It is needed to cover the possible uncertainties that arise from the capacity calculation, forecasting errors and other influencing phenomena. The calculation methodology for reliability margin consists of two steps. Firstly, the probability distribution of deviations between the expected power flows and actual flows is created. Then the risk level is decided and a reliability margin value corresponding to selected risk level is derived from the probability distribution. The more detailed calculation process of the reliability margins is something CACM requires to be defined as a part of the capacity calculation methodology proposal.

Operational security limits define the acceptable operating boundaries for secure grid operation, which is limited by thermal limits, voltage limits, short-circuit current limits, frequency and dynamic stability limits. The reasons behind these limits are further explained in chapter 4. All of the limits, except the thermal limits, are constants. Obviously though, the limits can be redefined if necessary. Another important factor in the calculation of the grids capability to remain within the operational security limits are contingencies. Contingencies are significant disturbances or faults that may occur in elements of the network. They can occur in the transmission system elements or in grid users' or in distribution network elements that are significant for the operational security of the transmission

network. For operational security limits and contingencies methodologies, the guideline states that both of them must be the same as used in operational security analysis. If that is not the case, TSOs shall explain the reasons for using different operational security limits or contingencies.

Remedial actions are actions performed by TSOs to maintain operational security or to give more capacity to the market, and they can be either non-costly or costly. Remedial actions that are used are for example countertrading and redispatching. Both of these measures are used in order to relieve physical congestion. Countertrading is a cross zonal exchange initiated by the system operators between two bidding zones. In redispatching one or several bidding zone system operators alter generation and/or load pattern in order to manage the physical flows of the power system. [8] The guideline states that every TSO must define the remedial actions to be taken into account in the capacity calculation in order to meet the objectives of the guideline. Remedial actions of other TSOs that have an effect on a specific capacity calculation region must also be taken into account. [13]

The generation shift keys (GSKs) represent the best possible forecast of the relation of a change in net position of bidding zones to a specific change of generation or load in the common grid model. Basically, GSKs define how each generator in the bidding zone takes part in the scaling of the power system when the capacity is calculated. A detailed method for the calculation of the GSKs is a part of the capacity calculation methodology. [14]

### **3.3 Common grid model**

To make the capacity calculation more effective and accurate the guideline requires a process to create a European Union wide grid model also known as a common grid model (CGM). The common grid model consists of each states' individual grid models (IGMs). The CGM holds main characteristics of the power system and is therefore the basis to perform the capacity calculation. The guideline states that the common grid model creation methodology shall contain at least definition for scenarios and individual grid models as well as a description of the merging process to create a common grid model from the individual grid models.

Scenarios are forecasted status of the power system for both day-ahead and intra-day timeframes. To create the scenarios all TSOs first individually develop IGMs for each timeframe. These IGMs shall then be combined and to describe a specific scenario, a forecasted situation for generation, load and grid topology in the common grid model.

An IGM is created for each country and for each time frame on hourly basis. The IGM covers all the network elements of the transmission system that are used in national and regional operational security analysis. To assist in the creation of the CGM all of the IGM building methods shall be harmonized to maximum possible extent.

In the current capacity calculation, as the CGM is yet to be implemented, each TSO uses their own grid model in the capacity calculation. In Nordic countries, a Nordic planning grid model is also used for the power system planning purposes, but this planning model is updated roughly once a year. This

leads to inevitable generalisations in the grid model and these hinder the accuracy of the calculation. The introduction of hourly grid model changes the possibilities in the capacity calculation and enhances the accuracy.

### 3.4 Other requirements

In article 29, the guideline sets the premises for coordinated capacity calculator. Each capacity calculation region shall establish their own coordinated capacity calculator. The coordinated capacity calculator is ordered to perform operational security analysis and capacity calculation. The capacity calculator is required to use the inputs for capacity calculation that are defined in the input methodologies chapter. Along with the input methodologies, the actual capacity calculation methodology shall also be applied. Finally, the capacity calculator is required to cooperate with neighbouring regional capacity calculators. The guideline requires a common grid model to be used in capacity calculation. With these inputs, the capacity calculator shall optimize the cross-zonal capacity without discriminating cross-zonal exchanges in order to promote internal power balance. [13]

In the future, the Nordic Regional Security Coordinator (RSC) does the capacity calculation in the Nordic countries. RSC is an entity that is established to provide services for Nordic TSOs, for example security analysis and capacity calculation.[15] RSC will start its operations in December 2017. As the Nordic RSC is nominated to be the common capacity calculator of the Nordic countries, it holds an important role in the implementation of the CACM.

The common capacity calculator changes the current situation where the TSOs define the cross border transmission capacities that are given to the market. Currently, both of the TSOs responsible of the cross-zonal transmission lines calculate the capacity to be given to the market. From the two values that is gathered from the calculations, the lower one is chosen to be given to the market.

Even though RSC start calculating the capacities, TSOs are still responsible for system security and they have a right to reduce the cross-zonal capacities for reasons of operational security. In addition, TSOs are required to validate all of the relevant cross-zonal capacities calculated by RSC. To promote transparency every three months capacity calculators shall report all the reductions done in the validation. The report should include the location, amount of change in capacity and reason of the change.



## 4. BASIS OF CAPACITY CALCULATION

As the EU target models goal is to create one electricity market for the whole EU the importance of calculating the cross-zonal transmission capacities rises. This is because an EU wide market promotes cross-zonal competitiveness and therefore the transmission capacity needed.

Cross-zonal transmission capacity is the capacity that is given to the market. Basically, it is the power flow, which can be transferred through cross-zonal transmission lines. Limitations to this power flow are set in order to maintain operational security and by the technical characteristics of the transmission lines. The technical maximum capacity of the cross-zonal transmission lines are defined by two main analysis: dynamic and steady state analysis. In steady-state analysis, the focus is on the voltage levels and power flows in different parts of the grid and through different network elements. In dynamic analyses, the main components that define the effects to the grid are voltage, frequency and angle stability.

### 4.1 Power system stability

Power system stability is defined as the power systems ability to regain such equilibrium that the integrity of the system remains after a physical disturbance.[16] This holds true for the whole power system. Therefore, in some cases a generator or a load can lose stability without the instability spreading throughout the grid. Stability is a balancing act between opposing forces and if a disturbance breaks this balance and leaves the grid in a state of imbalance the stability is lost.

The power system is under a constant change, which arises from the nature of the system. Loads and generation on the network are not constant and the differences create small shifts in the network balance. Furthermore, the grids topology is also a variable due to changing operating environments and faults on the network. Every one of these may create a disturbance in the power system, offsetting the equilibrium. [16; 17]

To overcome the instability introduced by the different disturbances, the power system is designed and operated in a manner that tries to account for the disturbances. This is how the power system stability effects to the cross-zonal transmission capacity. In some cases the power systems inability to recover from a disturbance can be the limiting factor when calculating cross-zonal power transmission capacities.

Power system stability can be divided into subcategories in order to split it into pieces that are more manageable. These subcategories can be observed from three viewpoints of the power system. First is the rotor angle stability, which is the power systems ability to keep the synchronized machines in synchronism in normal operating conditions as well as after a disturbance. Second is the ability of the power system to keep voltage level steady at all buses in normal and post-disturbance conditions.

Last factor is frequency stability, which is power systems ability to maintain a steady frequency whilst there is an imbalance between generations and load. [16]

#### **4.1.1 Rotor angle stability**

In rotor angle stability, the stability issue is found by studying the electromechanical oscillations of power system. In this category of stability, the basic element is the changing of synchronous machines output power, as the rotor angles vary. This means that the power systems synchronous machines have a tendency to remain synchronised given that the rotor angle difference stays within certain limits. If the limits are exceeded the stability of the machines is lost. When a generator of the power system rotates faster compared to other generators due to the input mechanical torque being bigger than output electrical torque the angular difference increases. This increase of the angular difference moves more load to the generator that is ahead increasing the electrical torque, stabilizing and lowering the angular difference. [16]

There are two components for the change in electrical torque: synchronizing and damping torque. For the power system to remain stable both of the torque components are required for every synchronous machine. A lack of synchronizing torque in the power system might lead to aperiodic or non-oscillatory instability. Aperiodic instability is seen as the increase of the rotor angle. If machine lacks damping torque it results to an oscillatory instability. This can be seen in as an increase in the amplitude of the rotor oscillations. [16]

#### **4.1.2 Voltage stability**

Voltage stability covers for controlling the power systems voltage as steady as possible in every bus of the system. Power systems voltages must be steady in normal operating conditions as well as after being subjected to a disturbance. The possible instability presents itself as a progressive fall or rise of voltages in some buses. The progressive change in voltage levels leads to loss of load in areas where the voltage reaches unacceptable levels. [16]

The biggest influence towards voltage instability is usually caused by reactive power losses and resulting voltage drops that occur as high levels of active and reactive power flow through inductive reactance. The typical properties of the power systems loads have a great effect on the occurrence of voltage instability. As a reaction to the power systems reduced voltage levels after a disturbance, the power consumed by the loads tends to be restored in the distribution voltage regulators, for example in tap-changing transformers. As the power consumed is restored to the state before the disturbance, stress is increased in the transmission system leading to more voltage reduction. Voltage stability may be lost when the load dynamics attempts to restore power consumption over the transmission systems capability. [16; 17]

In analysing voltage stability, it is seen useful to divide the analysis into two subcategories, which depend on the severeness of the disturbance. Large disturbance voltage stability is based on the power systems capability to control voltage levels after large disturbances such as system faults or loss of

generation. Determination of large disturbance stability requires the examination of the nonlinear dynamic performance of the system. This examination should be done over a sufficient time period in order to account for interactions of such devices as the transformers tap changer and generator field-current limiter. Small disturbance voltage stability is based on the power systems ability to control the voltage levels following small shifts in the system such as an incremental change of a load. However, the phenomena that arise from these perturbations are essentially of a steady-state nature, with the exception of the small-signal stability oscillations. [16]

### 4.1.3 Frequency stability

Frequency stability refers to the system's ability to maintain power systems frequency stable and within acceptable limits. This should be especially the case as the power system encounters large disturbances where the power system experiences a significant difference between generation and load. These large disturbances usually cause large changes in frequency, power flow, voltage and other system variables. These changes start such processes that are not modelled in the voltage stability analysis. Frequency stability is involved in large interconnected power systems when a phenomenon of islands appears in the power system. Islands are parts of the power system that are not connected to the main system and thereby create a separate power system within the power system. Stability of a power system including these islands is based on whether or not every island in the power system is stable. In these cases, the frequency stability is a concern. [16]

As every other stability related phenomena, frequency stability can also be analysed in two different time periods: short and long. The long time period phenomenon are a result of responses from prime mover energy supply or load voltage regulator. In short term phenomenon the influencing devices are generator control and protection as well as load shedding. [16]

## 4.2 Thermal limits

Along with voltage stability and rotor angle stability, thermal limit is an important factor when calculating the limits for cross-zonal transmission capacity. In capacity calculation, thermal limit means the limit in the power transmission that arises from the heating phenomena of power carried in the power system. The effects of thermal limits to cross-zonal capacity calculation are evaluated through load current, because the load current heats the devices. The ampacity of a series connected set of devices is the smallest ampacity of all the devices. In transmission lines a different set of devices is often series-connected and the calculation is not always that straightforward.

For most of the power systems devices, the ampacity depends on environmental conditions such as the temperature and wind. Due to this, the ampacity of the devices is defined at mean weather conditions. However, the weather conditions do not typically remain at the mean conditions and this has an effect on the ampacity. For example if the temperature is lower than as defined in the mean conditions it increases the ampacity for most of the power systems devices. The environmental conditions effect to the cross-zonal capacity calculation is disregarded in this thesis and where needed the mean conditions were applied.

### 4.3 N-1 principle

The most important criteria used when calculating cross-zonal capacities is the N-1-criteria. N-1-criteria means that the power system must at all times be able to withstand a single fault in such a manner that the faulted area of effect does not expand. The worst fault considering the power system is called a dimensioning fault. Dimensioning fault is not always the same; rather it varies depending on the grid topology and power flows in the system. Often it is the tripping of the biggest generation unit, bus bar fault or fault in cross-zonal transmission connection. [18]

In practice, N-1-principle means that the power systems transmission capacity is not the sum of the devices transmission capacities. Part of the capacity is reserved for the circumstances that results from the dimensioning fault. As the principle is applied to practice, the most uncommon dimensioning faults are allowed to result in more severe consequences. This is allowed in the practical application of the principle, because it is not economically sensible to cover for all the possibilities. The more uncommon conditions are usually temporary which further lowers the probability the consequences can be accepted. [19]

## 5. METHODS USED TO CALCULATE BORDER TRANSMISSION CAPACITY

The current capacity calculation method NTC, is used widely as the concept is quite simple. As the CACM guideline requires a coordinated capacity calculation approach capable of hourly calculation, two approaches are proposed that are to fulfill CACM expectations. CNTC is in short a new coordinated version of the previously used NTC method and sets out to fulfill the requirements of CACM. Along with the CNTC another approach, flow-based, is an option. These three approaches are discussed in this chapter.

The flow-based approach that is presented in this chapter is based on the flow-based method that is already in use in the Central Western Europe. As part of this thesis, a first part of CACM compliant CNTC approach has been developed. It is called CNTC method, and it is capable of calculating maximum allowed cross-border flows for bidding zone borders.

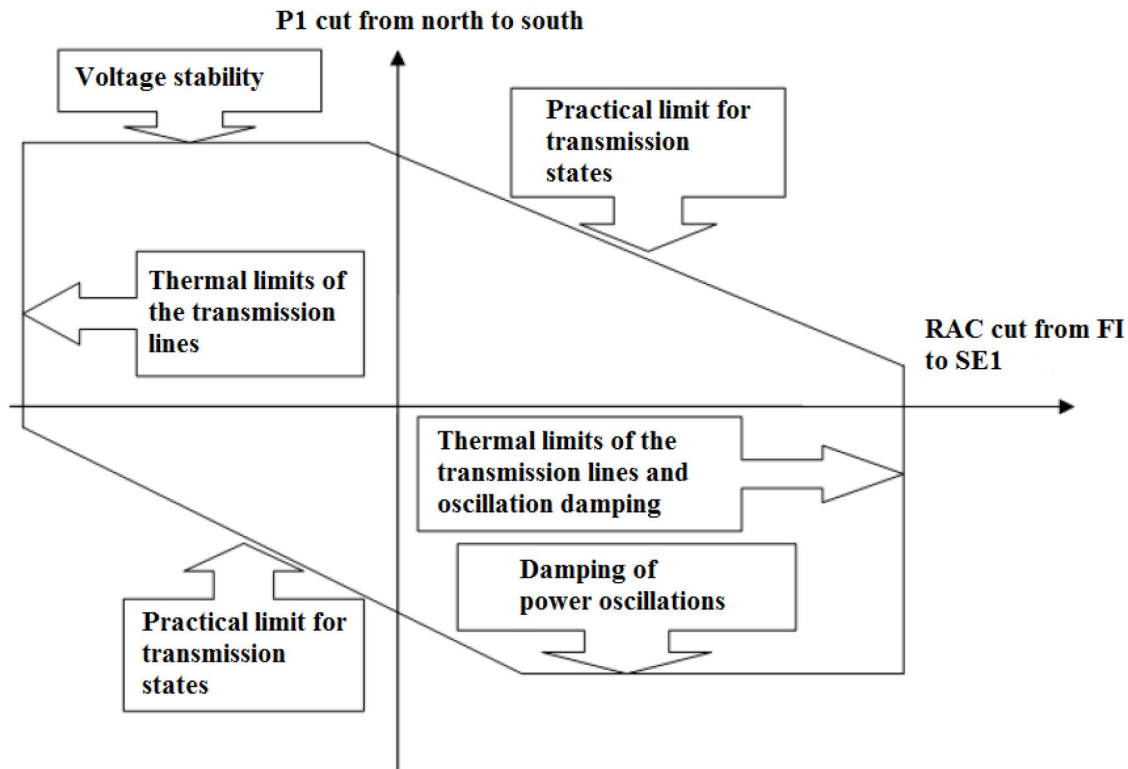
### 5.1 Net Transfer Capacity

The method currently used in Nordic countries for cross-zonal capacity calculation is NTC. The NTC method is similar throughout Europe; however, the calculation of the components and the input data varies by country. In Finland, the calculation is usually only done if something changes, for example major changes in topology, which leads to rather static net transfer capacity.

NTC is an upper limit for commercial power exchange on a specified bidding zone border. This means that the power transferred on a commercial basis is not necessarily the power that NTC calculation produces but rather something below this limit. NTC is calculated by subtracting the transmission reliability margin (TRM) from total transfer capacity (TTC). TTC is derived from technical limits while acknowledging the secure system operation criteria. TRM depends on the structure of the system, as the used TRM varies between TSOs and borders, and it covers for the inaccuracies that arise from the calculations. TRM also covers for variations in the power transmission due to imbalances in the production and consumption, which are caused by automatically activating reserves, or some other unanticipated variations. [20]

The base in calculating TTC comes from rated power for each equipment in the power system. The equipment include not only the transmission lines but also series capacitors, power and current transformers. The lowest rated power for a single equipment is set as the rated power for the whole subsystem. After this, the voltages and flows are calculated using steady state analysis iterating through the contingencies given by the TSOs and scaling the case as desired in order to find the technical transfer capacities for steady state. Finally, the dynamic stability analysis is conducted to find the possible limitations to TTC. In this part of the calculation, the limiting properties come from the matter discussed in chapter 4, which are dynamic stability, N-1 criterion and thermal limitations. To

complete the calculation of NTC a TRM is deducted from the TTC. In order to scale the case and reach the TTC for chosen border, the production and consumption is scaled as defined by the TSOs. TRM is usually a constant that every TSO defines to match their expectations of the possible uncertainties.



**Figure 4. Operating range diagram of the FI-SE1 transmission lines**

Currently Fingrid utilises a diagram of the operating range to verify that the capacity given to the power market is valid. This diagram is based on the values that are calculated using NTC method for the AC-line between FI and SE1 bidding zones. This diagram is shown in Figure 4. The cross-zonal transmission lines SE1-FI allowed power flow depends in the example case from the north-south cut's flow in Finland.

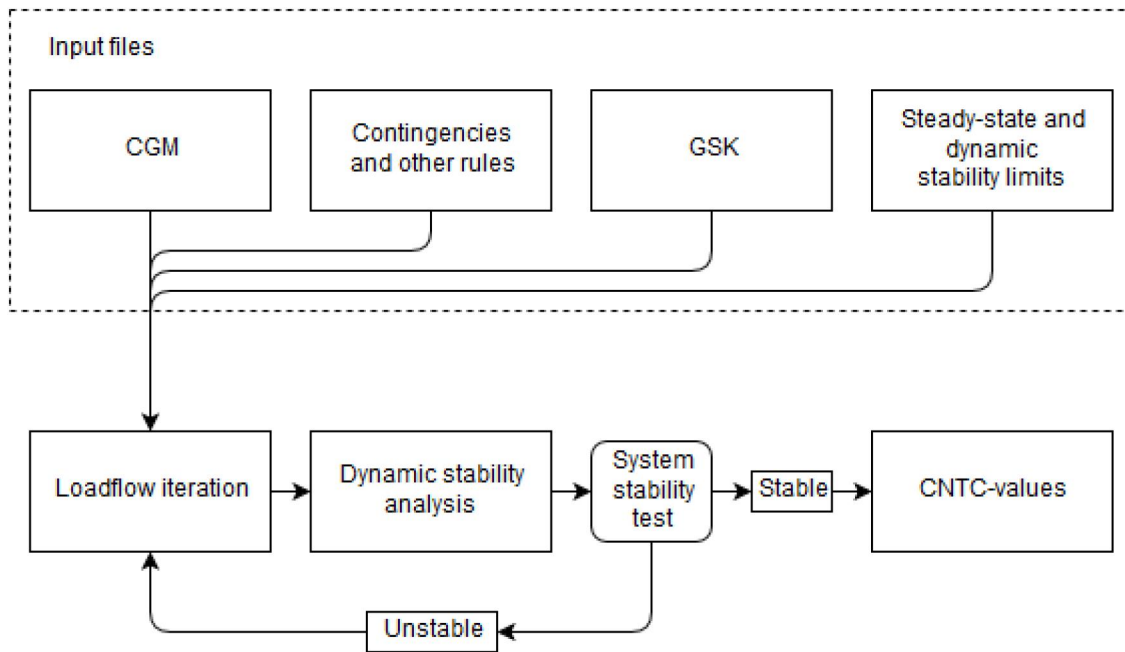
In the Nordic, the current NTC capacities are calculated more conservatively than N-1 principle states. In the cross border capacity calculation the used disturbance preparation principle is (N-1)-1, which means that the grid is capable of handling two separate disturbances with a 15 minute adaptation period. [1]

## 5.2 Coordinated Net Transfer Capacity

CNTC is an approach that is based on the current NTC approach. Focus on this thesis is in the first step on CACM compliant CNTC calculation, which is about finding the maximum cross-zonal exchanges. The method to calculate maximum exchanges, CNTC method, is introduced in this section. This method automates the calculations done in NTC and improves it by bringing in coordinated rules

and common grid model as described in CACM. CNTC method uses the same rules used in NTC as a basis but along with automating the calculations, it adjusts them to fulfil the CACMs requirements. Capacity calculation is based on steady state analysis and dynamic analysis.

CNTC is as a calculation process very similar to NTC, where the basis for the CNTC values is total transfer capacity. However, the calculation starts from forecasted state of the power system and therefore the TTC is not calculated as straightforwardly as in NTC. The forecast usually is based on the recent power system status and to other forecasted resources such as wind power production. The power systems recent state is gathered to common grid model that is then scaled in order to find the maximum power transmission capacity for a chosen bidding zone border. In short, a maximum allowed power flow for the chosen bidding zone border is found using steady state and dynamic stability analysis.



**Figure 5. CNTC-method calculation process**

The calculation is an iterative process, where the base case is scaled according to the predefined GSKs in order to find the largest acceptable cross-zonal transmission capacity. The grid the first approximation is done using steady state analysis only. Dynamic stability analysis requires much more computational power as the phenomena can be seen in analysis that is more detailed. In this analysis certain areas loads and generation is scaled stepwise in order to increase the flow in the studied bidding zone border. This is done until the load flow study fails to converge, other numerical problems occur or unacceptable voltages or power flows are found in the power system.

There is two main methods of scaling used in CNTC method prototype. First, load or generation on both sides of the studied border are scaled incrementally. This mean that the net position of the area is changed by a constant power. Second method changes the net position by a percent of existing loads or generation. In each iteration, a list of contingencies is run through and the same analysis is

done for all cases. Contingencies and acceptable range for voltage and flows (thermal limits) are defined by the TSOs.

After the steady state analysis is completed, a dynamic analysis is done in order to account for the different dynamic phenomena, which might destabilize the power system. The starting case for dynamic analysis is the one the steady state analysis found to be the last acceptable case i.e. the case with the maximum allowed flow in the steady state analysis. The same list of contingencies as in steady state analysis is used to create disturbances to the grid thus testing the stability of the power system. TSOs can define the limits of instability for voltage and frequency signals, which include the damping limits for the signals. The instability that is due to angle stability problems is thought to present itself in the voltage signals. If any of the contingencies create a situation where the power system stays unstable after the fault is cleared, the scaling done in the steady state analysis needs to be backtracked. This backtracking is done until a case that passes the stability criteria is found. CNTC value for the studied bidding zone border is taken from that case. This CNTC value is the maximum allowed power flow for the studied border. It is the first part of the CNTC calculation defined in the CACM guideline. In a meshed grid, maximum capacities cannot be given to the market for all borders simultaneously and for this reason, sharing rules are needed as CACM states. As stated in the introduction, sharing rules are out of the scope of this thesis.

The inputs required by CNTC method include a common grid model, list of contingencies, GSKs and operational security limits to be used in steady state and dynamic analysis. Both list of contingencies and the limits for both analyses are defined by the TSOs. A list of contingencies should include all the critical faults that TSO can define to their grid, or at least the ones that affect the transmission line whose limits are calculated. TSO also defines the limits used in steady state and dynamic analyses. In voltage analysis an upper and lower limit is required and a rate for oscillation dampening. CGM and GSKs are defined in the CACM guideline and are therefore inputs that are generated as defined in the guideline.

CNTC approach is a new approach to calculate cross-zonal capacities in the grid. As it is based on the well-known NTC method, meaning that the calculations done in order to define the capacity given to markets are tested by the TSOs and the values are understood within the market participants. CNTC approaches strong points are accurate capacity calculation, clarity and transparency towards market participants, however the capacity sharing is not at the same level as in flow-based approach. Rules for sharing the capacity define how the calculated maximum capacity is utilised for every border of a bidding zone.

The CNTC method developed in this thesis calculates the maximum transmission capacities border by border. Sharing rules and application of remedial actions are needed in order to develop the CNTC method to a full-fledged CACM compliant CNTC approach.



### 5.3 Flow-based

This chapter describes the flow-based approach to capacity calculation that is being developed in Nordic flow-based project by TSOs of Denmark, Finland, Norway and Sweden. Therefore the presented calculations and simplifications does not necessarily hold true outside of this region; however, this approach is rather similar to the one already in use in Central Western Europe. [21]

Flow-based capacity calculation approach differs from the NTC-based methods. In NTC-based methods, a transfer capacity is calculated for every cross-zonal border separately and TSOs must take into account the possible transit flows. TSOs will submit cross-zonal capacities to power exchanges before market clearing. This is different to the flow-based method where no maximum capacities but rather remaining available margins (RAMs) on critical network elements (CNEs) and power distribution factor matrixes (PTDFs) are given to the market. PTDF-matrix is derived from the CGM and it can be seen as a simplified grid model. The calculation process of PTDFs is further explained in chapter 5.3.1. Flow-based method simultaneously calculates all the flows and accounts for the transit flows. This means that flow-based efficiently shares the flow between different cross-zonal transmission lines and takes into account the different paths for flows. The flow-based method is embedded in to the market clearing, which means that the cross-zonal flows are calculated simultaneously with market outcome. This leads to that the actual calculation seems less transparent to market participants.[22]

The operational security limits are taken into account in the calculation of critical network element (CNE) parameter remaining available margin. In the flow-based method, CNEs are the network elements that limit the cross-zonal transmission capacity. For each CNE the limit of power transmission is presented by remaining available margin. The calculation of remaining available margin is presented in chapter 5.3.3. The CNEs work as a basis of the flow based calculation and they are defined by TSOs for respected bidding zones. [23]

The main benefits that flow-based method provides are its capability to allocate the flows efficiently and the possibility to account for the transit flows. The flow-based method allows the calculation to result into a situation where power is transferred cross-zonally in a non-intuitive ways. This is caused by the flow based methods aim to optimise the total socio-economic welfare. This means for example that power can be transferred from higher price zone to a lower price zone in order to manage congestion in other parts of the network. This differs from NTC-based methods where the power transfer direction is always from lower price zone to higher.

The uncertainty in the power flows that arises from the simplifications and forecasting errors is decreased by using flow reliability margins. The reliability margin is deducted from the physical capacity to create the market capacity as seen in the remaining available margin description. [24] The simplifications are substantial and require the reliability margin to take into account the made assumptions and other uncertainty that is caused by the calculation. However, with these simplifications the required computational capacity is much lower and the whole grid can be taken into consideration as the calculation is done.

### 5.3.1 PTDF-calculation

PTDF-matrix reveals how each node participate in the flow for a certain branch. In order for the flow-based method to accomplish this complicated result the calculation method somewhat simplifies the problem. The simplifications are done as the PTDFs are derived from standard AC power flow equations (equation 1 & 2). In the equations  $P_i$  is the real power,  $V_i$  is the voltage and  $\delta_i$  is the voltage angle of the node  $i$ .  $V_k$  is the voltage and  $\delta_k$  is the voltage angle in the node  $k$ .  $G_{ik}$  is the conductivity and  $B_{ik}$  is the susceptance between the nodes  $i$  and  $k$ .

$$P_i = V_i \sum_{k=1}^n V_k (G_{ik} \cos(\delta_i - \delta_k) + B_{ik} \sin(\delta_i - \delta_k)) \quad (1)$$

$$Q_i = V_i \sum_{k=1}^n V_k (G_{ik} \sin(\delta_i - \delta_k) - B_{ik} \cos(\delta_i - \delta_k)) \quad (2)$$

The standard AC power flow equations are linearized which simplifies the equations. First approximation done in the linearization process is to approximate branches conductance to zero and susceptance to only depend on reactance. This approximation gives equations 3 & 4. [24]

$$P_i = V_i \sum_{k=1}^n V_k (B_{ik} \sin(\delta_i - \delta_k)) \quad (3)$$

$$Q_i = V_i \sum_{k=1}^n V_k (-B_{ik} \cos(\delta_i - \delta_k)) \quad (4)$$

The second simplification is a result of normal voltage angles, which are usually small. This leads to simplification of the sine and cosine functions,

$$\sin \delta \approx \delta \text{ and } \cos \delta = 1 \quad (5)$$

This then simplifies the AC power flow equations,

$$P_i = V_i \sum_{k=1}^n V_k (B_{ik} (\delta_i - \delta_k)) \quad (6)$$

$$Q_i = V_i \sum_{k=1}^n V_k (-B_{ik}) \quad (7)$$

Finally, the last simplification is done based on the assumption that the magnitudes of voltages are close to reference voltage, which if the calculation uses per unit values is one and thus the product of the voltages is close to one. This simplification transforms the power flow equations.

$$P_i = \sum_{k=1}^n (B_{ik} (\delta_i - \delta_k)) \quad (8)$$

$$Q_i = \sum_{k=1}^n (-B_{ik}) \quad (9)$$

After the simplifications, the reactive power  $Q$  turns into constant term depending only on the properties of the grid. These equations provide the relation between power injection and flow between the nodes.

The linearization process done when creating the PTDF calculation are severe. As the resistance is estimated to be zero, it removes the effects of the conductance and makes susceptance only to depend on reactance. This removes the changes induced by the losses in the power system. Along with this,

the angle difference estimation furthers the uncertainty. The simplification done in removing the voltages creates a simplification. Maximum error caused by this simplification matches the difference of the nodal voltage to the nominal voltage, which is at maximum 5%. This estimation gives little perspective to the scale of simplification done in the linearization of the AC-power flow.

### 5.3.2 Generation shift keys

The initial PTDFs are calculated for every node and the transformation to bidding zones needs to be done, which in itself creates more inaccuracy. This transformation is done using generation shift keys (GSKs). These shift keys are used in flow-based calculation method to describe the effects to a bidding zone when changing the net position of a node. The definition of the GSKs is critical when improving the accuracy of flow-based method. [24]

The problem in generating the GSKs is that there is not a theoretically optimal way to generate them. This problem can be solved in empirical manner, where the best strategy is found via testing with actual cases and results. For example, a simple GSK strategy is so called flat participation, where each node is set to handle same sized portion of the desired generation shift. This easily leads to problems as this strategy could give more generation that is physically possible. The optimal strategy have not yet been found, but it may well be that it varies between different bidding zones and time windows. The study of generating the GSK is however very important as the GSK parameters are used in the calculation of the zonal PTDFs.

When generating the GSKs it may be reasonable to consider about the type of node, which would be the first to react to shift in generation. One method to classify nodes would be by the type of generation they have, as typically one type of generation would have the capability to react to changes in cross-zonal transmission. The information that is needed to produce the knowledge about the order of which generation is the first to react is difficult.

### 5.3.3 Remaining available margin

Along with PTDF matrix, another parameter is important when grid constraints are provided to the market optimization; this is remaining available margin (RAM). This margin indicates the available capacity in the critical network elements, which can be used by the allocation mechanism. RAM is calculated from the maximum capacity given to each CNE with equation 10.

$$RAM = F_{max} - FRM - FAV - F_{ref}, \quad (10)$$

$F_{max}$  is the maximum capacity given to the CNE, FRM is flow reliability margin, FAV is final adjustment value and  $F_{ref}$  is the reference flow at zero net positions when using the base cases PTDF matrix.

RAM tends to be positive, however this is not guaranteed. As the RAM is calculated for CNEs maximum capacity and the CNEs estimated load may be over the maximum capacity, this can lead to

negative RAM. In such case where RAM is negative, the market coupling algorithm is forced to relieve the congestion from the CNE.

## 6. SOFTWARE TO CALCULATE BORDER TRANSMISSION CAPACITY

In this thesis, the goal was to create a software implementing the CNTC calculation method for cross-zonal transmission capacity calculation. As discussed earlier the CNTC method implements both steady state and dynamic analysis. Methods to analyse these phenomena are already well implemented into few different software and a pre-existing one was chosen to be used. The chosen software was PSS®E and because of PSS®E's application programming interface (API) utilizes Python programming language, was Python chosen as the programming language to be used for the software.

The focus of the software was to make it as understandable as possible for a typical user, which would be person working in Fingrid or other Nordic TSOs with little to none programming experience and lots of experience using PSS®E. This basis meant that a suitable software development method needed to be used in order to keep the different sections of the software understandable to the typical user. As a result, behaviour-driven software development was used. In short, behaviour-driven development focuses on producing understandable documentation for each feature of the software first before starting the actual coding. The benefits of this method are the well-documented features and early involvement of the stakeholders to the design process.

The software consist of three individual parts: the initialization of calculation, steady state analysis and dynamic analysis. The initialization part collects all the data, which is to be used in the calculation as well as sets up PSSE ready for the simulations. In steady state analysis a power flow study is ran and if the results are good, loads of the network are scaled in a matter, which increases the load in the to-be-calculated cross-border cut. Finally the dynamic analysis part that initializes the dynamic calculation and iterates through the list of contingencies checking only the ones chosen in the power flow stage.

### 6.1 Behaviour-driven development

Behaviour-driven development (BDD) is a software development method that focuses on encouraging collaboration between developers, subject-specific technical experts and other non-technical participants. The process begins with detailed discussion of the desired behaviour of the software. After this, the collaboration is further enhanced with feature documentation that is done using natural language. This use of natural language helps the non-developers to discuss the matter and it enhances the understanding of the features, which is necessary to produce desired software.

In this thesis, the application of BDD was done using python-based Behave. Behave enables the essential components of BDD which are the natural language definitions of features and the linking of these features to be used for testing purposes. Behave breaks BDD features down to three main components which are Given, When and Then. These are the keywords used to create the features of the

software and each of them serves a single purpose in the testing phase. Given is used in the feature to represent the premises of the testing. To run the feature keyword When is used. Finally, to ensure that everything went according to plan Then represents the state after steps defined in Given and When.

Testing the features defined is also done through Behave. Due to this, Behave introduces few keywords to be used in features. Each feature is partitioned to smaller parts, called scenarios. These scenarios are the core unit in the testing phase when using Behave, using them the full feature is described, and through them the feature is tested. With scenarios, the feature can include outline-keyword that gives the possibility to test the feature with multiple cases. These cases are presented in the examples section.

Feature: Contingency file parsing

@contingency

**Scenario Outline:** Contingency file is parsed successfully

**Given** path is <file\_path>

**and** the contingencies are meant for common grid model <iscgm>

**When** contingency file is parsed

**Then** number of contingencies is <number>

**and** in <contingency> there is <number\_faults> faults

Examples: Contingency files

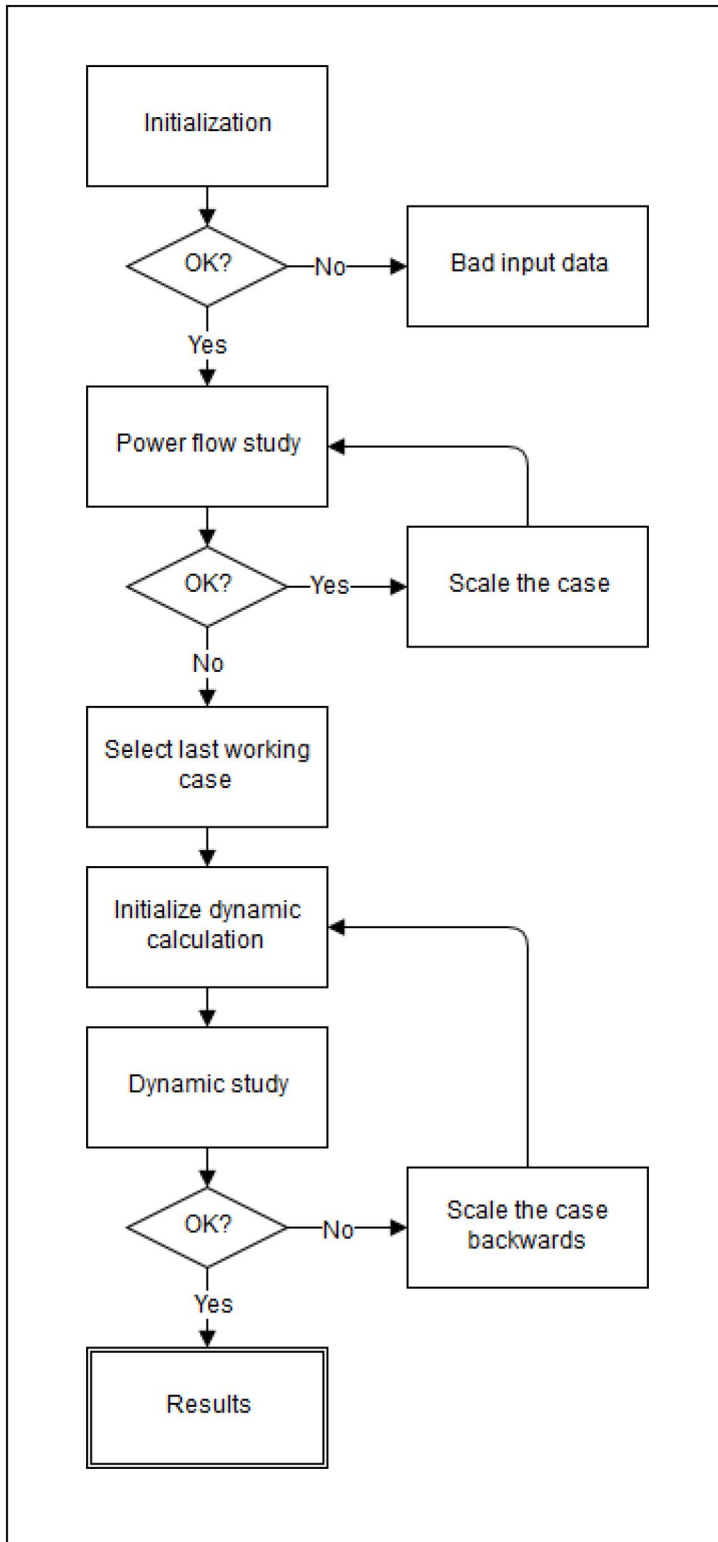
<i>file_path</i>	<i>iscgm</i>	<i>number</i>	<i>contingency</i>	<i>number_faults</i>
.\fil.con	False	76	OL43 - HT4	1

**Program 1.** *Example of a natural language feature file used in CNTC-development*

As seen from Program 1 the Behave language makes the BDD technique to use pseudo-natural language by presenting the possibility to define variables. These variables gives the possibility to use one scenario as an outline for testing multiple cases with one scenario.

## 6.2 Software

Because of the CNTC-calculation, the software was partitioned into three separate pieces: initialisation, power flow and dynamic analysis. These handle different sections of the calculation generating results as inputs for the next section until the result is achieved. As the initial input data has to be gathered from multiple locations, it was seen as a best choice to create an own initialisation section responsible for handling this phase. The other two, steady state and dynamic analysis are a natural consequence of the calculation method.

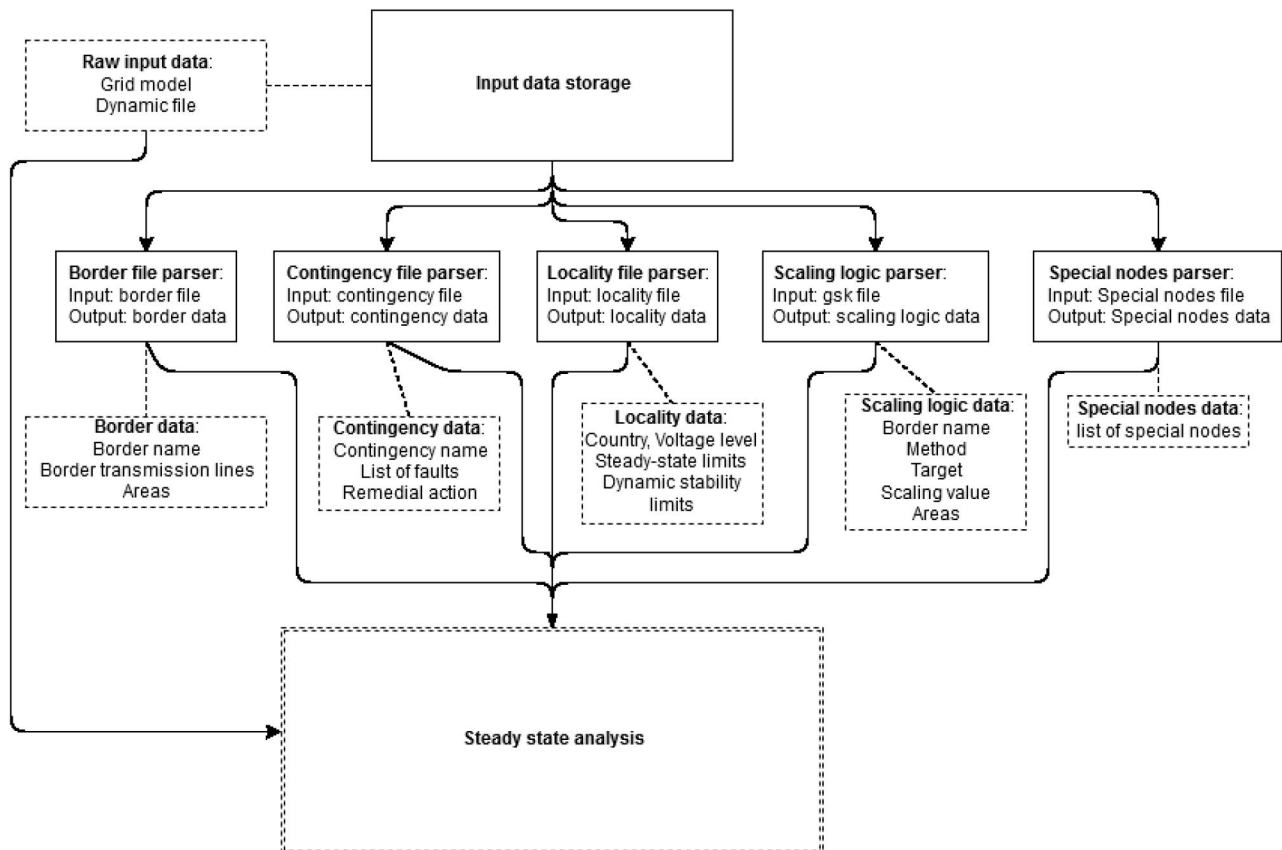


**Figure 6. High-level block-diagram of the software**

The sections presented in Figure 6 are further elaborated in the following subchapters. In every section of the software, some sanity checks are also done in order to verify the success of the PSSE-simulations. If any of the sanity checks fails, the reason is written to log-file and the software successfully exits without returning any sort of result for the bidding zone border currently calculated.

## 6.2.1 Initialisation

In the scope of the thesis, the software was developed for calculating capacities between Finland and the first bidding zone in Sweden (SE1). In the future, the software however is required to be able to calculate every bidding zone border in Northern Europe. Due to this, few functions in initialisation are overly capable considering the scope. In the initialisation phase, five different files containing necessary information for the CNTC-calculation need to be parsed. Figure 7 presents the initialisation process.



**Figure 7. CNTC initialisation**

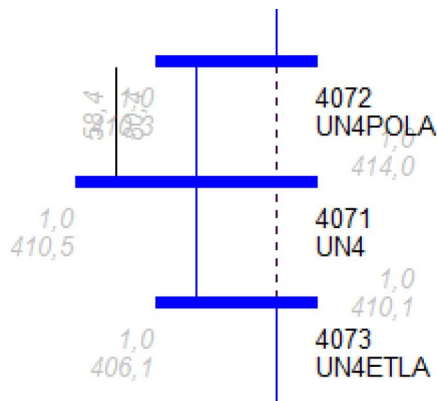
Border data file includes the bidding zone borders that are to be calculated. A single border data unit includes the name of the border, transmission line data used that complies with the grid model and the bidding areas that are required to be checked in the validation of steady state and dynamic analysis results. This data file is parsed in border data parser, which returns a single border data unit to be used in CNTC-calculation.

Contingency data file includes all the possible contingencies to be used for the grid models topology. A single contingency data unit includes the name of the contingency, the border it affects, a list of faults and the necessary remedial actions used when applying this contingency. The contingency data file is parsed in contingency parser, which returns a list of contingencies that should be calculated for the bidding zone border that is to be calculated.



Locality data file contains the local operational security limits for every country and for every voltage level. Locality data includes the steady state limits for voltage and for dynamic analysis the limits for voltage and frequency. For steady state, the limits are simple values of voltage for each voltage level. In dynamic analysis however, the voltage limits include damping, minimum, maximum and limit for the end voltage of the dynamic analysis. For frequency in dynamic analysis the limits are simple values not-to-be crossed.

Scaling logic file contains the scaling logic to be used when calculating the maximum transmission capacity for the chosen bidding zone border. Scaling is the mechanism that provides the CNTC-method the possibility to calculate the transmission capacities as the boundaries can be found by pushing the case until something goes wrong in the analysis section. Scaling logic data includes the border the data covers, method of scaling, the target to be scaled, scaling value and the areas of scaling. The scaling value is either the actual power that is to be scaled or the percent of scaling. This depends on the chosen method of scaling, which can either be incremental scaling or by the percent scaling. The target specifies whether the logic wants to scale the loads, or the generation for the areas defined.



**Figure 8. Virtually modelled series compensation nodes that are to be removed from the security checks**

Finally the last data file is special nodes. These nodes are nodes that exist in the grid model but are not supposed to be checked during the calculation. For example in Finland, the series compensation is simulated as a separate virtual node from the actual substation node as shown in Figure 8. Because of this, for Finland the special nodes include all of the series compensation that is presented in this format in the grid models. The parsed data is a list of nodes.

As well as the parsed files, the calculation needs the actual grid model and dynamic file. The dynamic file specifies the dynamic analysis data that is necessary when dynamic analysis is performed. These files do not need any kind of preparation, so they are just passed to the calculation and are expected to be usable.

### 6.2.2 Steady state analysis

After the initialisation the steady state analysis is performed. In steady state analysis, the grid models scaling is done. This means that generation or load on the other side or both sides of the studied border are increased/decreased in order to find the maximum allowed power flow for the border. The scaling is continued as long as all of the steady state checks pass. Including the scaling, the contingencies are ranked by the dimensioning power. This is done in order to limit the number of contingencies used in the dynamic analysis. A figure that presents this process in detail can be found from Appendix 1: Steady state analysis process.

Initially the steady state analysis runs a power flow study to the grid model. A power flow study is ran for every contingency and after every power flow study the voltages of every node and every transmission lines' flows are checked to be within limits. The limits for voltages are given in the locality file and flow limits are gathered from the grid model. If the grid model passes the initial steady state analysis, as in every voltage and flow is within limits for every contingency and in the base case, the scaling of the grid model begins.

The voltage checks iterate through every node that is in the border data defined areas between voltages that user defined, but a default argument is a margin between 300-500 kV. This voltage limit defines the nodes that are checked in the analysis, e.g. all the nodes with nominal voltage in between the defined limits. The default margin was chosen as the voltage levels may vary in the grid models and all of the roughly 400 kV nodes wanted to be included to the checking process. The transmission lines between these nodes are checked in the flow checks. The thermal limits are included in the grid model and the comparison is done between the simulated flows and the thermally limiting flows. As said in the initialisation phase some of the nodes are not to be checked as defined in the special nodes list. As the power flow study iterates through the contingencies every node that is set to be in fault is also added to the special nodes list for the duration of the checks. This is done because the faulty nodes break the voltage limits, as a natural cause of the fault. The checks are done with the fault on in the grid. After the contingency is checked, the nodes that were added to the special node list are removed.

In the scaling phase, the steady state analysis has two main goals: to find the maximum of power flow for the grid model using the defined scaling logic and to evaluate the worst contingencies. The maximally scaled case is analysed in the dynamic stability analysis. The analysis in steady state is considerably faster than dynamic stability analysis. Due to this, it was seen as reasonable to first find the maximum of the steady state and backtrack the scaling if necessary in the dynamic analysis.

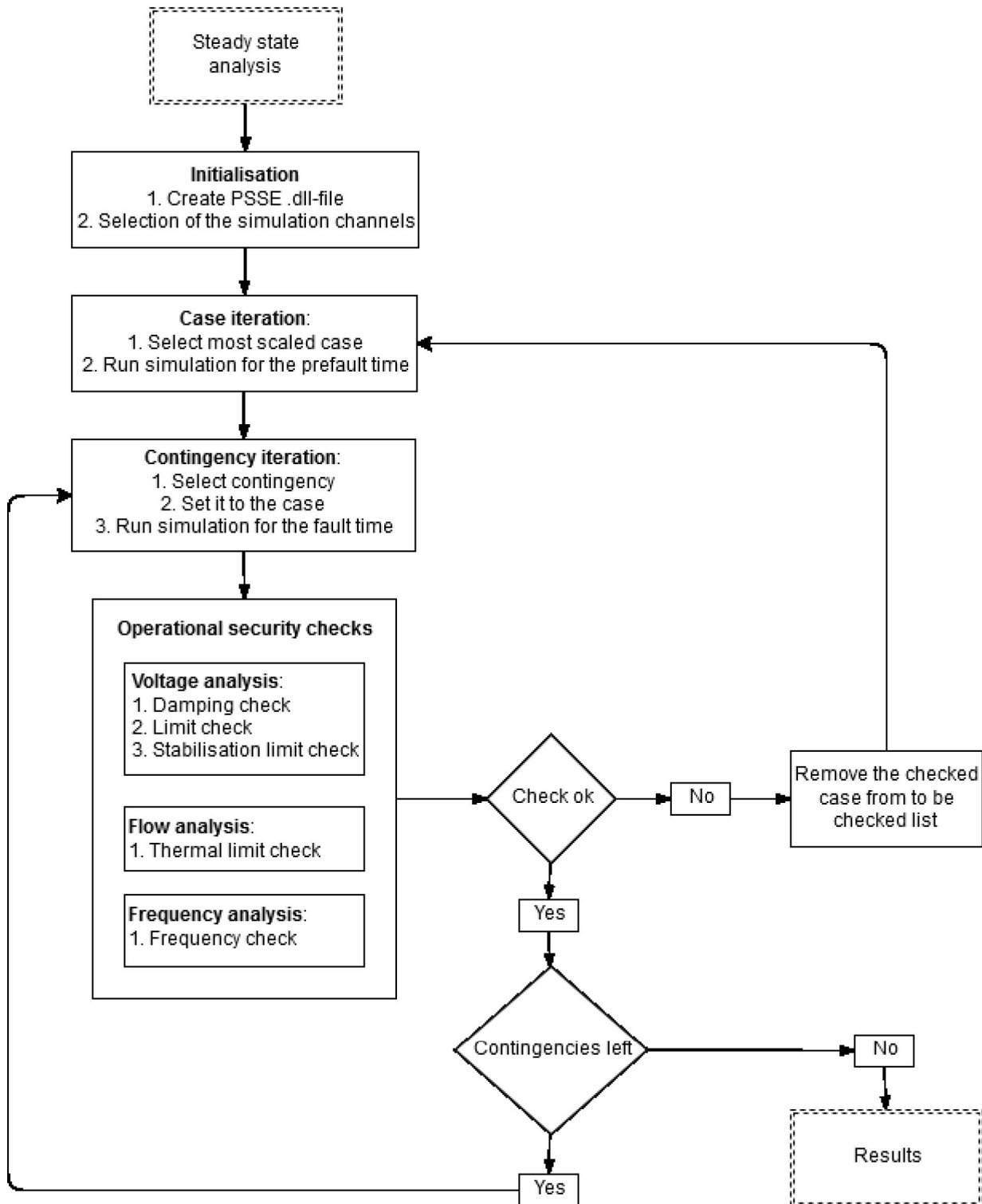
The finding of the steady state maximum is rather straightforward. Given that the base grid model was able to pass the initial power flow study, the case is scaled using the logic defined in the scaling logic data file. If the scaling is successful, a power flow study is ran using all the contingencies given for the border currently calculated. This scaling process is continued as long as a case breaking the operational security limits is found. As the first faulty case is found, the limiting contingencies are marked with the sum of scaling.

After the first faulty case the scaling is continued. This is done in order to find the worst contingencies to be used in the dynamic analysis. The number of rounds in this over-scaling phase is predefined by the user. As the scaling proceeds and the contingencies are iterated through, the sum of scaling is marked as the dimensioning power for each dimensioning contingency. This means that if the presented contingency leads to a situation where the operation security limits are violated the contingency is marked with the sum of scaling. With this process, the number of contingencies to be calculated in the dynamic analysis is limited as much as the user wants them to be. Analysis of this elimination of the contingencies used in the dynamic phase is shown in the case study chapter.

### 6.2.3 Dynamic analysis

The dynamic analysis is ran after the steady state analysis has provided it the results of the contingencies to be analysed and the scaled cases. The dynamic stage takes from the input data parser as an input the dynamic limits and the dynamic conversion file. The analysis begins from the maximally scaled case and iterates through the scaled cases as long as a case that passes the dynamic analysis is found. In every iteration the dynamic voltages, frequency and flows are analysed. This process is shown in Figure 9.

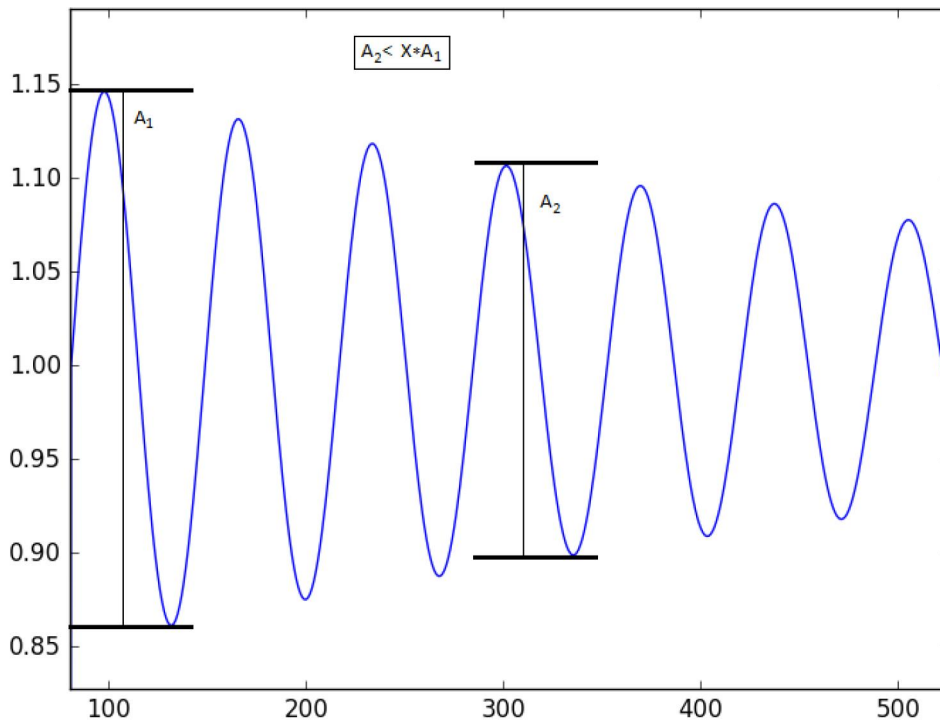
A single iteration round in dynamic analysis iterates through the worst contingencies for the grid model. The dynamic simulation time can be set by the user, as well as the time before the contingency is set and the duration of the contingency. The possible remedial actions are left out of the scope, as stated in the introduction. The iteration procedure is as follows: simulate the defined time before contingency, set the contingency to the grid model, simulate the time defined for the contingency to exist in the grid, remove the contingency and finally simulate to the end of the simulation time. After the simulation, the analysis tool checks the signals produced by the simulation software. The signals are list of values where every value indicates the signals level for the time step. This procedure is completed for every contingency that was collected in the steady state analysis.



**Figure 9. Dynamic analysis process**

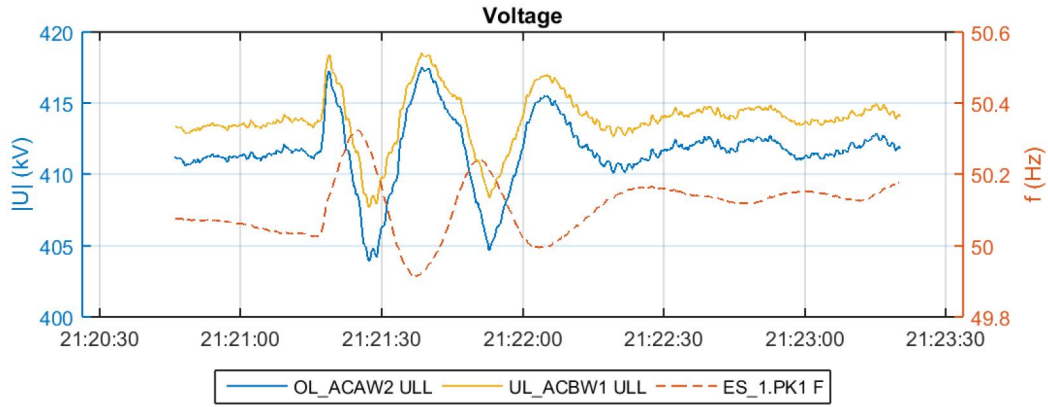
The checks done for each contingency simulations are voltage, frequency and flow checks. These checks are seen as sufficient for the period where the calculation is to be conducted. If any of the checks fails the case is determined as invalid and a lesser scaled case is chosen to the iteration. The values for the checking are defined in the locality data file, and vary depending on the country.

The most complicated checking procedure is the voltage check. For every voltage signals produced by the simulation the minimum voltage, last voltage and damping are analysed. The minimum voltage level and last voltage level are rather straightforward. The locality values define the limit for each parameter. The minimum voltage analyser finds the lowest voltage level after the fault and checks whether it is under the defined limit. For the last voltage level, the analyser takes the average of the last hundred values and checks whether this is within limits. The signals are analysed after the fault has been removed.



**Figure 10. Amplitude damping**

The basis for analysing the oscillations damping is rather simple. The oscillation amplitude should reduce by some predefined value in some predefined number of oscillations. The principle is presented in Figure 10. Basically, the idea is to find the local minimums and maximums between the predefined number of oscillations and check the change in amplitude. However, as the signals often are noisy the checking becomes somewhat more difficult. A typical voltage signal after fault is presented in Figure 11. The noise in the signal creates local minimums and maximums and the calculation of damping becomes much harder. This problem is easily solved, as the nature of the oscillation is understood. The frequency of the most typical oscillation is around 0.1-2 Hz [16] which can be used when estimating the time between the peak values. This estimation of the typical frequency for the oscillation was done in order to simplify the calculation. As the time between can be estimated the local minimums and maximums created by the noise can be skipped.



**Figure 11. Example of noisy voltage-signals.**

The frequency and flow checks are simple limit checks. In the locality values the maximum and minimum for frequency is defined and these are typically constants. The end limit for the frequency isn't set as the limits used in the study for the whole signal are set to be strict enough. The checks are done in similar fashion as the minimum checking is done for voltage signals. The flow limits, which are the thermal limits, are defined in the grid model. The checking is done just by finding the flow signals maximum from the simulation and comparing it to the limit defined in the grid model.

## 7. CASE-STUDY FI-SE1

To test out the developed method, the necessary data for the cross-zonal transmission line between Finland (FI) and Sweden's first bidding zone (SE1) testing was collected. The testing of the method was done with the Nordic Planning Model, which is a grid model of the synchronous Nordic power system done in cooperation with all of four Nordic TSOs. The contingencies that affect the power transmission on the chosen transmission line are specified by both TSOs, Fingrid and Svenska Kraftnät. The scaling logic used to find the maximum transmission limit was defined by Fingrid.

The comparison of the results given by CNTC-method was done to the currently in use NTC-values. The NTC-values are calculated in the Nordic Planning model, so the results were thought to be comparable. The comparison to the flow-based method was not possible to be done, as the flow-based approach currently is not capable of producing results.

First, the proposed method to limit the number of contingencies in the dynamic analysis is shown. The contingency analysis was done with the same data collected to verify the CNTC-method. After the contingency analysis, the actual case study is explained. Finally, the results are shown.

### 7.1 Contingency analysis

As discussed in the description of the software, the steady state analysis is much faster than dynamic analysis. Especially, as the number of contingencies used in the analysis grows, the calculation of border transmission slows down tremendously with every dynamic contingency analysis. The software is required to calculate results in a reasonable time considering the time scales defined in the CACM.

A proposal to eliminate the contingencies used in the dynamic analysis is that, the contingency should be analysed in the dynamic analysis only if the contingency violates the operational security limits in the steady state analysis. In other words, if the contingency is a limiting contingency in the steady state, it supposedly is a limiting contingency in the dynamic analysis. This method was tested with two cases analyse whether this method is usable in limiting the number of analysed contingencies.

The testing process was an extended version of the CNTC-method where all the contingencies were analysed in both steady state and dynamic analysis and the dimensioning powers were collected. The dimensioning power is in this instance the sum of scaling that forced the case to violate the operational security limits. As in CNTC, first the steady state analysis was completed with upwards scaling as long as the case stayed within operational limits for all the contingencies. After a scaled case that violated the operational security limits were found, the scaling was continued linearly for ten rounds totalling at 500 MW's of upscale after the non-converged case. In every scaling round, the contingency analysis was completed and for all the contingencies resulting in case out of the operational security limits, the contingency was marked with the total of scaling as a dimensioning power.

After the steady state analysis, all of the cases were analysed in the dynamic scope. If a contingency resulted in signals that were out of the operational security limits the contingency were again marked with a dimensioning power. The smallest dimensioning power was the one to be documented in the results.

Typically, in the cross border capacity calculation the limiting phenomenon depends on the direction of the flow. When exporting from Finland to Sweden, the limiting analysis has been the dynamic analysis and for the import case, the steady state analysis has set out the limit for power transmission. Due to this, the contingency analysis was done for both cases separately.

## **7.2 The Case: FI-SE1**

The case study was run with seven different scenarios of Nordic Planning models. The grid models are further explained in the grid models chapter. The case study has two separate parts, first in which the calculation is done on import case, which means that power is imported to Finland from Sweden. The second part is the export case, in which Finland exports power to Sweden through the AC-connection.

To calculate the transmission capacities, border data is also needed. The data is explained in the border data chapter. Border data holds the data of the transmission lines that are focus of the study. Including this, the scaling logic and contingencies are included in the border data. Everything else in the border data are static in different grid models, outside of the scaling logic which changes between the export and import cases.

### **7.2.1 Grid models**

The basis for the cross border capacity calculation is the grid model. In this case study the verification of the proposed method was done with the Nordic planning grid model. The Nordic planning grid model is done in cooperation with all the Nordic TSOs. This model is used in planning the Nordic grid.

The Nordic planning model holds the most accurate data at hand of the Nordic grid. However, the model is a static model, which means that the generation data and load data used in the model are estimates of the real time steady state operation. The grid model incorporates data of every primary component used in the grid; these are for example the power transformers and series compensation. This grid model was chosen to be used as it supposedly provides the most accurate results in the capacity calculation.

In this case study there was five different Nordic planning grid models used for the case where the power is imported from Sweden to Finland. Four of the models were different versions of the grid model. The separation between the models was done by the season, two of the models the winter situation and the other two model summer. The difference in versions inside a season was the basis used in creation of the grid model. For both, summer and winter, one model was based on Nordic grid



model made from grids topology on summer. The other one was done based on the winter model of the Nordic grid model. The last of the models was a winter model of the predicted grid for year 2017. In the 2017 model the transmission capacity between northern and southern Finland was enforced with one transmission line. For the export case there was two different grid models, which were separated by season, one for winter of 2016 and another one for winter of 2017. In the export models the difference between the two years is the same as in import models; the transmission capacity inside Finland was enforced.

<b>Grid model</b>	<b>Production</b>	<b>Consumption</b>	<b>RAC import</b>	<b>Fennoskan import</b>	<b>Estlink import</b>	<b>Russia import</b>
Winter 2016 version Winter	10700	13340	1140	1180	-200	530
Winter 2016 version Summer	10460	13340	1580	1180	-150	40
Summer 2016 version Winter	6210	8460	1120	1180	-180	50
Summer 2016 version Summer	6450	8470	1110	1180	-400	50
Winter 2017	10600	13220	1130	1180	-240	530
Export 2016	9450	9170	-1350	-1200	990	1290
Export 2017	9330	9150	-1290	-1200	990	1290

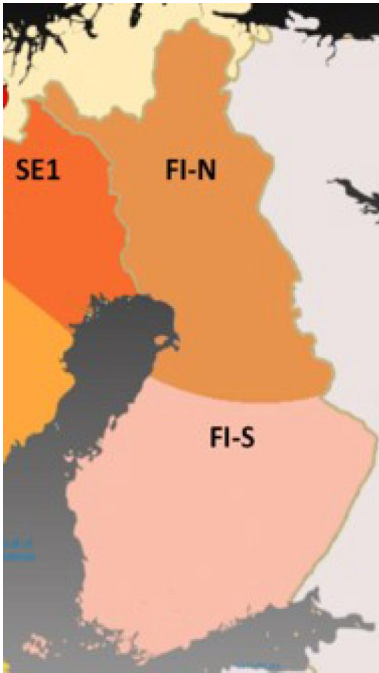
**Table 1. General data of the used grid models**

Table 1 presents general data from the Finland's bidding zone collected from the used grid models. All numerical data is presented in MW's. Production and consumption are positive, but naturally the consumption consumes the produced power. The import data is seen as power flowing towards Finland. That is to say, that for example the RAC import is seen as power flows from Sweden to Finland. The cross border transmission data is collected from the base case, which is then scaled in order to maximise the capacity.

### **7.2.2 Border data**

The CNTC-calculation software expects input data that specifies the border that is to be calculated. In this case study the border transmission lines between Sweden and Finland were collected from the grid model. As the border is chosen the method needs the scaling logic, which is used in order to maximise the power transmission on the chosen border. The used contingencies are the ones that both TSOs use in normal operational security analysis of the chosen border.

In between the Sweden's first bidding zone (SE1) and Finland there currently is two 400 kV transmission lines. The power transmission over these lines is to be maximised in this case study. The transmission line data was collected from the grid models manually. The data included the node numbers, which indicate the transmission lines both ends. This data was used to collect the sum of power transmission.



**Figure 12. Rough outline presenting P1 cut of Finland**

The scaling logic for the chosen border in both import and export situations were defined by Fingrid. The simplest method of scaling was to scale the consumption. This is due that the scaling can be done as uniformly as possible for the chosen area. The scaling in import situation is done in the southern Finland where most of the consumption of Finland is located. The balancing power in this scaling method comes from the slack bus that is located in Sweden. This method of scaling is the simplest in maximising the power transmission in the border transmission lines. The export situations scaling logic was to downscale the consumption of the southern Finland nodes. The rough division of southern Finland and northern Finland is shown in Figure 12.

## 7.3 Results

The two different analysis results are collected in this chapter. First the results of the contingency analysis are shown. After this the case study results are shown for both export and import cases.

### 7.3.1 Contingency analysis results

The capability to reduce the number of contingencies analysed in the dynamic analysis phase was studied with two different cases. First, an import case was used as a basis for the analysis. Secondly, an export case was studied.

In the import case the limiting contingencies were different in steady state analysis and in dynamic analysis. As the first non-convergent case was found the case was further upscaled by 500 MWs. Despite this, some of the contingencies listed by the TSOs did not violate the operational security limits. The limiting factor was found in the steady state analysis for the import case.

The limiting factor was supposed to be found from the dynamic analysis in the export case. In the contingency analysis this result was not found, rather the steady state analysis is the limiting method of analysis. In the contingency analysis any indication of the relation in the limiting contingencies between the two analyses methods was not found for the export case. This means that the limiting contingencies were different in steady state and dynamic analysis.

For cases where the limiting analysis method is steady state analysis, the reduction of the analysed contingencies should not be done. However, if the limiting analysis method can be verified to be steady state analysis the removal of the contingencies in the dynamic analysis is not necessary as the dynamic analysis is redundant.

With the tested cases the method to limit the number of contingencies could not be proved as usable. This is due to the lack of cases where the limiting analysis method is the dynamic analysis. If the limiting power is found in the steady state analysis, the case does not represent a case where the method would be used.

### 7.3.2 Case study results

The capacities presented are the technical capacities as the method to allocate the capacities and to calculate the reliability margin in CNTC is yet to be defined. The CNTC methods results are compared to the currently in use NTC methods technical capacities in the chapter 8. The case study results for the import case are documented in Table 2. It is important to note, that CNTC values are calculated using only the N-1 principle, whereas the comparison values for NTC are calculated in respect of the (N-1)-1 situations and accounting the limitations that arise also from the amount of reserves.

<b>Grid model</b>	<b>CNTC technical capacity (MW)</b>
Winter 2016 version Winter	2120
Winter 2016 version Summer	2040
Summer 2016 version Winter	1660
Summer 2016 version Summer	1590
Winter 2017	2340

**Table 2. Case study CNTC-results in import cases**

As it can be seen from Table 2 the CNTC method successfully calculated import transmission capacities as the capacities are somewhat similar to the current NTC capacities. The great difference in the transmission capacity was found in the Winter 2017 case, in which the transmission capacity from

northern Finland to southern Finland was enforced. This growth of over 700 MWs in transmission capacity was remarkable and the possible reasons for all of the cases are discussed in the chapter 8.

In the calculation of the import transmission power an interesting phenomenon considering the dimensioning contingencies were noted. In this instance, the dimensioning contingencies are contingencies that were the first to force the case to violate operational security limits. In all of the five cases of Table 2, the dimensioning contingency was one of two different contingencies. This implies that only two contingencies is needed in the analysis of the RAC-border in the import case.

The CNTC-calculation values for the two export cases are documented to Table 3. The two grid models used are indicated in the grid model column.

<b>Grid model</b>	<b>CNTC technical capacity (MW)</b>
Winter 2016	1780
Winter 2017	1480

***Table 3. Case study CNTC-results in export cases***

From the results shown in Table 3 it can be seen that the CNTC method was capable of producing reasonable transmission capacities in the export case. In comparison to the import case it was notable that the enforcing of the transmission capacity between northern and southern Finland did not improve the transmission capacity to Sweden. The data in Table 3 suggest the contrary, the enforcing lowered the export capacity. However, the number of studied cases does not provide enough evidence to make this suggestion significant. In order to properly validate the result more thorough analysis of the grid models are in place especially if the number of grid models is this low. However, as the CGMs become available for the calculation these problems are expected to ease.

The presumption was that in the export case the limiting analysis method would be dynamic analysis. This was not the case found in this case study. In previous Fingrid's internal studies of the export capacity the limit has been significantly lower and the limiting analysis method has been dynamic analysis. For both export cases the limiting analysis method was steady state analysis. The dimensioning contingency phenomenon that was present in the import case did not appear in the export calculation. This might be due to the lack of usable grid models simulating the export situation in the Nordics, which lowered the number of studies on the contingencies.

## 8. DISCUSSION

As shown in the results the tested CNTC-method was capable to produce technical transmission capacities for the import case. The current NTC technical transmission capacity for the import case is 1600 MWs and this is a bit over the lowest transmission capacity found over the five import cases analysed. The current capacity is calculated using the same grid models as the ones used in the case study. The capacity deviations were over 700 MWs in these five cases. This shows that there is value in calculating the technical transmission capacities for all seasons using the common grid model, and not only apply average annual capacity values calculated with equivalents for other parts of Nordic system. When the hourly common grid models become usable for the calculation, the accuracy is expected to increase.

The current technical import capacity of 1600 MWs is a result of the Finnish grids capability to withstand surplus or deficit in an island operation in addition to the amount of fast disturbance reserves maintained in Finland. The possibility of island operation in Finland arises from the (N-1)-1 criterion used in the operational planning. The amount of reserves and the (N-1)-1 criterion was not taken into account in the CNTC-method. The results presented in the case study results show what the grid is capable of handling when applying the N-1 principle. They are not comparable to today's NTC values due to the fact that NTC values are calculated applying the (N-1)-1 criterion. More detailed socio-economic and technical studies about the need for the (N-1)-1 principle should be conducted as the limited cross border transmission capacity definitely affects the electricity prices in Finland.

For the export case, the calculation was capable of producing results that were a bit over the current NTC-values of 1200 MWs. Some deviations in the transmission capacity is seen in the results, but as the number of viable cases analysed was limited the results are not capable of showing effects to technical export transmission capacity.

The results show that the developed CNTC method was able to calculate technical transmission capacity for the FI-SE1 border in both export and import cases. The number of export cases was low which was due to the lack of recent situations where there was export from Finland to Sweden. Further validation of the method is obviously needed before the method can be taken into use in the Nordics. This validation can be done after the common grid models are developed to be available for such calculation. Despite the need of further validation, the developed method shows capability of calculating the technical transmission capacity for the studied border.

The variance presented in the results suggests that more frequent technical transmission capacity calculation would improve the accuracy of the capacities, especially as with the hourly common grid model. If the accuracy in the capacity calculation is increased, it might be sometimes possible to give more transmission capacity without violating the operating security limits. In addition, the more accurate cross-zonal capacities improve the system security.

To further develop the CNTC-method, the accuracy of the scaling logic should be increased. This could be done by focusing on the scaling of the generation instead of the consumption that was used in the case study. This should be the first step in finding the optimal scaling logic, which should also reflect the market participants. Nevertheless, the most reasonable scaling logic is something that needs more studying. Along with the scaling logic, a method to account for the remedial actions used in the operational planning should be developed in the future.

To finalise the developed method into a fully CACM compliant CNTC methodology, a methodology to determine the capacity sharing rules should be developed. The sharing rules are important within the meshed grid where the bidding zones are connected with many cross border transmission lines to a number of different bidding zones. In a meshed grid, the cross-zonal transmission capacities are interdependent. This holds especially for the Norway's borders, but not necessarily in Finnish borders. In this situation, the calculated technical maximum capacity cannot be given to the market, as the technical maximums are not simultaneously feasible. The sharing rules determine the logic for sharing the capacities for different bidding zone borders.

The number of contingencies is a vital performance meter for the calculation as the dynamic analysis slows down rather quickly as the number of contingencies increases. The analysis of how the number of contingencies can be reduced should be continued. The study should include studying of previously published papers on this subject and more case studies reflecting the methods found, especially such case studies where the dynamic stability is the limiting analysis method. So far, the results show that the contingencies cannot be reduced with the proposed contingency limiting method. However, dynamic phenomena are often limiting the technical transmission capacities in Nordic region. A method to limit the contingencies analysed in the dynamic analysis should be developed.

The flow-based capacity calculation methodology is better at allocating the power flows between bidding zone borders in case where interdependencies between these bidding zone borders exist. However, flow-based expects the technical transmission capacities for the CNEs as input. The CNTC-methodology calculates the technical transmission capacities for the cross border lines accurately. Naturally, from these premises the solution could possibly be a mixture of the two methodologies, where the CNTC approach is used to calculate the technical capacities for CNEs and flow-based allocates the capacities for each border.

The CNTC-method needs to be better validated before implementing it. The basic functionality is working, but if the method is used in real calculations of cross border transmission capacities, the software is to be tested for various cases. This process has been done in small scale already, but as the software is a prototype more larger scale testing should be conducted. This is to find the possible bugs and wrong assumptions made in the development of the software. The thorough validation process is definitely necessary, as the calculation resolution is changed to one hour, as with that calculation frequency the validation of every cross border transmission capacity by hand is not anymore possible.

## 9. CONCLUSIONS

This thesis set out to improve the current NTC-methodology to make it CACM guideline compliant. The current NTC approach as it is currently utilised is not CACM compliant. As the CACM guideline, is in the implementation phase the methodology needs transforming in order to comply with the guideline. CACM gives two different options for the capacity calculation, flow-based and a coordinated NTC-methodology.

To develop the CNTC-methodology, the CACM requirements for the capacity calculator were analysed and partitioned into manageable pieces. Based on these requirements the NTC-methodology was modified while holding on to the major components that form the basis of NTC. All of the components were developed to the CNTC-method, whilst keeping in mind the guidelines requirements. The developed CNTC-method is capable of analysing both steady state and dynamic phenomena, which are seen as the fundamental security analysis methods in cross zonal capacity calculation.

The developed CNTC-method was tested with a case study for a single border, the AC cross border between Finland and Sweden. Along with the case study, a mechanism to reduce the number of contingencies analysed in the dynamic analysis was tested. This method to reduce the number of contingencies however, was not capable of limiting the number of contingencies. In the case study the necessary input data was collected from both TSOs, Fingrid and Svenska Kraftnät. The case study was done with all of the recent planning grid models, which model the whole Nordic synchronous system in normal operating conditions as accurately as possible.

The calculated transmission capacities varied over 700 MWs. When compared to the current NTC-values the results went from marginally lower to over 650 MWs higher capacities. As the variance in the border transmission capacity is great, the case study suggests that a more frequent calculation of the capacities would be in place. The results also suggests that this change would lead to more accurate transmission capacities and changes in the transmission capacities depending on the season. Due to the varying transmission capacities the use of coordinated capacity calculation approach is recommended. This holds especially as the hourly common grid models are viable to be used in the calculation.

The results show that the goal of this thesis was achieved, as the CNTC method was able to calculate reasonable technical capacities and the calculation is done based on most of the requirements in the CACM guideline. The variance in the calculated capacities when compared to the current NTC-values are due to a grid reliability policy that further limits the capacities if the reserves in the calculated area are not sufficient along with other factors as discussed in the discussion chapter.

## REFERENCES

- [1] TSOs in Denmark, Finland, Norway and Sweden, Nordic Grid Code, web page. Available (accessed 10/10): [https://www.entsoe.eu/fileadmin/user\\_upload/\\_library/publications/nordic/planning/070115\\_entsoe\\_nordic\\_NordicGridCode.pdf](https://www.entsoe.eu/fileadmin/user_upload/_library/publications/nordic/planning/070115_entsoe_nordic_NordicGridCode.pdf).
- [2] Statkraft, Hydropower, web page. Available (accessed 11/11): <http://www.statkraft.com/energy-sources/hydropower/>.
- [3] Energinet, Electricity generation, web page. Available (accessed 11/11): <http://www.energinet.dk/EN/KLIMA-OG-MILJOE/Miljoerapportering/Elproduktion-i-Danmark/Sider/Elproduktion-i-Danmark.aspx>.
- [4] Official Statistics of Finland (OSF), Production of electricity and heat, web page. Available (accessed 11/11): [http://www.stat.fi/til/salatuo/2015/salatuo\\_2015\\_2016-11-02\\_tie\\_001\\_en.html](http://www.stat.fi/til/salatuo/2015/salatuo_2015_2016-11-02_tie_001_en.html).
- [5] Byman Karin, Electricity production in Sweden, 1, 2016, 7 p.
- [6] Fingrid, Nordic power system and interconnections with other systems, web page. Available (accessed 11/11): <http://www.fingrid.fi/en/powersystem/general%20description/Nordic%20power%20system%20and%20interconnections%20with%20other%20systems/Pages/default.aspx>.
- [7] ENTSO-E, Interconnected network of Northern Europe, web page. Available (accessed 12/9): [https://www.entsoe.eu/Documents/Publications/maps/Map\\_Northern-Europe-3.pdf](https://www.entsoe.eu/Documents/Publications/maps/Map_Northern-Europe-3.pdf).
- [8] ENTSO-E, The Network Code on Capacity Allocation & Congestion Management (NC CACM), web page. Available (accessed 06/07): <http://networkcodes.entsoe.eu/market-codes/capacity-alloc-congestion-management/>.
- [9] Fingrid, Balancing power market, web page. Available (accessed 11/16): <http://www.fingrid.fi/en/customers/Balance%20services/management/powermarket/Pages/default.aspx>.
- [10] Fingrid, Frequency control reserves, web page. Available (accessed 16/11): <http://www.fingrid.fi/EN/ELECTRICITY-MARKET/RESERVES/RESERVETYPES/Pages/default.aspx>.
- [11] Nord Pool, Market Data, Nord Pool, web page. Available (accessed 11/20): <http://www.nordpoolspot.com/Market-data1/#/nordic/map>.
- [12] Nord Pool, Day-ahead market, web page. Available (accessed 11/11): <http://www.nordpoolspot.com/How-does-it-work/Day-ahead-market-Elspot-/>.
- [13] A guideline on capacity allocation and congestion management, L 197, 2015.
- [14] GENERATION AND LOAD SHIFT KEY IMPLEMENTATION GUIDE, 2016, pp. 6-7-8.
- [15] ENTSO-E, Regional Security Coordinators, web page. Available (accessed 11/8): <https://www.entsoe.eu/major-projects/RSC/Pages/default.aspx>.



- [16] P. Kundur, Power System Stability, in: CRC Press, 2012, pp. 1-12.
- [17] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziaargyriou, D. Hill, A. Stankovic, C. Taylor, T. Van Cutsem, V. Vittal, Definition and classification of power system stability IEEE/CIGRE joint task force on stability terms and definitions, IEEE Transactions on Power Systems, Vol. 19, No. 3, 2004, pp. 1387-1401.
- [18] H.L. Elovaara Jarmo, Sähköverkot I - Järjestelmätekniiikka ja sähköverkon laskenta, 1st ed. Otatieto, Helsinki, 2011, .
- [19] Kantaverkkowiki: N-1-kriteeri, in: Kantaverkko Wiki, Fingrid Oyj, 2016, pp. 180.
- [20] Fingrid, Determining the transmission capacity, web page. Available (accessed 09/14): <http://www.fingrid.fi/fi/sahkomarkkinat/markkinaliitteet/Rajakapasiteetit%20ja%20siirrot/Siirtokapasiteetin%20m%C3%A4%C3%A4ritt%C3%A4minen%20eng%202015.pdf>.
- [21] Konttinen Lasse, Flow-based kapasiteettilaskentahanke, Fingrid, web page. Available (accessed 03/13): [http://www.fingrid.fi/fi/asiakkaat/sahkomarkkinat\\_ja\\_edunvalvonta/markkinaintegraatio/Flow%20based%20-kapasiteetinlaskentahanke/Sivut/default.aspx](http://www.fingrid.fi/fi/asiakkaat/sahkomarkkinat_ja_edunvalvonta/markkinaintegraatio/Flow%20based%20-kapasiteetinlaskentahanke/Sivut/default.aspx).
- [22] P. Sörös, D. Divényi, D. Raisz, Flow-based capacity calculation method used in electricity market coupling, 2013 10th International Conference on the European Energy Market (EEM), pp. 1-7.
- [23] ENTSO-E, ENTSO-E Critical Network Element Implementation guide, web page. Available (accessed 11/09): [https://www.entsoe.eu/Documents/EDI/Library/critical\\_network\\_element\\_implementation/10e%20Critical%20Network%20Element%20Implementation%20Guide%20V1R1.pdf](https://www.entsoe.eu/Documents/EDI/Library/critical_network_element_implementation/10e%20Critical%20Network%20Element%20Implementation%20Guide%20V1R1.pdf).
- [24] Flow-Based project group, Methodology and concepts for the Nordic Flow-Based Market Coupling Approach, 1, 2014, Available: [http://www.statnett.no/Global/Dokumenter/Kundeportalen/20140512\\_WP1\\_Public\\_Nordic\\_FB\\_report\\_Technical.pdf](http://www.statnett.no/Global/Dokumenter/Kundeportalen/20140512_WP1_Public_Nordic_FB_report_Technical.pdf).

## APPENDIX 1: STEADY STATE ANALYSIS PROCESS

