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Simulation Model of the Future Nordic Power Grid Considering the Impact of HVDC Links

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PROBLEM DESCRIPTION

SINTEF has an on-going activity on establishing a simplified, representative PowerFactory simulation model of the future Nordic electric power system. This model includes existing and new High Voltage Direct Current (HVDC) interconnections to adjacent markets. It is intended to be used for different national and international research projects, as well as for educational purposes. The model is a representation of the expected grid in 2030, however not necessarily an accurate and exact replication of the real system.

This masters thesis is a continuation from a specialisation project during the fall of 2015. The main task is to continue to developing, expanding and increasing the performance of the Nordic power system model. This involves the addition of missing HVDC links in the eastern part of the Nordic system, and implementation of Modular Multilevel Converter (MMC) for modern HVDC links based on Voltage Source Converters (VSC). The system grid has to be modified and new system nodes added for compatibility with market models.

After the model has reached a satisfactory level of completion, the task is to perform contingency analysis and dynamic simulations of high import and export scenarios. The final goal is to study what impact an increasing number of HDVC links have on the Nordic grid, and indicate the potential exchange capacity.

PREFACE

This master's thesis represents the final work of my two-year MSc in Electric Power Engineering at the Department of Electric Power Engineering, NTNU. My work during this last year has taught me a great deal about the Nordic power system and modelling in general. I have been lucky enough to receive responsibility for development of a simulation model created a SINTEF. At the end, I hope I have made a valuable contribution and that the model will be useful in future work.

Trondheim, 01.07.2016

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ACKNOWLEDGEMENTS

First, I want to thank Ole-Morten Midtgård, professor at NTNU, for helping me with the practicalities surrounding the work of this master's thesis. He has been very supportive and provided me with guidance.

I am grateful to Til Kristian Vrana, Research Scientist at SINTEF Energy Research. He has been my main source of support during development of the simulation model.

Additionally, I would like to thank DIgSILENT for providing me with a PowerFactory4Thesis license and upgrading it to PowerFactory 2016. The people at DIgSILENT have also been kind enough to give their support on a couple occasions were I had technical issues with my installation.

Along the way, my family have been my most eager supporters. I very much appreciate their continuous support throughout the five years of my higher education.

My fellow MSc students from *Electric Power Engineering*, this last thanks goes to you. These last two years at NTNU have been great, thanks to your friendship and the experiences we have had together.

ABSTRACT

As Europe is shifting to an increasingly larger share of non-dispatchable renewable energy sources, the cross-border power flow changes. This thesis considers further development of an existing PowerFactory simulation model designed to fit with new power flow situations influencing the Nordic power system. Today, there are many HVDC links connecting Europe to the Nordic grid, and there are several new links being built and planned. The thesis work is a continuation of an earlier specialisation project and focuses on implementing all existing links and those currently planned to be commissioned by 2021 in a common model, giving a total HVDC exchange capacity of 11 820 MW. In addition, four new links thought possible to be commissioned by 2030 are available in the model, giving an additional capacity of 7 400 MW.

To test the completed model, a contingency analysis has been performed to find the limits of what power exchange is possible without significant changes in the grid, and what is possible given the right upgrades. Four scenarios have been studied considering maximum import and export in 2021 and 2030. Results have also been verified by simulations. The analysis has proven that the model is flexible and can handle a large variation of power flow situations.

For the 2021 high import scenario with reduced load, it is indicated that the full HVDC exchange of 11 820 MW can be utilised for import, provided that some minor grid upgrades are implemented. For the same scenario, the export capacity is not more than 7 170 MW. Without any further significant upgrades, the available import capacity for 2030 is 17 280 MW. During contingency analysis it was shown that the Swedish grid is the primary limiting factor for export and the Norway was limiting for import. Results indicate that by significantly upgrading the Swedish grid, the export capacity can be up to 14 200 MW, and by strengthening the South-Eastern Norwegian grid the import capacity can be up to 19 220 MW.

SAMMENDRAG

I Europa øker stadig andelen energi fra ikke-kontrollerbare fornybare energikilder. Dette fører til endringer i lastflyten på tvers av landegrensene. Denne masteroppgaven dreier seg om videreutvikling av en eksisterende simuleringsmodell i PowerFactory som er lagt opp til nye situasjoner som oppstår som følge av dette. I dag finnes det mange HVDC-lenker som kobler Europa til det nordiske kraftsystemet, i tillegg til flere som er i ferd med å bygges og planleges. Arbeidet i denne masteroppgaven viderefører arbeidet fra et tidligere fordypningsprosjekt og fokuserer på implementering av alle lenker som er planlagt idriftsatt innen 2021 i en felles modell. Disse har en total utvekslingskapasitet på 11 820 *MW*. I tillegg inkluderer modellen fire nye lenker som er tenkt idriftsatt innen 2030 med en ekstra utvekslingskapasitet på 7 400 *MW*.

For å teste den ferdige modellen har det blitt utført en analyse for å teste linjeutfall for å tilfredstille krav til *n-1*. Detter er blitt gjort for å finne grenser for hvilken effekt som kan overføres uten større endringer i nettet, og eventuelt hva som er mulig hvis nødvendige oppgraderinger blir gjort. Fire scenarioer er studert for å vurdere maksimal import og eskport i 2021 og 2030. Resultatene har også blitt verifisert ved simuleringer. Analysene har vist at modellen er fleksibel og kan håndtere en stor variasjon av lastflytsituasjoner.

For 2021-scenarioet med redusert last indikerer resultatene at den tilgjengelige utvekslingskapasiteten på 11 820 *MW* kan bli fullt utnyttet for import, forutsatt at noen mindre endringer i nettet blir gjort. For det samme scenarioet kan kun 7 170 *MW* utveksles for eksport. Uten noen flere større endringer er kapasiteten for import 17 280 *MW* i 2030. Analysen viser at det svenske kraftnettet primært er den begrensende faktoren for eksport, mens det norske kraftnettet er begrensende for import. Resultatene indikerer at større oppgraderinger av det svenske nettet kan øke kapasiteten for eksport opptil 14 200 *MW* og at forsterkning av det sørnorske nettet kan øke kapasiteten for import til 19 220 *MW*.

CONTENTS

ACRONYMS

CSC	Current Source Converter
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
LCC	Line Commutated Converter
MMC	Modular Multilevel Converter
PWM	Pulse With Modulation
SVC	Static Var Compensator
UK	United Kingdom

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1 INTRODUCTION

1.1 BACKGROUND

The model has a large focus on the HVDC interconnections between the Nordic countries and the rest of Europe. This is because new HVDC interconnections are being planned and built and several more are expected to come in the following years to come.

Energy generated from renewable sources is increasing in the continental European power system. This leads to scenarios where the peak generation is higher than the load, but the energy cannot easily be stored. Norway is expected by many to become the green battery of Europe, and pumped hydro will be increasingly utilised. In the event of such an over-supply in the rest of Europe, the price of power will be low. Norwegian hydropower generators will then reduce their power output and the import from HVDC interconnections will be high.

There is a need to investigate how much power can be transmitted to/from the Nordic grid. This will be beneficial to determine the available capacity for HVDC power in the future system.

1.2 OBJECTIVES

Primary development objectives are to:

- Include missing HVDC links.
- Change relevant two-level VSC converters to MMC.
- Include new AC system buses to coincide with market data.
- Adapt AC system voltage to 400 kV and move generators from the system voltage to 22 kV.
- Modify AC system layout to accommodate new HVDC links and AC buses.
- Refine overall consistency and performance of the model.

When development is complete, the research objectives are to:

- Develop power flow scenarios of very high import and export.
- Identify possible bottlenecks and/or voltage problems in the future Nordic grid.

- Investigate the performance of MMC in PowerFactory compared to the two-level VSC using the developed test system.

1.3 METHOD

The work done as part of this thesis relies heavily on the use of the DIgSILENT PowerFactory simulation tool. During a study of how the model is built up, relevant theory is studied to understand the concepts. Further modifications and upgrades to the model are studied and tested. Continuous testing and validation is performed by use of tools such as eigenvalue analysis and dynamic simulations.

1.4 LIMITATIONS

This thesis does not go into detail about the control systems used in the model for generators and HVDC links.

The model is a simplified, aggregated version of the Nordic grid and does not represent a detailed version of the real system. Therefore, the model is not suitable for small-scale stability studies and should only be used for large-scale phenomena and power flow studies.

1.5 PREVIOUS WORK

The model has been been developed by SINTEF, mainly during the first months of 2015. A complete AC system Nordic grid has been implemented, with the most buses concentrated on the southern Norwegian and Swedish grid. The systems and controllers for VSCs and Current Source Converters (CSC) are thoroughly implemented. Generators are implemented with governors and PSS controls.

A specialisation project was undertaken by the student during the fall of 2015. The model was extended and many HVDC links were improved, mainly in the southern Norwegian grid. Only Storebælt and Konti-Skan were included in the Swedish/Eastern Danish part.

2 HVDC TECHNOLOGY

DC transmission has been around since the start of electric power transmission. During the last 60 years, several advances have been made. Today, HVDC systems are in use all around the world, with several of them connected to the Nordic power system.

2.1 CURRENT SOURCE CONVERTER

2.1.1 Basic Functionality of Thyristors

A thyristor is a semiconducting device similar to a diode, and can in some ways be described as a controllable diode. A symbol of the thyristor can be seen in Figure 2.1. A diode will only conduct if it is forward biased, that is the voltage at its anode has a higher potential than the voltage at its cathode. The same applies to a thyristor, but it also requires a current applied to its gate terminal. When no gate current is applied, the thyristor will, because of its construction block current in both directions, regardless of the forward biased voltage.

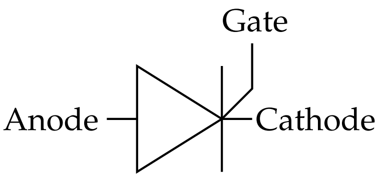


Figure 2.1: Symbol of a thyristor

The gate current pulse is only required to unblock the thyristor and does not need to be applied continuously. Turning on the thyristor by applying this pulse is called firing and can be delayed relative to the phase of the AC voltage. This delay is called the firing angle, α, and is usually expressed in degrees. An important characteristic of the thyristor is that it can only be turned on, and never off. Once a thyristor has started conducting, it will continue conducting until it becomes reverse biased and the current falls to zero. Reverse bias means that the voltage at its cathode is more positive than the voltage at its anode. When the thyristor is inactive and reverse biased, it needs sufficient time, specified as t_{off}, to regain its blocking ability. If the blocking ability is not

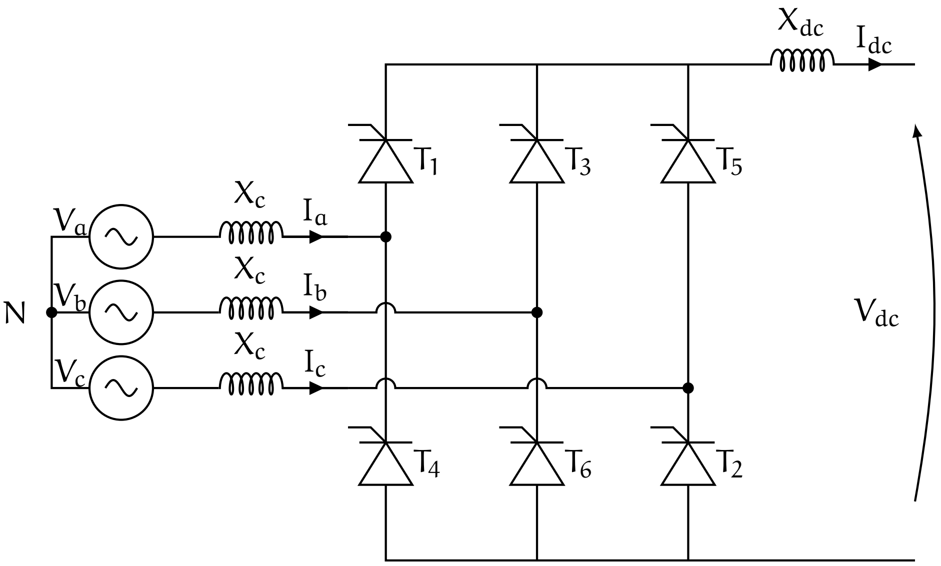


Figure 2.2: Basic six pulse CSC converter

restored until the thyristor becomes forward biased again, it will turn on and conduct, even though a firing pulse has not been applied. [1], [2]

2.1.2 Basic Structure of the Current Source Converter

An HVDC converter based on thyristors is a Current Source Converter (CSC), or Line Commutated Converter (LCC). This is because it requires an external AC voltage source to operate. A basic CSC from three phase AC to DC voltage is called a six-pulse converter, shown in Figure 2.2. The figure shows six thyristor valves, a DC smoothing reactor, X_{dc}, and the commutation reactance, X_c.

A thyristor valve is a stack of several thyristors connected in series and/or parallel to achieve the necessary current and voltage rating of the converter. When a valve receives a firing pulse, all the thyristors in the valve fire simultaneously. The DC smoothing reactor is important for smoothing the ripple on the DC side and preventing large fault currents. The commutation reactance, X_c, represents the leakage reactance of converter transformer windings and filters at the converter side of the transformer. [2]–[4]

2.1.3 Commutation

As the AC voltage varies periodically, the forward voltage of each thyristor vary with the same frequency and it will be positive for a third of the period, or 120°. Two thyristors will always be on and conducting. During the sequence, the conducting pair is changed several times. This change is a process called commutation, where one thyristor starts conducting at the same time as another stops. Because of the commutation reactance, this process is not instantaneous and both thyristors will be conducting. The current in the thyristor turning off goes to zero, simultaneously as the current in the thyristor turning on rises to the full current. The change takes place for a duration defined as the commutation overlap and is given by the overlap angle, μ, in degrees relative to the AC voltage. [3]

2.1.4 Effect of Firing Angle

Considering the thyristor at $\alpha = 0°$ and without commutation reactance, the converter is similar to a diode bridge and the DC voltage, V_d, is given by

$$V_d = \frac{3\sqrt{2}}{\pi} V_{LL} \tag{2.1}$$

where V_{LL} is the AC line to line voltage at the converter terminals.

Due to the delay given by the firing angle, the DC voltage will decrease with increasing firing angle. The DC voltage is then given by

$$V_d = \frac{3\sqrt{2}}{\pi} V_{LL} \cos\alpha \tag{2.2}$$

The effect of the commutation reactance is also very important when considering the DC voltage and will give another voltage drop. The equation for the DC voltage of a practical six-pulse CSC is then given by

$$V_d = \frac{3\sqrt{2}}{\pi} V_{LL} \cos\alpha - \frac{3X_c}{\pi} I_d \tag{2.3}$$

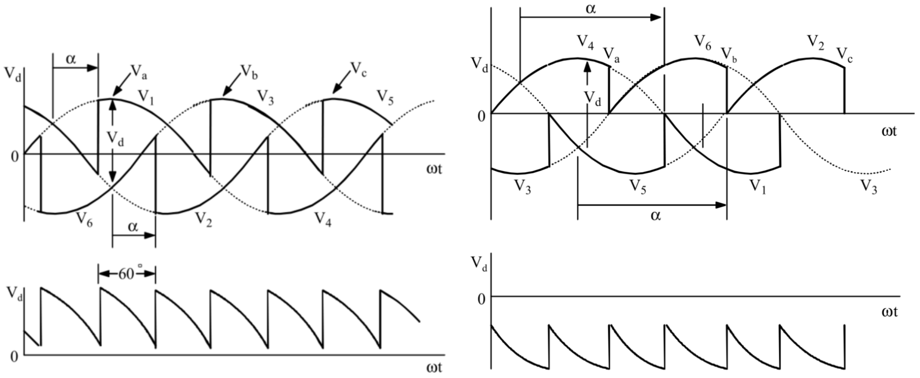
where X_c is the commutation reactance of one phase and I_d is the DC current.

When the converter is operating at no load, the voltage drop due to the commutation reactance is negligible. Equation (2.2) then shows the direct relation to the firing angle. If $0° \leqslant \alpha < 90°$, the average DC voltage decreases until it eventually becomes zero at $\alpha = 90°$. If $90° < \alpha \leqslant 180°$, the average DC voltage is negative and decreases until it eventually becomes equal to the negative of equation (2.1). A negative DC voltage means that the converter is operating as an inverter, since the direction of current cannot be changed. This is what allows the thyristor to be used for controllable HVDC transmission. In a HVDC system both the rectifier and inverter are operated by setting the firing angle, thereby setting the voltage at each end. How the correct firing angle is obtained for the two, is different. The control systems are set up such that one side controls the voltage directly, while the other measures and regulates the voltage at the other end to achieve the desired power flow, or DC current. Voltage and power are normally controlled by respectively inverter and rectifier [2]. The relationship for voltage at both ends is given by

$$V_{dR} = V_{dI} + R_d I_d \tag{2.4}$$

where V_{dR} is the DC voltage at rectifier end, V_{dI} is the DC voltage at inverter end, and R_d is the resistance of the DC cable.

Figure 2.3 show some operative characteristics of a six-pulse CSC. In the figures, V1,V2,V3 etc. correspond to T1,T2,T3 etc. used to indicate the thyristor valves in Figure 2.2. Figures 2.3a and 2.3b show the converter in respectively rectifier and inverter mode and the resulting DC voltage. Note that the commutation overlap is not shown in the figures.



(a) Rectifier mode **(b)** Inverter mode

Figure 2.3: Current source converter in rectifier and inverter mode [1]

2.1.5 Inverter Mode of Operation

In inverter mode of operation it is common to refer to the extinction angle, γ, given by

$$\gamma = 180 - \alpha - \mu \tag{2.5}$$

This angle signifies the available turn-off time for the thyristor valve and is measured from the instance the current of a valve goes to zero until it again becomes forward biased. All thyristors have a minimum turn-off time, t_{off}, usually in the range $400 - 600\mu s$, giving $7.2 \leqslant \gamma_{min} \leqslant 10.8°$ [5]. The value can be both higher and lower and largely depends on the type of thyristor, which again depends on the application. γ_{min} is the absolute minimum possible extinction angle for the thyristor to successfully restore its ability to block current when it is forward biased, given by

$$\gamma_{min} = \omega t_{off} \tag{2.6}$$

In order to ensure safe operation, some margin is added to obtain the actual operating angle. If the extinction angle becomes lower than the minimum angle, the thyristor valves will fail to commutate from one valve to another. This is called commutation failure and will be discussed later. [1], [2]

2.1.6 Reactive Power Demand

The AC current in a CSC will always be lagging the AC voltage, due to the delayed firing of the thyristors. Consequently, the reactive part of the current will never be positive, i.e, the converter will always consume reactive power.

The reactive power demand is dependent on the firing angle for the rectifier and the extinction angle for the inverter, given by

$$Q_{cR} = P_d \tan\left[\cos^{-1}\left(\cos\alpha - \frac{X_c}{2}\cdot\frac{I_d}{I_{dN}}\right)\right] \tag{2.7}$$

$$Q_{cI} = P_d \tan\left[\cos^{-1}\left(\cos\gamma - \frac{X_c}{2}\cdot\frac{I_d}{I_{dN}}\right)\right] \tag{2.8}$$

where P_d is the active power through the converter, I_d the DC current, I_{dN} the nominal DC current, and Q_{cR} and Q_{cI} are the reactive power demand of rectifier and inverter. To minimise the reactive power demand, the converter is usually operated at lowest allowable angle. This will however depend on the strength of the AC system and stability requirements of the converter. A CSC-HVDC converter station will in most cases need to be equipped with means for reactive power compensation, such as a switched capacitor bank or an SVC. [1], [2]

2.1.7 Harmonics

In addition to demanding reactive power, CSC will introduce harmonic currents according to

$$I_{h_{6p}} = 6n \pm 1 \qquad n = 1, 2, 3... \tag{2.9}$$

where $I_{h_{6p}}$ is the harmonic currents from a six-pulse converter.

Special filtering equipment is needed to remove the harmonics. For HVDC systems, the required use of several components in series and parallel led to the development of twelve-pulse converters, which are in use for most, if not all, systems today. They have the advantage of removing half the harmonic currents, now given by:

$$I_{h_{12p}} = 12n \pm 1 \qquad n = 1, 2, 3... \tag{2.10}$$

where $I_{h_{12p}}$ is the harmonic currents from a twelve-pulse converter.

Two six-pulse converter bridges are arranged in series, but the AC-side of one bridge is phase shifted 30° by use of a Y/Δ transformer [1], [3].

2.1.8 Commutation failure

When a CSC is operating as an inverter, it is crucial that the extinction angle remains above the minimum level at all times. If becomes less than the physical limit, given by γ_{min}, the thyristor will not regain its ability to block current when it is forward biased and experience commutation failure. The thyristor is then behaving like a diode and have no means of control. A failure to commutate from one valve to another leads to failure in the succeeding converter arm. Commutation failure can be caused by several reasons [2]:

- Increasing magnitude of the DC current increases the overlap angle, μ. Since the inverter is keeping the DC voltage constant, the extinction angle decreases until it becomes too low.
- Reduced magnitude or phase shift of the AC-side voltage. To maintain stable DC voltage, the firing angle of the inverter has to increase, decreasing the extinction angle.
- The AC-side voltage is distorted, leading to a reduced extinction angle.

2.2 VOLTAGE SOURCE CONVERTER

The Voltage Source Converter (VSC) is a more modern HVDC technology than the CSC and makes use of the Insulated Gate Bipolar Transistor (IGBT), instead of the thyristor. Recent VSCs use multilevel technology such as the Modular Multilevel Converter (MMC).

2.2.1 Basic Functionality of the Two-Level VSC

The power flow though a VSC is determined by the power flow across the converter phase reactor, X_c, and is given by

$$P = \frac{|U_c||U_v| \sin \delta_{cv}}{|X_c|} \tag{2.11}$$

$$Q = \frac{|U_c|^2 - |U_c||U_v| \cos \delta_{cv}}{|X_c|} \tag{2.12}$$

$$S_b = P + jQ = \sqrt{3} U_c I_c^* \tag{2.13}$$

where P and Q are the active and reactive power delivered to the AC grid, $|X_c|$ is the phase reactance, $|U_c|$ and $|U_v|$ are the magnitudes of the voltage at respectively AC side and valve side of the phase reactance, δ_{cv} is the phase difference between the two voltages and S_b is the rated apparent power for the converter.

Control signals for the VSC are used to modulate the valve voltage by use of Pulse Width Modulation (PWM). The voltage can be set to have any phase angle and magnitude. It can be proven that the active power is sensitive to changes in the phase angle difference, and the reactive power is sensitive two difference in the voltage magnitudes. Active power is then controlled by modulating the phase angle of the valve voltage to lag or lead, and the reactive power is controlled by modulating the magnitude of the valve voltage to a value higher or lower than the AC side voltage magnitude. This is shown in Section 2.2.1.

P	$\delta_{cv} > 0$	Inverter
	$\delta_{cv} < 0$	Rectifier
Q	$\lvert U_v \rvert > \lvert U_c \rvert$	Demand
	$\lvert U_v \rvert < \lvert U_c \rvert$	Supply

2.2.2 Reactive Power Capability

Unlike a CSC, a VSC has the capability to supply reactive power. The converter can control active and reactive power independent of each other, any operate at any point inside the curve shown in Figure 2.5. The figure is inspired by [6].

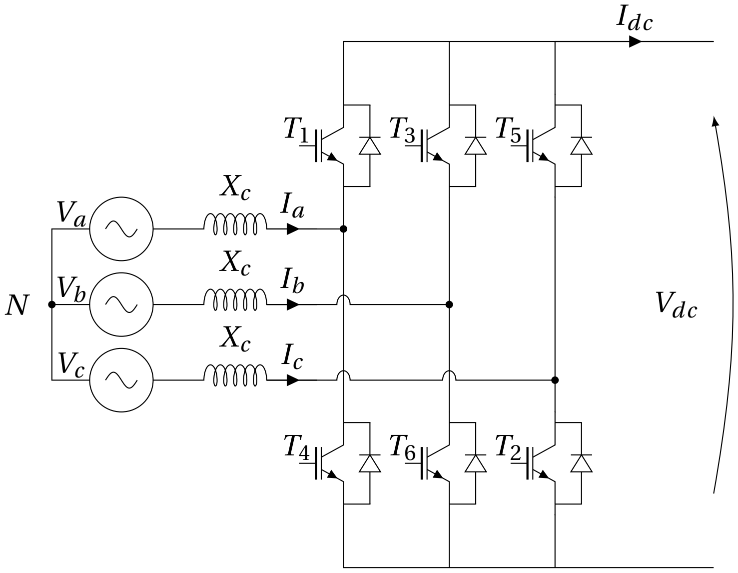


Figure 2.4: Three-phase Two-Level Voltage Source Converter

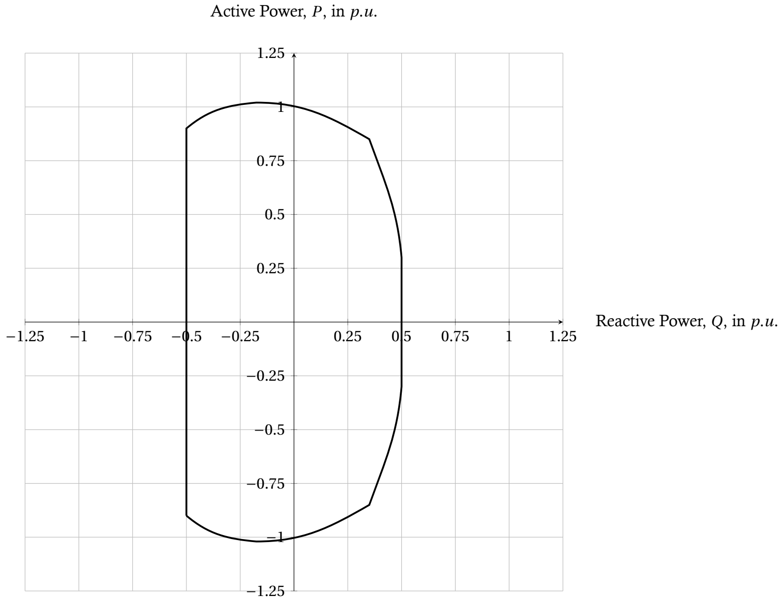
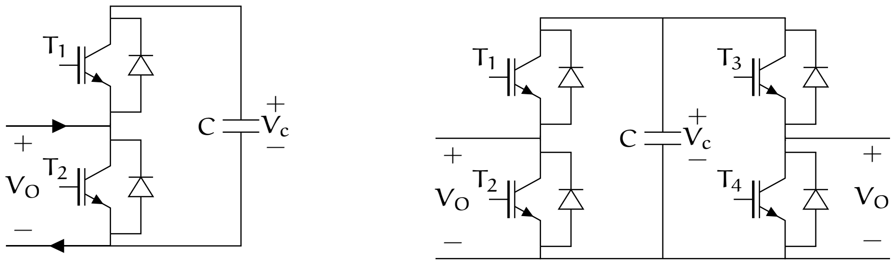


Figure 2.5: Reactive power capability of a voltage source converter

2.2.3 Modular Multilevel Converter (MMC)

2.2.3.1 *Structure of MMC*

The general structure of a three-phase MMC type converter is shown in Figure 2.8. Each *phase unit* consists of two *arms*. There are n *submodules* in each converter arm. A submodule contains all the necessary power electronics and several modules are put in series to withstand the full rated voltage of the converter. Two common configurations of the submodule are half-bridge and full-bridge, shown in Figure 2.6. Half-bridge is the primary configuration used for HVDC systems, therefore the full-bridge type is not described further.



(a) Half-bridge (b) Full-bridge

Figure 2.6: MMC submodule configurations

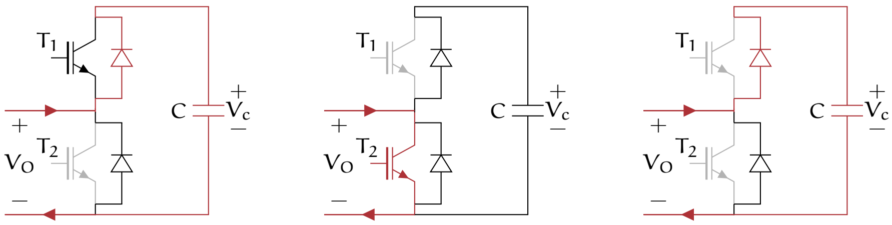
Every half-bridge MMC submodule, or *cell*, consists of two switches with anti-parallel diodes and a capacitor. The capacitor is what allows for the modularity and gives the MMC its unique abilities. The half-bridge cell only has two levels, meaning the cell output voltage, V_O, is either $V_O = 0$ or $V_O = V_c$, the full capacitor voltage. There are three available states:

INSERTED (ON) T_1 is on, T_2 is off and $V_O = V_c$. The capacitor charges when the current is positive and discharges when negative.

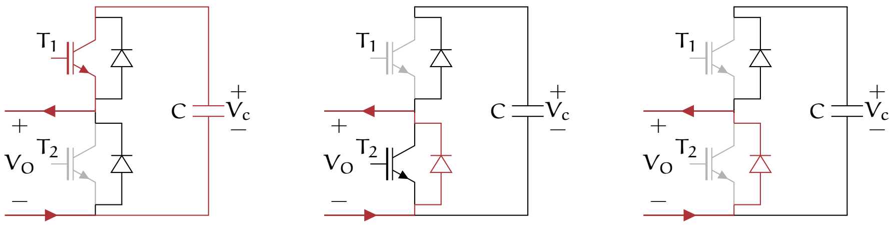
BYPASSED (OFF) T_1 is off, T_2 is on and $V_O = 0$. The capacitor voltage is constant and its charge remains unchanged.

BLOCKED T_1 is off, T_2 is off and $V_O = 0$. The current can only conduct through the diodes. With positive current, $V_O = V_c$ and the capacitor charges, otherwise $V_O = 0$ and the capacitor charge is unchanged.

All possible states of the MMC are shown in Figure 2.7. Figures 2.7a to 2.7c show inserted, bypassed and blocked state for positive current, and figures 2.7d to 2.7f show inserted, bypassed and blocked state for



(a) Inserted, positive **(b)** Bypassed, positive **(c)** Blocked, positive



(d) Inserted, negative **(e)** Bypassed, negative **(f)** Blocked, negative

Figure 2.7: MMC states

negative current. Switches that are turned off are grey, and the current conducting path is drawn in red.

Ideally, the capacitor voltage of each cell, V_c, should be kept constant. To ensure a stable, balanced operation, careful and precise control has to be implemented to keep the capacitor balance.

2.2.3.2 *Operation of MMC*

Since each phase unit has two arms, there are a total of $2n$ submodules in each phase unit, and in total $6n$ submodules in the converter [7]. The number of activated submodules in each arm varies sinusoidally, but the number of activated submodules in each phase unit will stay constant. Voltage output from the converter will then have $n+1$ levels. When all cells in one arm are bypassed, the other arm will have the full DC voltage. Each cell then has to be able to withstand the full DC link voltage divided by the number of submodules per arm.

2.2.3.3 *Design of MMC parameters*

Parameters of the MMC vary depending on the power rating, S_{MMC}, and the rated DC voltage, V_{dc}. A method for designing MMC parameters is described in [7]. It starts with finding the arm capacitance, C_{arm}, using the energy-to-power ratio, E_s. This value should be in the range $30\,\frac{kJ}{MVA}$ to $40\,\frac{kJ}{MVA}$ and can for a three-phase converter be found by:

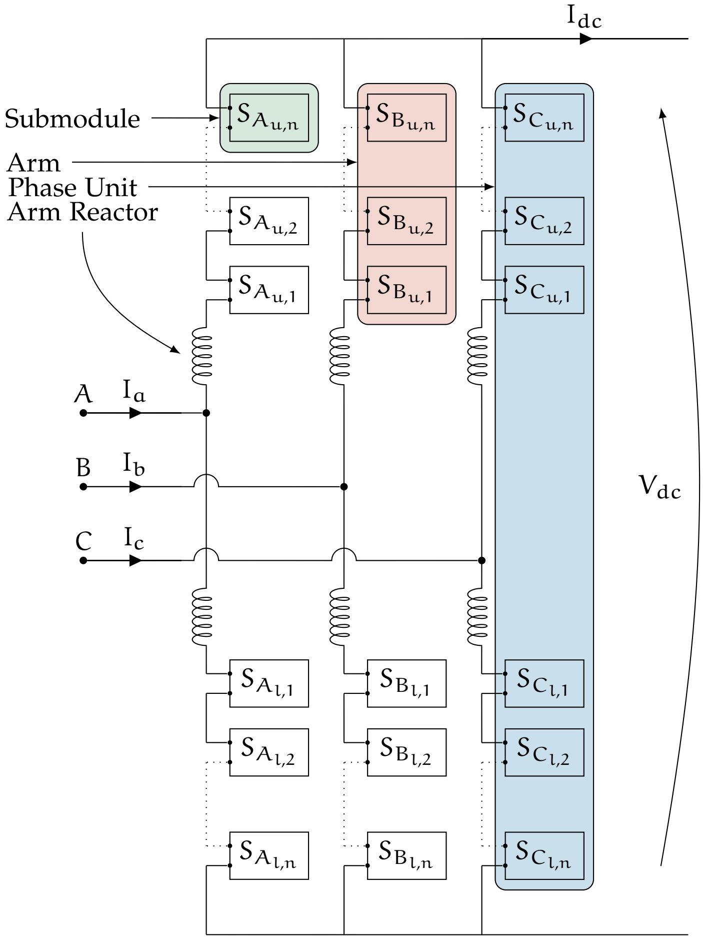


Figure 2.8: Structure of an MMC

$$C_{arm} = \frac{S_{MMC} E_s}{3V_c^2} \tag{2.14}$$

Individual cell capacitor size, C_{cell} is found by:

$$C_{cell} = nC_{arm} \tag{2.15}$$

where n is the number of submodules per arm.

Determining the size of the arm inductance, L_{arm}, is more complex. It is of great importance to avoid resonance with the arm capacitance at even integer harmonics, especially the second and fourth. The inductance value that causes inductance can be calculated by:

$$L_{arm_{res}} = \frac{1}{C_{arm}\omega^2} \frac{2(h^2-1)+M^2h^2}{8h^2(h^2-1)} \tag{2.16}$$

where h is the harmonic order, M is the modulation index amplitude and ω is the AC operating frequency in radians.

Figure 2.9 shows the inductance values causing resonance with the arm capacitance for the second and fourth harmonics at $M = 1$. To avoid resonance, the chosen value of the arm inductance should be above the $h = 2$ curve.

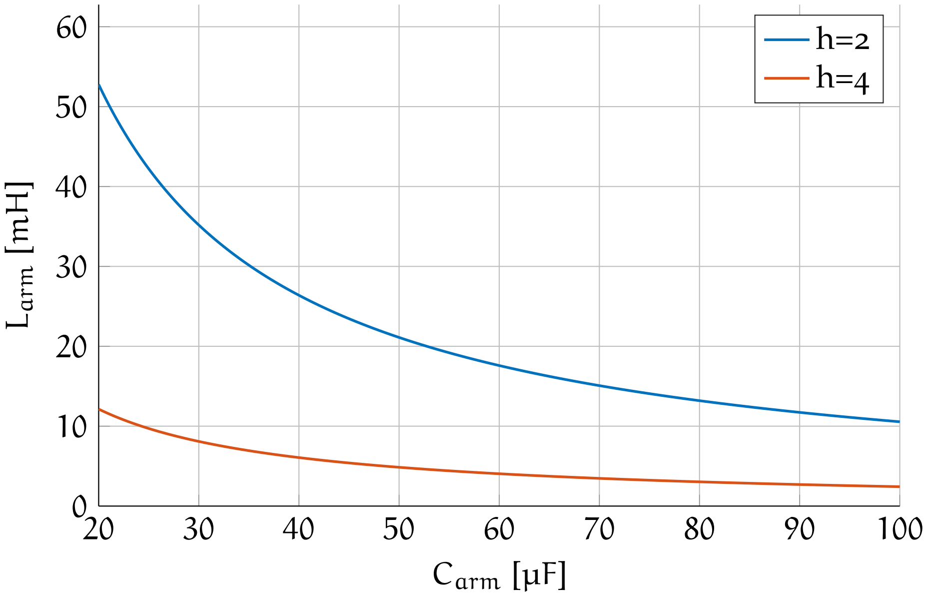


Figure 2.9: MMC arm inductance resonance

2.3 CONFIGURATIONS OF HVDC

Separate from the choice of conversion technology is the decision of cable configuration for the HVDC connection. The most suitable setup will vary depending on the project requirements. Several configurations have been tested and are in use today, but the ones listed here are the ones used in the model of this thesis. The main thing separating the different configurations is how the return of current is managed and the redundancy of the system. In HVDC, a cable is called a pole. If it is a system with one pole, it is called monopolar. If the system has more than one cable, and operate at both positive and negative voltage, it is called bipolar. The different configurations are described in the following subsections and shown in Figure 2.10. The figures are inspired by [6].

2.3.1 Monopolar

A monopolar system consists of only one pole and comes in two variations: with ground return, as in Figure 2.10a, or metallic return, as in Figure 2.10b. The metallic return does not require full insulation, but if a fully rated cable is installed, it allows a future upgrade to a bipolar system. Ground return can cause problems with corrosion and magnetic fields. If the system is to be used with ground return, special permission is required to allow operation.

2.3.2 Bipolar

A bipolar system is the one with most flexibility because of a double converter configuration, shown in Figure 2.10c. It has redundancy, such that one pole can operate without the other, but with the condition that the ground return is used for such a situation. The two poles have opposite voltage polarity, symmetric about $0\,\mathrm{V}$. Each converter is rated for the voltage of one pole, or half of the absolute potential difference between the two poles.

In steady-state, current flows from pole to pole, with no current returning through ground. This is only true if the converters are rated for the same current, since the converter pairs of each pole operate voltage and current of their respective pole independent of the other. During disturbances, or if the converters of the separate poles control the current at different setpoints, there will be a current offset. This current will have no other way to return than through ground in order to keep the system in equilibrium.

2.3.3 Symmetric Monopole

A system classified as a symmetric monopole has no ground point, hence need no ground return. It is shown in Figure 2.10d. Instead, two fully rated cables rated at the same voltage, but with opposite polarity symmetric about $0\,V$, are used. Only one converter is used at either end of the cables, which has to be rated at the full absolute voltage difference between the two poles.

2.3.4 Back-to-back

In cases where power is to be transferred between two different synchronous areas, an HVDC system with rectifier and inverter in the same station can be used. Such a configuration is called back-to-back, shown in Figure 2.10e.

2.4 DESIGN OF SIMPLIFIED CSC-HVDC LINKS

In the specialisation project [8], a method was developed for implementing CSC converters only modelled in one end, depending on the power flow direction. This involves representing the DC-side as a set of voltage sources (export) or a current source (import), as shown in Figure 2.11.

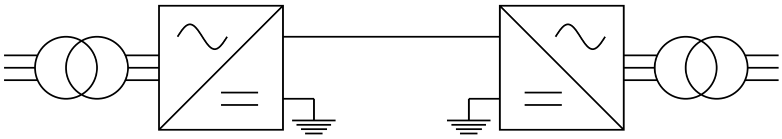
The current source is modelled as an ideal current source in parallel with a conductance, G, [9] as shown in Figure 2.12. Desired output current is set by adjusting the nominal current of the current source. When $G = 0$, the source behaves as an ideal current source and a constant DC voltage is present at its terminals. When $G > 0$, the nominal current of the current source, I_N, is the sum of the desired output current and the short-circuit current trough G:

$$I_N = I_{setp} + G \cdot V \tag{2.17}$$

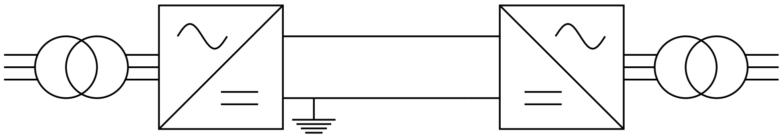
where V is the voltage at the DC current source terminals.

When exporting, the converter operates as rectifier with active power control. On the DC-side, the dual voltage sources are active and remain constant, while the converter controls the current. When importing, the converter operates as an inverter with DC voltage control. In this case, the DC voltage sources are inactive, and the DC-side two-way current source is turned on.

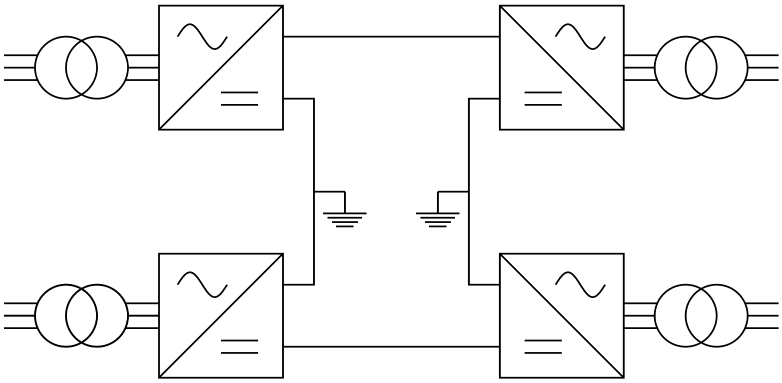
I_N, the nominal current of the source, is found be modifying equation (2.17):



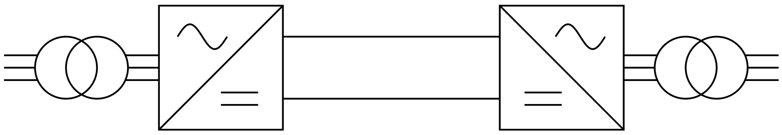
(a) Monopolar with ground return



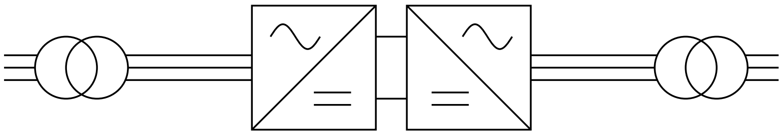
(b) Monopolar with metallic return



(c) Bipole



(d) Symmetric monopole



(e) Back-to-back

Figure 2.10: HVDC configurations

$$I_N = \frac{P_{setp}}{V_{nom}} + G \cdot V_{nom} \tag{2.18}$$

where P_{setp} is the setpoint for the receiving end of the link, V_{nom}, is the nominal voltage of the converter and G is the internal conductance of the current source.

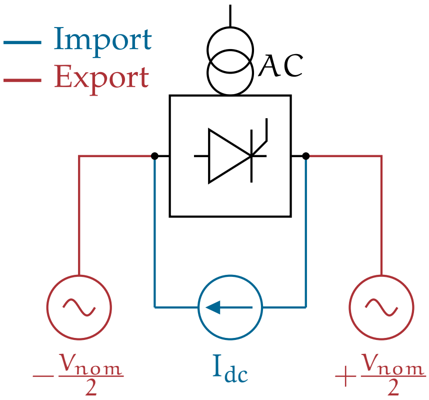


Figure 2.11: Simplified CSC converter model

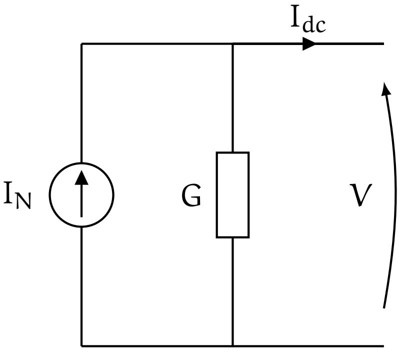


Figure 2.12: DC Current source

The *droop*, or the sensitivity of the current to changes in the terminal voltage is calculated by:

$$\rho = \frac{P_{nom}}{G{V_{nom}}^2} \tag{2.19}$$

where ρ is the droop of the current source, P_{nom} is the nominal active power output and $I_{dc_{nom}}$ is the DC link current at nominal active power.

Equation (2.19) can then be rearranged to find the value of the current source conductance:

$$G = \frac{P_{nom}}{\rho {V_{nom}}^2} \tag{2.20}$$

3 HVDC IN THE NORDIC POWER SYSTEM

3.1 EXISTING INTERCONNECTIONS

This section provides an overview of the existing HVDC interconnections in the Nordic power system. Each subsection describes the link groups.

3.1.1 Konti-Skan

In 1965, the first HVDC link connecting Sweden and Denmark went into operation, called Konti-Skan (1) [10]. It was the first interconnection between the Scandinavian power system and the continental European system, going from Lindome in Sweden to Vester Hassing in Denmark. The link consisted of a single cable in a monopolar scheme rated at 1 kA at a voltage of 250 kV, giving a nominal power of 250 MW.

After several upgrades, the link now consists of two poles with the same power rating of 380 MW, rated at 1.35 kA and 285 kV [11].

3.1.2 Skagerrak

In 1977, the second HVDC link between Nordic countries went into operation, this time connecting Kristiansand in Norway and Tjele in Denmark [12]. This was a CSC-based bipole link, rated ±250 kV and 250 MW per pole, named Skagerrak 1 and 2. Skagerrak 3 was added in 1993, a CSC-based monopole rated at 350 kV and 440 MW. In 2014, Skagerrak 4, a VSC-based monopole rated 500 kV and 700 MW was put into operation. The fourth pole required a reconfiguration of the link. Skagerrak 1 and 2 are now configured as a bipole and Skagerrak 3 is configured as a bipole with Skagerrak 4 in an novel switching scheme.

3.1.3 Storebælt

In 2010, the Storebælt HVDC link was put in service, connecting the asynchronous power systems of Western and Eastern Denmark, going from Fraugde to Herslev [13]. The link uses CSC-HVDC rated at 400 kV and 600 MW. It is a monopolar system with metallic return.

3.1.4 NorNed

In 2008, the NorNed HVDC link was commissioned, connecting Feda in Norway and Eemshaven in the Netherlands [14]. NorNed uses CSC-HVDC with a single converter at each end, and is rated for 700 MW. The system is configured as a symmetrical monopole rated at ±450 kV

3.1.5 Fenno-Skan

Fenno-Skan is the only link system connecting two Nordic countries. It connects Dannebo, Sweden with Rauma, Finland and consists of two poles [15]. Fenno-Skan 1 was commissioned in 1989 as a monopolar link at 400 kV with a power rating of 500 MW. In 2011, Fenno-Skan 2 was added with a voltage rating of 500 kV and power rating of 800 MW. In Sweden, the converter stations for the two poles are located 70 km apart due to AC grid constraints.

3.1.6 SwePol

In 2000, the SwePol link was commissioned, connecting Karlshamn, Sweden and Ustka, Poland [16]. The link uses CSC-HVDC rated at 450 kV and 600 MW. It is monopolar system with metallic return.

3.1.7 NordBalt

NordBalt was commissioned late 2015 and connects Nybro, Sweden with Klaipeda, Lithuania [17]. It is a 700 MW symmetrical monopole VSC-HVDC system rated at ±300 kV.

3.1.8 Baltic Cable

Kontek was commissioned in 1994 and connects Trelleborg, Sweden with Lübeck, Germany [18]. It is a monopolar CSC-HVDC system at 450 kV, with a power rating of 600 MW. The system uses a ground electrode and no return cable.

3.1.9 Kontek

Eastern Denmark and Germany are connected by the Kontek connection, commisioned in 1995, with converter stations in Bjæverskov and Bentwisch [19]. Kontek is a monopolar CSC-HVDC system at 400 kV, with a power rating of 600 MW. The Baltic Cable crosses the Kontek cable in the Baltic sea.

3.1.10 Vyborg

Vyborg is a back-to-back CSC converter station in Vyborg, Russia on the border of Russia and Finland [20]. It consists of four units, each with a power rating of 355 *MW*, giving a total capacity of 1 420 *MW*. In reality, only 320 *MW* is commercially available [21]. The link is primarily used for power transfer from Russia to Finland, but in 2015 the first transfer of power from Finland to Russia was made. Only the fourth unit allows bi-directional power exchange.

3.1.11 EstLink

EstLink 1 was commissioned in 2006 and connects Espo, Finland with Harku, Estonia. It is configured as a symmetric monopole at ±150 kV, and uses two-level VSC converters with a power rating of 350 *MW* [22].

In 2014, EstLink 2, a CSC-HVDC link connecting Anttila, Finland and Püssi, Estonia, was commissioned. The pole is configured as a monopole with metallic return, having a voltage rating of 450 kV and power rating of 650 *MW* [23]

3.2 PLANNED INTERCONNECTIONS

3.2.1 NordLink

NordLink is currently in construction and will go from Tonstad in Southern Norway to Wilster, Germany. It will be a bipolar VSC-HVDC system with a total capacity of 1 400 *MW*, rated at ±525 kV [17]. The system is expected to become operational in 2020, and will be the longest HVDC link in Europe until NSNLink becomes operational.

3.2.2 NSN Link

NSN Link is currently in construction and will go from Kvilldal in Southern Norway to Blyth, UK. It will be a bipolar VSC-HVDC system with a total capacity of 1 400 *MW*, rated at ±525 kV [24]. The HVDC cables will be longest in the world when the system becomes operational in 2021.

3.2.3 Kriegers Flak Combined Grid Solution

Kriegers Flak is an offshore wind farm being developed on the eastern coast of Denmark [25]. The German wind farm Baltic 2 is less than

30 km from the new project and is connected to the German mainland via another wind farm, Baltic 1. Kriegers Flak and Baltic 1 are to be connected by an AC cable. The existing cable is run at 150 kV, while the new installation will be 220 kV, requiring an offshore transformer. A back-to-back converter station will be located on land in Bentwisch, Germany. In March 2016, a final decision was announced for the project, called Kriegers Flak Combined Grid Solution (CGS), and ABB received the order [26]. The converter will be able to transfer 400 MW.

3.2.4 NorthConnect

NorthConnect is a planned HVDC link connecting Peterhead, Scotland to Sima or Samnanger in Norway [27]. After the decision was made to go forward with the NSN-Link project, the current state of the project remains uncertain. The currently projected date for the system to become operational is by 2022. It will likely be a bipolar VSC-HVDC system with a total capacity of 1 400 MW, rated at ±525 kV.

3.3 HYPOTHETICAL FUTURE INTERCONNECTIONS

In order to study the impact of

The power rating of VSCs keep has been increasing dramatically the last ten years. Advancements happen in steps, with some projects featuring record-breaking voltage rating and others pushing the limits of current rating. During the next ten years, the technology is likely to be developed even further. Today, the highest voltage rating is that of the Skagerrak 4 connection, rated at 500 kV, but in 2020 NordLink will exceed that and go into operation at 525 kV. In 2018, the Caithness Moray HVDC link in Scotland is scheduled to be commissioned [28]. With a power rating of 1 200 MW, it will have the highest rated current of 1.9 kA.

By taking these factors into account, this project assumes all the additional future HVDC converters in the Nordic grid to be MMC-based VSCs with a power rating of 1 000 MW at 525 kV. A bipole link then has a capacity of 2 000 MW.

4 MODEL DESCRIPTION

This chapter describes the structure of the model and how it is implemented in PowerFactory. First, is a description of how PowerFactory is used as a modelling tool and all the general components used. Next, is a description of the model specific components used and the structure of the model. Last, is a description of the model development and the issues encountered

4.1 ABOUT POWERFACTORY COMPONENTS

All graphical objects in PowerFactory are of an *element* class, with many having an additional *type*. An element represents a physical component, such as a line or bus bar, which have its own specific variables depending on where it is placed. A type, such as a line type, is more generic and represents parameters common for multiple objects of the same element. Type parameters are generally static, non-changing parameters that are independent from the specific parameters defined for each individual object. If a type parameter is changed, it changes for objects utilising that type.

4.2 AC GRID STRUCTURE

The power system of this model is a simplified version of the Nordic grid, with an extensive focus on the Norwegian and Swedish grid, shown in Figure 4.1. The Norwegian grid is most detailed and is updated with the planned expansions until 2030. The Finnish grid is partly included as two buses, Pikkarala and Kangasala, with the prior connected to Norway. Denmark is modelled as just two buses, Jutland and Sjælland. Jutland is asynchronous from the rest of the Nordic grid and is also connected to a bus in Germany, Hamburg, representing the rest of the continental European grid.

There are 33 AC system nodes in the model, divided into zones as used by Nord Pool. These mostly have buses at 400 kV buses, but some are at 300 kV, 220 kV or a combination. All buses have both a generator and a load. In addition, some buses have a Static Var Compensator (SVC) to provide reactive power support. Table 4.1 shows basic info for all the buses, including whether or not they have an SVC or are connected to HVDC links.

4.3 LOADS

All loads in the system are modelled using the same load type. The parameters of this type are given in Table A.1.

Loads can be scaled individually by specifying the scaling factor, S_f. Considering voltage dependency of the loads, the actual active and reactive power, P and Q, are given by [29]:

$$P = S_f \cdot P_0 \left[aP \left(\frac{v}{v_0} \right)^{e_{aP}} + bP \left(\frac{v}{v_0} \right)^{e_{bP}} + cP \left(\frac{v}{v_0} \right)^{e_{cP}} \right] \tag{4.1}$$

$$Q = S_f \cdot Q_0 \left[aQ \left(\frac{v}{v_0} \right)^{e_{aQ}} + bQ \left(\frac{v}{v_0} \right)^{e_{bQ}} + cQ \left(\frac{v}{v_0} \right)^{e_{cQ}} \right] \tag{4.2}$$

where V_0 and P_0 describe nominal voltage and active power and V is the actual voltage. e_{aP}, e_{bP} and e_{cP} are factors describing the type of load. aP, bP and cP give the weighting of each type ($aP + bP + cP = 1$). The load types are:

0 constant power

1 constant current

2 constant impedance

Similarly for the reactive power exponents.

From Table A.1, it can be seen that the loads are 40 % constant power, 30 % constant current and 30 % constant impedance. Since 400 kV-buses have nominal voltage at 1.05 p.u., the nominal voltage of the loads at these buses is also set to 1.05 p.u.

Active and reactive power load for all AC system nodes are shown in Table 4.2.

4.4 GENERATORS

Generators are synchronous generators and all use the same type. The parameters are shown in Table A.6.

The active power generation capacity is set by specifying the number of parallel machines, n_g, for every single generator. Since they use the same generator type, the maximum active power for each generator bus, P_{max}, will be an integer multiple of the maximum active power for one machine, $P_{g,max}$, which is $225\,MW$. Maximum active power for each bus is then given by:

$$P_{max} = n_g \cdot P_{g,max} = n_g \cdot 225\,MW \tag{4.3}$$

Every generator also has an initial dispatch, $P_{g_{ini}}$. This comes from the original power flow data used for the basis of the model. Combined with the number of parallel machines, the initial active power dispatch for each bus is given by:

$$P_{ini} = n_g \cdot P_{g,ini} \tag{4.4}$$

The number of parallel machines and the resulting active power generation for all AC system nodes are shown in Table 4.2.

4.5 TRANSFORMERS

Parameters for transformers are shown in Appendix A.3.

4.6 LINES AND CABLES

As described in [30] the grid is not an exact representation of the real system. This is primary because the aggregated has low number of buses. Lines which should be connected to buses that or non-existent in the model are connected to a nearby bus in such a way that no false bottlenecks are created. Most power lines connect Norwegian buses, hence these are shown separately in Table 4.3. Table 4.4 shows the rest of the power lines in the model.

4.7 STATIC VAR COMPENSATORS

The *Static Var System (SVS)* element in PowerFactory is used to represent SVCs. The SVCs included in the model are listed in Table 4.5.

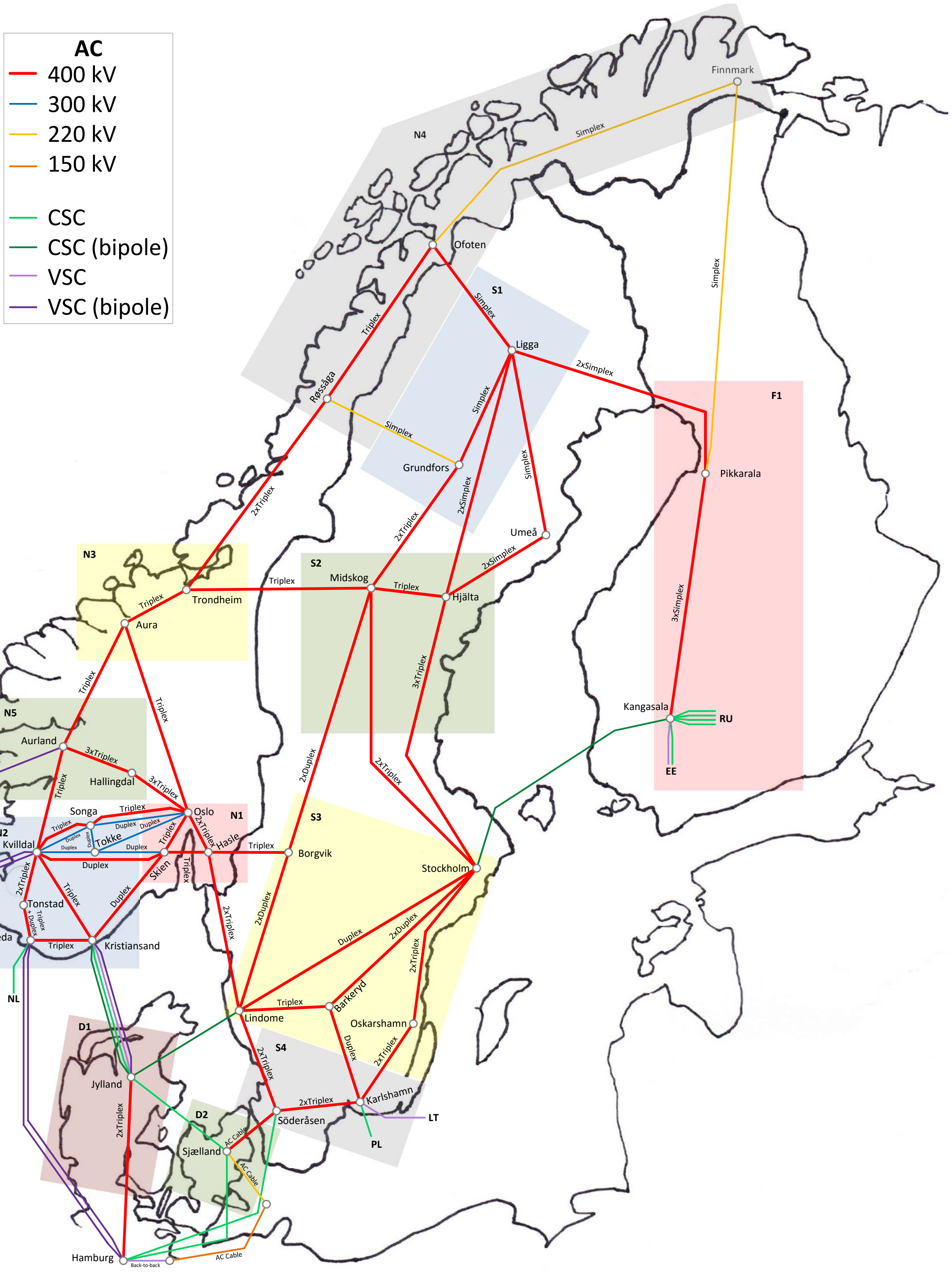


Figure 4.1: Overview of the Nordic grid after 2030

Table 4.1: Basic info for AC system nodes

	Node		Bus voltage [kV]				
Area	Name	Id	400	300	220	SVC	HVDC
N1	Hasle	HAS	✓			✓	
	Oslo	OSL	✓	✓			
	Skien	SKI	✓	✓		✓	
N2	Feda	FED	✓				✓
	Kristiansand	KRS	✓			✓	✓
	Kvilldal	KVI	✓	✓			✓
	Songa	SON	✓	✓			
	Tokke	TOK		✓			
	Tonstad	TON	✓				
N3	Aura	AUR	✓				
	Trondheim	TRD	✓				
N4	Finnmark	FIN			✓		
	Ofoten	OFO	✓		✓		
	Røssåga	RSG	✓		✓		
N5	Aurland	AUR	✓				
	Hallindal	HLD	✓			✓	
S1	Grundfors	GDF	✓				
	Ligga	LIG	✓		✓		
	Umeå	UME	✓				
S2	Midskog	MSK	✓				
	Hjälta	HJT	✓				
S3	Barkeryd	BAK	✓				
	Borgvik	BVK	✓				
	Lindome	LIN	✓				✓
	Oskarshamn	OSK	✓				
	Stockholm	STH	✓				✓
S4	Karlshamn	KHM	✓			✓	✓
	Söderåsen	SDA	✓			✓	✓
F1	Kangasala	KAN	✓			✓	✓
	Pikkarala	PIK	✓		✓		
D1	Jylland	JUT	✓				✓
	Hamburg	HAM	✓				✓
D1	Sjælland	SJL	✓				✓

Table 4.2: Load and generation for all nodes

	Load		Generation			
Node	P $[MW]$	Q $[Mvar]$	$P_{g_{ini}}$ $[MW]$	Parallel Machines	P_{ini} $[MW]$	P_{max} $[MW]$
Hasle	0	0	0	0	0	0
Oslo	4 210	692	200	8	1 600	1 800
Skien	1 229	115	200	4	800	900
Feda	3 121	297	150	12	1 800	2 700
Kristiansand	1 000	515	100	1	100	225
Kvilldal	94	0	220	8	1 760	1 800
Songa	0	0	200	4	800	900
Tokke	0	0	200	2	400	450
Tonstad	4	0	210	6	1 260	135
Aura	200	30	190	2	380	450
Trondheim	1 719	239	190	6	1 140	1 350
Finnmark	200	48	210	2	420	450
Ofoten	200	48	210	2	420	450
Røssåga	1 927	446	200	14	2 800	3 150
Aurland	3 042	980	200	12	2 400	2 700
Hallingdal	201	11	210	12	2 520	2 700
Grundfors	1 250	300	210	22	4 620	4 950
Ligga	200	48	210	4	840	900
Umeå	0	0	210	4	840	900
Midskog	2 700	500	150	6	900	1 350
Hjälta	0	0	220	16	3 520	3 600
Barkeryd	500	100	150	10	1 500	2 250
Borgvik	30	10	0	0	0	0
Lindome	4 860	880	170	20	3 400	4 500
Oskarshamn	300	80	150	8	1 200	1 800
Stockholm	2 000	750	200	26	5 200	5 850
Karlshamm	500	150	150	4	600	900
Söderåsen	9 350	2 000	150	20	3 000	4 500
Pikkarala	1 500	400	160	8	1 280	1 900
Kangasala	5 600	1 250	200	26	5 200	5 850
Sjælland	1 000	1 000	120	8	960	1 800
Sum	46 937	10 889			52 660	62 325

Table 4.3: Power lines in Norway

Line		Type	Voltage	Number	Length
Node 1	Node 2		[kV]		[km]
Kristiansand	Skien	Triplex	400	1	140
Kristiansand	Kvilldal	Triplex	400	1	180
Kristiansand	Feda	Triplex	400	1	75
Feda	Tonstad	Triplex	400	1	50
Feda	Tonstad	Duplex	400	1	50
Tonstad	Aurland	Triplex	400	1	300
Aurland	Hallingdal	Triplex	400	3	110
Aurland	Kvilldal	Triplex	400	1	180
Tonstad	Kvilldal	Triplex	400	1	110
Tonstad	Kvilldal	Triplex	400	1	110
Kvilldal	Skien	Duplex	300	1	200
Kvilldal	Skien	Duplex	400	1	200
Skien	Hasle	Triplex	400	1	100
Hallingdal	Oslo	Triplex	400	3	160
Oslo	Hasle	Triplex	400	1	80
Kvilldal	Songa	Triplex	400	1	70
Songa	Oslo	Triplex	400	1	200
Kvilldal	Songa	Duplex	300	1	100
Songa	Tokke	Duplex	300	1	40
Skien	Tokke	Duplex	300	1	150
Kvilldal	Tokke	Duplex	300	1	100
Oslo	Tokke	Duplex	300	1	200
Skien	Oslo	Triplex	400	1	120
Aurland	Aura	Triplex	400	1	400
Aura	Trondheim	Triplex	400	2	150
Aura	Oslo	Triplex	400	1	400
Trondheim	Røssåga	Triplex	400	2	400
Røssåga	Ofoten	Simplex	400	1	600
Finnmark	Ofoten	Simplex	220	1	600

Table 4.4: Power lines to or in Sweden, Denmark and Finland

Line		Type	Voltage	Number	Length
Node 1	Node 2		[kV]		[km]
Kangasala	Pikkarala	Simplex	400	3	480
Ligga	Pikkarala	Simplex	400	2	400
Ofoten	Ligga	Simplex	400	1	300
Røssåga	Grundfors	Simplex	220	1	150
Ligga	Grundfors	Simplex	400	1	330
Ligga	Hjälta	Simplex	400	2	450
Ligga	Umeå	Simplex	400	1	200
Hjälta	Umeå	Simplex	400	1	150
Grundfors	Midskog	Triplex	400	2	240
Trondheim	Midskog	Triplex	400	1	270
Midskog	Hjälta	Triplex	400	1	110
Midskog	Borgvik	Duplex	400	2	470
Midskog	Stockholm	Triplex	400	2	520
Hjälta	Stockholm	Triplex	400	3	460
Stockholm	Lindome	Duplex	400	1	440
Stockholm	Barkeryd	Duplex	400	2	280
Stockholm	Oskarshamn	Triplex	400	2	250
Oskarshamn	Karlshamm	Triplex	400	2	160
Hasle	Lindome	Triplex	400	1	200
Hasle	Borgvik	Triplex	400	1	110
Lindome	Borgvik	Duplex	400	2	200
Lindome	Barkeryd	Triplex	400	1	160
Barkeryd	Karlshamm	Duplex	400	1	190
Lindome	Söderåsen	Triplex	400	2	210
Söderåsen	Karlshamm	Triplex	400	2	110
Jutland	Hamburg	Triplex	400	2	300
Söderåsen	Sjælland	Cable	400	2	60

Table 4.5: Default SVC ratings

Node	Max Nr. Capacitors	Q_{max} [$Mvar$]
Skien	8	200
Hasle	16	400
Kristiansand	25	500
Hallingdal	4	100
Karlshamn	25	1 000
Söderåsen	25	1 000
Kangasala	20	500

4.8 CURRENT SOURCE CONVERTERS

The *Rectifier/Inverter (Two-connection)* is used to represent CSCs based on thyristors.

4.8.1 Control System

In order to maintain the desired power flow under safe conditions, a control system for the HVDC link has to be set up. As described in Section 2.1.4, the inverter controls DC voltage and the rectifier regulate the DC voltage on the rectifier end to obtain the desired current. The inverter measures the DC voltage and sets the voltage such that the voltage at the rectifier end is 1p.u. The inverter side voltage will then be lower due to the voltage drop of the DC cable resistance.

4.8.1.1 *Rectifier Control*

The rectifier is used to control the DC current. This is done by *constant firing angle range control* involving use of the converter transformer tap changer to adjust the AC voltage at the converter terminals, to keep the firing angle constant. As long as the tap is within its range, the firing angle is constant. If the tap is at its maximum or minimum value, the firing angle will be adjusted accordingly, but the range of the firing angle has been limited.

4.8.1.2 *Inverter Control*

The inverter is controlled similarly to the rectifier, but is controlling the DC voltage. This is done by *constant extinction angle range control* involving use use of the converter transformer tap changer to adjust the AC voltage at the converter terminals, to keep the extinction angle constant. As long as the tap is within its range, the extinction angle is constant. If the tap is at its maximum or minimum value, the firing angle will be adjusted accordingly, but the range of the extinction angle has been limited. Keep in mind that the firing angle is the real controlling angle of the converter and the extinction angle is just a measure.

4.9 VOLTAGE SOURCE CONVERTERS

The *PWM Converter (Two-connection)* is the element used to represent VSCs, both the regular two-level type and the half-bridge MMC type. A disadvantage of this module is that it does not have a type. That means that duplicate settings have to be specified for all HDVC links using the same type of VSCs.

If the two-level type is used, the modulation method has to be specified as sinusoidal PWM, rectangular PWM or no modulation. If the MMC type is used, values for the arm reactor, R_{arm} and L_{arm}, has to be specified. In addition, the submodule capacitance and number of submodules per arm is needed for RMS and EMT-simulation.

4.9.1 Capability Curve

All VSCs have a capability curve, as mentioned in Section 2.2.2. This curve gives the maximum possible reactive power at any active power operating point. The values are in per unit of the nominal apparent power of the converter. An absolute maximum reactive power of 0.5 p.u. is possible when active power is 0.5 p.u. or less. The capability curve used in the model is inspired by the figure in [6] and oral information. The values are not valid for all converters nor an average of several values, but they are known to have been used in an at least one type.

4.10 HVDC LINKS

The Nordic power system today has one of the highest concentration of HVDC links in the world. The number of HVDC links will increase in the coming years and their total power by 2030 will be well above today's level.

Henceforth, it useful to define the terms the terms *link group* and *link system* as:

LINK GROUP collection of HVDC links with the same name, connecting the same locations.

LINK SYSTEM collection of converters sharing the same current.

There are a total of 15 link groups, 23 link systems and 47 converters in the model. The technology, voltage and power differs for each link.

Table 4.7 shows all the links included the model. The *Nr.* column identifies the pole number, but it also gives information of the link system. Rows with numbers on the form *1+2* denote a link system consisting of pole *1* and *2*. If one of the numbers are grey, the two poles have different ratings and are specified separately, with the black number identifying the specified pole.

4.10.1 CSC

The CSCs are all modelled simply as six-pulse converters and no filters for harmonics or reactive power compensation are included. This is because the model is not intended to have that degree of detail. For reactive power, one must instead rely on SVCs which are placed at or nearby all buses with CSC-HVDC links.

Throughout the model, the representation of *ground* for HVDC links is done by a DC voltage source rated at 1 kV that is set to 0 p.u., henceforth called a *ground source*. It has an internal resistance of 1 Ω to have a somewhat realistic grounding resistance.

A monopole link consists of a transformer, converter and a DC reactor on the HV-side at both ends, connected by a DC cable. If the link has metallic return, a cable at 1 kV is connected on the low voltage side of the converter. If the link has ground return, a ground source is connected at the low voltage side. The LV-side is directly connected to a 1 kV DC cable or a ground source, depending on if it has metallic or ground return, respectively.

Bipole links are basically the same as to monopoles, where one converter has positive rated voltage connected to its HV-side and the other has negative rated voltage connected to its LV-side. The LV-side from the first converter and the HV-side from the other are directly connected to the same ground source.

4.10.1.1 *Simplified Links*

For many of the HVDC links, only the end connected to the Nordic grid is connected. This is done my modelling the DC-side either as a set of DC voltage sources, or as a DC current source, as shown in Figure 2.11.

The current source is implemented using the *DC Current Source (Two-terminal)* element in PowerFactory. Equation (2.20) is used to find the value of the conductance, G of the current source, assuming a droop of approximately 7–9 %. Great accuracy is not required and 10^{-2} decimal precision is used for the value of G.

Table 4.6: Parameters for simplified CSC-HVDC links

Name	G	P_{nom}	$I_{N_{nom}}$
NorNed			
SwePol			
EstLink 2			
Vyborg 1-4			

4.11 POWER FLOW SETTINGS

Power flow is run by executing the *Load Flow* function in PowerFactory. This function has multiple options which affects the calculation. The settings used throughout the model are shown in Table 4.8.

A user of the model should keep in mind that these settings are saved in the currently activated *study case*. This means that the settings should be checked whenever a new study case is created.

Table 4.7: Basic info for the HVDC links

Link			Voltage	Power	Nr. of	AC Buses	
Name	Nr	Type	[kV]	[MW]	Con	From	To
Skagerrak	1+2	CSC	±250	500	4	N2KRS	D1JUT
	3+4	CSC	350	440	2	N2KRS	D1JUT
	3+4	MMC	500	700	2	N2KRS	D1JUT
	5	MMC	±525	2000	4	N2KRS	D1JUT
NorNed		CSC	±450	700	1	N2FED	—
NSN-Link	1	MMC	±525	1400	2	N2FED	—
	2	MMC	±525	2000	2	N2FED	—
NorthConnect		MMC	±525	1400	2	N3AUR	—
NordLink	1	MMC	±525	1400	2	N2KRS	D1HAM
	2	MMC	±525	2000	2	N2KVI	D1HAM
Baltic Cable		CSC	400	600	2	S4SDA	D1HAM
Kontek		CSC	400	600	2	D2SJL	D1HAM
Kriegers Flak		MMC	400	600	2	D2SJL	D1HAM
Storebælt		CSC	400	600	2	D2SJL	D1JUT
Konti-Skan	1+2	CSC	±285	380	4	S3LIN	D1JUT
NordBalt		MMC	±300	700	1	S4KHM	—
SwePol		CSC	450	600	1	S4KHM	—
Fenno-Skan	1+2	CSC	400	500	2	S3STH	F1KAN
	1+2	CSC	500	800	2	S3STH	F1KAN
EstLink	1	VSC	±150	350	1	F1KAN	—
	2	CSC	450	650	1	F1KAN	—
VyborgLink	1	CSC	±90	355	1	F1KAN	—
	2	CSC	±90	355	1	F1KAN	—
	3	CSC	±90	355	1	F1KAN	—
	4	CSC	±90	355	1	F1KAN	—

Table 4.8: Power flow settings in PowerFactory

	Basic Options
Calculation Method	AC Load Flow, balanced, pos. sequence
Reactive Power Control	Automatic Adjustment of Transformers
	Consider Reactive Power Limits
Temperature Depend.	...at 20°
Load Options	Consider Voltage Dependency of Loads
	Active Power Control
Active Power Control	as Dispatched
	Consider Active Power Limits
Balancing	Distributed slack by synchronous gen.
	Advanced Options
Load Flow Method	Newton Raphson (Power equations)
Load Flow Initialisation	Consider transformer winding ratio
Tap adjustment	Direct
	Iteration Control
Max. Number of Iter.	Newton Raphson - 400
	Outer Loop - 100
	Number of steps - 1
Max. Acceptable	Nodes - 1 kA
Load Flow Error	Model Equations - 0.1 %
Convergence Options	Auto. iteration step size adaption
	Auto. model adaptation for convergence

5 MODEL DEVELOPMENT

This chapter describes new implementations to the model, provides additional detailed information and gives an overview of the problems that have surfaced during development.

5.1 MODELLING PROCEDURE

Development and testing of the model is largely comprised of trial and error. Whenever a change is made to a setting or a new object is added, there is no guarantee that it will work on the first try. The system is complex and a small change can make the whole system not converge, unstable or otherwise non-functional. Figure 5.1 roughly shows the process of adding a new object or making a change to the model.

5.2 AC SYSTEM

5.2.1 Nominal system voltage

The nominal voltage for all previous 420 kV buses has been changed to 400 kV buses. Along with this, the HV-side of the connected transformers have also been set to 400 kV. In order to still have the nominal operating voltage of the high voltage grid at 420 kV, the voltage setpoint of generators is now set to 1.05 kV The actual grid voltage will then be a bit lower due to voltage drop in the generator transformer.

The colours have also been changed such that green, which is usually the colour used for 1.0 p.u. is now used for 1.05 p.u. The max/min bounds for the other colours has been shifted accordingly by 1.05.

According to [31], the minimum voltage in the Norwegian grid is 0.93 p.u. Since the base voltage has been changed from 420 kV to 400 kV, making the nominal voltage 1.05 p.u., this value and the voltage range is adjusted according to Table 5.1.

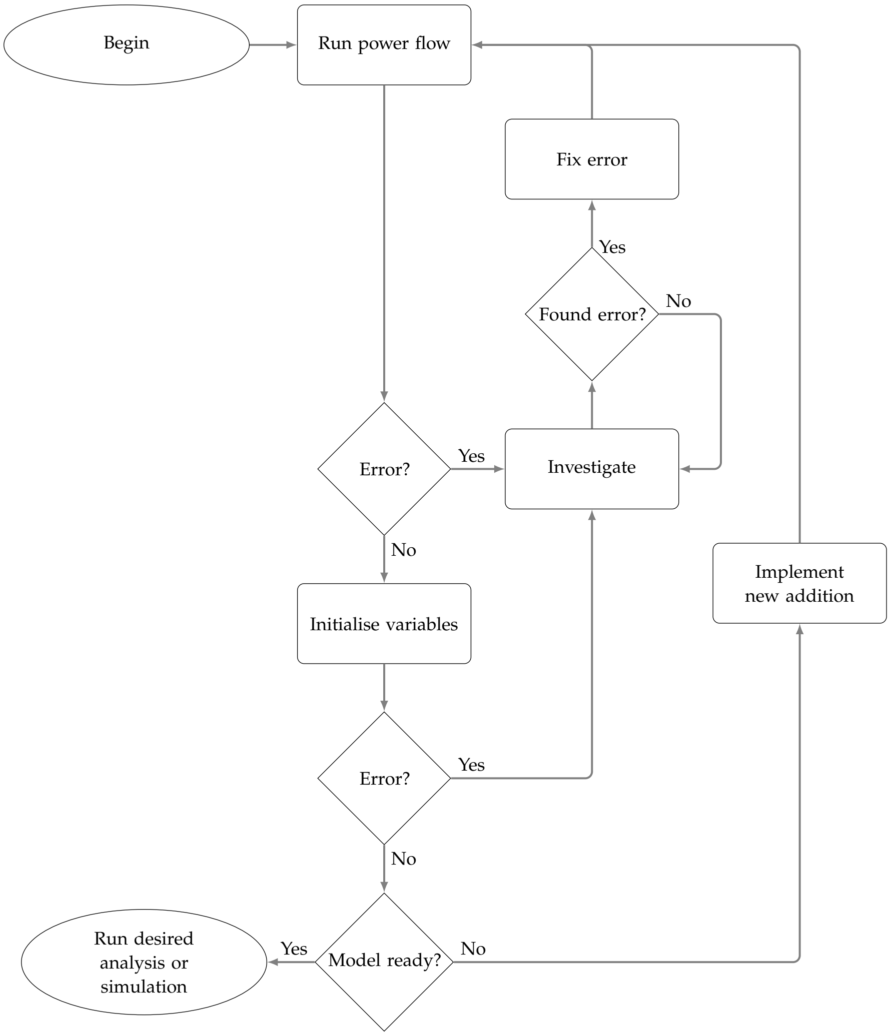


Figure 5.1: Flowchart of the modelling procedure

Table 5.1: Adjustment of allowed per unit voltages for the new system base

V_{old} [p.u.]	V_{new} [p.u.]
1.10	1.155
1.05	1.1025
1.00	1.05
0.95	0.9975
0.93	0.9765
0.90	0.945

5.2.2 New Nodes

A future use of the model can be to link with market data. This can yield more realistic data and be used to study the feasibility of different scenarios. New nodes, shown in Table 5.2, have been added in order to better accommodate future linking with a market models.

Table 5.2: New AC buses

	Name		Bus voltage [kV]		
Area	Long	Short	400	300	220
N2	Songa	SON	✓	✓	
	Tokke	TOK		✓	
N4	Finnmark	FIN			✓
S1	Umeå	UME	✓		
S3	Oskarshamn	OSK	✓		

Some generation capacity has been added to all the new buses, shown in Table 5.3, but the numbers are not accurate. Tokke and Finnmark at the moment only has two machines and are thought to have slightly less capacity than Songa and Umeå with four machines. Oskarshamn is implemented with eight machines, since it is the location of a large nuclear power plant. The number of parallel machines both can easily be changed when needed.

Table 5.3: Generator capacity for new AC buses

	Number of Parallel Machines	Maximum Power [MW]
Songa	4	900
Tokke	2	450
Finnmark	2	450
Umeå	4	900
Oskarshamn	8	1 800

5.2.3 AC Cable Sjælland–Söderåsen

The AC cable connecting Eastern Denmark and Sweden had insufficient capacity, resulting in overloading when all of the Sjælland HVDC interconnections were transmitting. Modelled as two 400 kV cables rated at 1.5 kA.

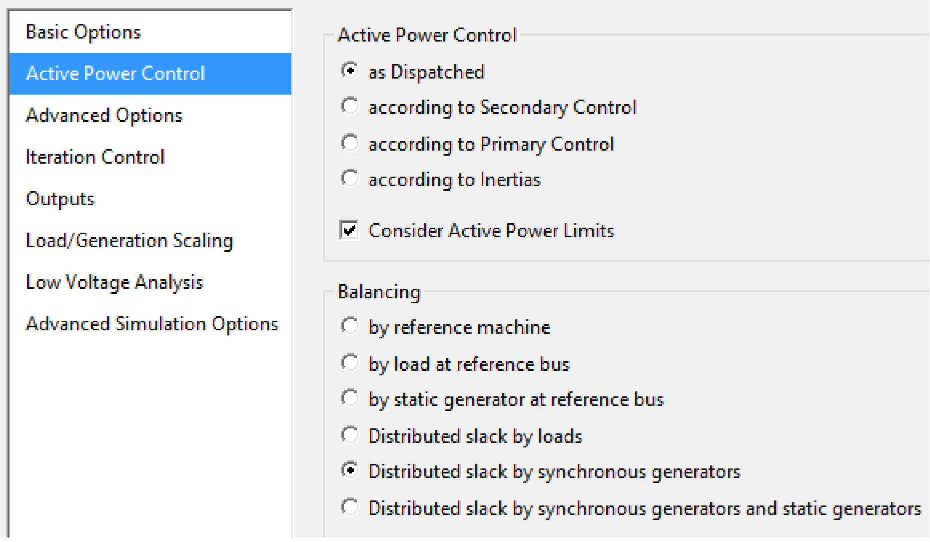
Information from Energinet.dk [25] says the connection has a capacity of 1 700 MW export from Denmark and 1 300 MW import to Denmark. The different capacities are due to bottlenecks in the Swedish grid. The connection today consists of two 400 kV and four 132 kV cables, some of which will be replaced in the near future due to ageing cables.

Taking into account the updated information, the cable Sjælland-Söderåsen is now modelled as three 400 kV cables rated 1 kA.

5.2.4 Continental Europe Generators

The model considers only the dynamics of the Nordic power system. As such, the buses in West Denmark (D1), are not part of this system. The D1 grid is very simplified and is not a realistic representation, nor an interest of investigation of this project. The area is mainly regarded as an infinite generator or load, dependent on the import/export state of the Nordic grid, as not to pose any problems. Originally, the PowerFactory element *External Grid* was used as a slack bus and intended to provide this function, but it has proved not functional, not providing any active power. This problem arose due to the way PowerFactory handles balancing during calculation of power flow. As shown in Figure 5.2, several options are available for balancing in the *Advanced* pane of the *Load Flow Calculation* window. In the model, the option *Distributed slack by synchronous generators* is used. This means that the active power dispatch is changed for all generators to account for the slack, instead of a single reference machine. Since the external grid is not a synchronous generator, its active power remains equal to the initial dispatch.

The solution was to increase the generator capacity to an extremely large number, and set the load to be equal to in the middle of the generators active power range. This provides the needed flexibility and allows the generator to deliver and extract a very large amount of active power. Generators can operate in the range 100 MW to 225 MW, making the initial dispatch be 162.5 MW. To allow a large flexibility, the generator at both the Jutland and Hamburg buses are set to 100 parallel units. Accordingly, the loads at the same buses are set to $500 \cdot 162.5\,MW = 81\,250\,MW$. This is summarised in Section 5.2.4.



Active Power Control

● as Dispatched
○ according to Secondary Control
○ according to Primary Control
○ according to Inertias

☑ Consider Active Power Limits

Balancing

○ by reference machine
○ by load at reference bus
○ by static generator at reference bus
○ Distributed slack by loads
● Distributed slack by synchronous generators
○ Distributed slack by synchronous generators and static generators

Figure 5.2: Settings for *Load Flow Calculation*

Table 5.4: Capacity for synchronous generators in the D1 area

Name	Parallel Generators	Generator Dispatch [MW]	Load [MW]
Hamburg	500	162.5	81250
Jutland	500	162.5	81250

5.3 VOLTAGE SOURCE CONVERTERS

5.3.1 New Converters

Four new VSC-HVDC links have been added, shown in Table 5.5. All of these are modelled only in the Nordic end of the link and use the MMC-type, except for EstLink 1 which uses the traditional two-level converter.

Table 5.5: New VSC-HVDC Links

Link Name	Type	Voltage [kV]	Power [MW]	Nr of Con
NorthConnect	MMC	±525	1400	2
Kriegers Flak	MMC	400	600	2
NordBalt	MMC	±300	700	1
EstLink 1	VSC	400	600	1

5.3.1.1 *Kriegers Flak Combined Grid Solution*

Implemented with all the correct voltage levels. Back-to-back on land in Germany. Subseas AC 150 kV from the converter station to the wind farms. 220 kV from the offshore transformer to 400 kV offshore in Germany.

Kriegers Flak CGS Currently has very high losses due to the multiple transformers.

Due to PowerFactory having issues with multiple voltage controlling elements connected to the same bus, a slight workaround is needed. Using a line with low resistance is not working, as modal analysis takes an infinitely long time to compute. The solution is to use a *Series reactor* element to connect to DC terminals of the converters. A similar solution using the series reactor as a workaround element is also proposed on the DIgSILENT website, used to connect buses of different voltage levels. The series reactor is set to have an internal resistance of 0.01 Ω.

5.3.2 Calculation of nominal apparent apparent power

The rule of thumb used for the apparent power is that at fully rated active power, the maximum reactive power should be 35 % of the nominal apparent power, S_n. This is related to the capability curve mentioned earlier. When speaking of active power, one refers to power delivered to the grid on the receiving end, after all components in the HVDC system. The sending end power thus have to be quite a bit higher than the specified value. This fact was not sufficiently considered in the original values for apparent power and the rectifier could not deliver any reactive power when transferring maximum active power, i.e., the top of the capability curve was reached.

To ensure stable voltages at both ends, the ability of the VSC to regulate reactive power is crucial. There, the nominal apparent power was changed for all converters according to

$$S_n = \frac{P_{rec_{max}}}{1 - 0.35^2} \tag{5.1}$$

where S_n is the nominal apparent power and $P_{rec_{max}}$ is the active power into the rectifier when maximum active power is delivered to the receiving grid.

It is worth noting that in the model, power is specified for the inverter, but the maximum active power is flowing through the rectifier. Hence, reason $P_{rec_{max}}$ is used in this calculation.

By setting the active power at the inverter to the specified maximum for each link, the power at the inverter was measured. The power drawn from/delivered to the grid can change slightly depending on the voltage, but will be approximately the same. Calculation of the apparent power rating for all converters were done using equation (5.1) and adjusted.

5.3.3 Calculation of MMC Parameters

A spreadsheet of HVDC project data from Til Kristian Vrana suggests that NordLink and NSN Link have 31 levels, Skagerrak 4 has 29 levels and NordBalt has 35 levels, but these values are unconfirmed. Another source, with values allegedly provided by Statnett, claims that Skagerrak 4 has 30 submodules per arm, with a submodule capacitor size of 1.2 mF [32].

Using the method described in Section 2.2.3.3 values for the parameters of the MMCs are found. An energy-to-power ratio of $E_s = 40\,\frac{\mathrm{kJ}}{\mathrm{MVA}}$ gives a results in about 1.2 mF as suggested. There, the same energy-to-power ratio is used for all the other converters as well. Since the values are not precise, the arm capacitances has been rounded to the nearest integer and multiplied by the number of submodules to retrieve an integer value for the cell capacitor.

All converters in PowerFactory also need a specified arm resistance, R_{arm}. Since no general value or method were found, all converters are set to use the R_{arm}/L_{arm} ratio from the PowerFactory *Offshore wind farm* example system, where $R_{arm} = 6\,\mathrm{m\Omega}$ and $L_{arm} = 60\,\mathrm{mH}$. Then the arm resistance of MMC converters is found by:

$$R_{arm} = 0.1 \cdot L_{arm} \tag{5.2}$$

The resulting parameters are listed in Table 5.6. Parameters for the Offshore wind farm system are shown as a reference, labelled as PF Example. Arm capacitance and inductance are in the same range as the other calculated values.

Table 5.6: New table

Converter	V_{dc} [kV]	S [MVA]	n	C_{cell} [mF]	C_{arm} [µF]	L_{arm} [mH]	R_{arm} [mΩ]
Skagerrak 4	500	785	30	1.26	42	40	4
Kriegers Flak	280	500	16	1.36	85	25	2.5
NordBalt	600	785	34	0.986	29	50	5
NordLink 1	525	785	30	1.14	38	40	4
NordLink 2	525	1 110	30	1.62	54	30	3
PF Example	300	450	200	10	50	60	6

5.4 SPECIFYING HVDC POWER FLOW

Several settings can be quite tedious to change, such as the active power flow of HVDC links. This requires manually changing rectifier/inverter and setpoints for all converters in the link. When testing different configurations, this can be a time consuming process. A script has been developed to improve this process, shown in Appendix C.2.

5.4.1 Power Flow on an HVDC line

Power flow from sending to receiving grid on a HVDC line is shown in Figure 5.3. The power loss in the line is dependent on the current in the line. R_t and R_c are not physical resistances, but represent transformer and converter losses respectively. R_l represent the physical resistance of the line and is directly dependent on the current.

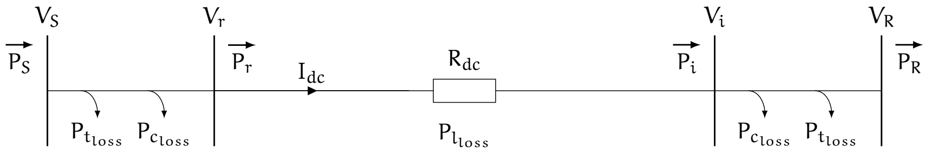


Figure 5.3: Loss in dc line

Either the rectifier or inverter power is known. The power flow from rectifier to inverter can be found my taking into calculating the line losses:

$$P_r = P_i + R_{dc} I_{dc}^2 \tag{5.3}$$

Converter losses depend on the converter type and specifications. Transformer losses are proportional to the short circuit resistance of the transformer, r_k, given in percentage. This loss will then be equal to this as a percentage of the converter output power. Since the power output to the receiving grid, P_R, is specified for an HDVC link, the power input to the inverter from the DC line, P_i, is found by:

$$P_i = \frac{P_R}{1 - r_k} \tag{5.4}$$

5.4.2 Settings for CSC

5.4.2.1 *Calculation of Loss in CSC-HVDC Link*

Active power is controlled by the rectifier, while the inverter controls DC voltage. The active power of interest is that delivered to the receiving grid, thus the specified rectifier power has to account for the losses.

A script is used to set the correct power, along with the other required settings required for each converter in the link system, see.

The rectifier voltage, V_r, is held constant to $1.0\,\text{p.u.}$ at the nominal voltage, V_{nom}. By solving the quadratic equation (5.1), the DC current, I_{dc}, can be calculated by:

$$I_{dc} = \frac{V_{nom} - \sqrt{V_{nom}^2 - 4R_{dc}P_i}}{2R_{dc}} \tag{5.5}$$

where R_{dc} is the DC line resistance and P_i is the inverter power input.

Since the CSCs are modelled lossless, the setpoint for active power at the rectifier, P_r, is found by inserting values from equations (5.4) and (5.5) into equation (5.3).

In order to keep $V_r = 1.0\,\text{p.u.}$, the inverter voltage, V_i, is set such that:

$$V_i = V_r - R_{dc}I_{dc} \tag{5.6}$$

Power flow reversal for the CSC-HVDC links require some parameters to be changed. The required settings for import and export are shown in Table 5.7.

Table 5.7: Settings for changing power flow direction for CSCs in the model

Flow direction	**Import**	**Export**
Converter control	Voltage	Power
Transformer tap control	Extinction angle	Firing angle
Angle setpoint	18°	15°

6 ANALYSIS AND SIMULATION

In this chapter, power flow scenarios are developed depending on the HVDC import/export power. Contingency analysis is performed to find the maximum HVDC power before violations of continuous operating constraints occur. Solutions are then suggested to avoid the violations. Next, RMS simulations of specific events are made to investigate the dynamic stability of the system, taking into account the results from the contingency analysis.

When talking about the HVDC power flow, it is convenient to use the terms *import* and *export*, defined as active power *to* and *from* the Nordic grid, respectively. They will be used exclusively referred to the Nordic grid.

6.1 STUDY OF HISTORIC POWER FLOW PATTERNS

Yearly reports of the availability and energy transferred of all Nordic HVDC links are published by ENTSO-E [33], [34]. These are useful for finding out how much each link is utilised as import and export, but they do not should how the links operate in relation to each other at at any given time. This is needed to find realistic scenarios.

Data for the Nordic load, generation and HVDC link power flows have been collected from NordPool [35] for the years 2013 to 2016 and organised. This is useful for understanding the relation between the different links and the patterns for which they operate. Although the market situation and flow will likely be quite different in 2016, this analysis of past flows still yields an indication of the future flow patterns.

The data shows that, at least in the last four years, the maximum total import to the Nordic grid has been 5 000 MW, while maximum export has been 5 800 MW. These values are far from the scenarios studied in this analysis, which can be considered quite extreme. The actual capacity available today is 9 020 MW, proving that all links are not fully utilised simultaneously. The links are rarely operating at their full rated capacity because of restrictions, reserve capacity and market demand. Regardless, the scenarios studied in this analysis are intended to maximise the power flow, ultimately to the full HVDC link capacities.

Table 6.1: Generation and load for the base case

Group	Area	Generation [MW]		Load [MW]
		Initial	Actual	
Norway	N1	2 400	2 231	5 439
	N2	6 120	5 696	4 219
	N3	1 520	1 413	1 919
	N4	3 640	3 384	2 327
	N5	4 920	4 573	3 243
	Total	18 600	17 297	17 147
Sweden	S1	6 300	5 856	1 450
	S2	4 420	4 109	2 700
	S3	11 300	10 504	7 690
	S4	3 600	3 346	9 850
	Total	25 620	23 815	21 690
Finland	Total	6 480	6 024	7 100
East Denmark	Total	960	892	1 000
Nordic	Total	51 660	48 028	46 937

During the highest recorded export, the load is between 50 % and 90 % of the load at highest import in each area. Considering the total Nordic load, the maximum import load is approximately 70 % of the maximum export load.

6.2 SCENARIOS

6.2.1 Base Case Data

Load and generation of the initial power flow situation is shown in Section 6.2.1, similar to in Table 4.2, but aggregated for the areas. The same kind of table is shown for all the following scenarios. Even though initial generation and load are changed, the generator dispatch cannot be known until the power flow is calculated since balancing by synchronous generators is used. The dispatch of all generators will be changed by the algorithm to reach the required output.

In this case, all HVDC links are off. This is not a realistic situation, and likely incorrect since the state of the HVDC links in the original data is unknown.

6.2.2 Scenario 1: 2021 High Import

All HVDC links expected to be operational by 2021 are importing maximum possible power, such that the total import is up to 11 780 MW. Initial load is the same as the base case. The number of active generators is reduced such that the reduction in initial dispatch is approximately equal to the desired HVDC import capacity.

6.2.3 Scenario 2: 2030 Very High Import

This scenario extends upon *scenario 1*. All the future hypothetical HVDC links are importing maximum possible power, such that the total import is up to 19 220 MW. Generation is reduced even more to make higher import possible, but no generators are completely turned off.

6.2.4 Scenario 3: 2021 High Export

All HVDC links expected to be operational by 2021 are exporting maximum possible power, such that the total export is up to 11 780 MW. Initial generation is the same, but the load is scaled using scaling factors to approximately 70 % of the initial load. The 30 % reduced load corresponds to the desired power export.

6.2.5 Scenario 4: 2030 High Export

This scenario extends upon *scenario 3*. All the future hypothetical HVDC links are exporting maximum possible power, such that the total import is up to 19 220 MW. Load is reduced even more.

6.3 PROCEDURE FOR ANALYSIS OF SCENARIOS

An initial operating point is found by adjusting the base case data to make sure the power flow converges. Quick RMS simulations are performed to validate that the state is not completely unstable. This is done because the RMS simulation can sometimes report problems even at the first time step.

When the initial power system state is determined, a contingency analysis is performed by following these steps:

1. Determine initial high flow situation.

2. Determine the worst *n-1* cases.

3. Reduce HVDC power until the worst *n-1* case is ok and find the maximum HVDC power.

4. Suggest improvement for *n-1* cases and find the new maximum HVDC power.

When the contingency analysis is complete, an RMS simulation analysis is performed to investigate the dynamic stability of the system following load or generation events, by following these steps:

1. Start with the worst *n-1* case including suggested improvements.

2. Run loss of generation event for export scenario, and loss of load event for import scenario.

3. Determine if the system is within allowed limits. If not, reduce HVDC power until the system is in an accepted state.

PowerFactory maintains project settings and variables differently depending on if they should remain constant or are allowed to change for different operating conditions [36]. The basic structure of a project is *Project* → *Study Case* → *Variation* → *Operation Scenario*. These can be described as:

PROJECT contains the main grid model with all its components, including a project library with all user defined elements, types and controllers.

STUDY CASE defines the calculation/simulation parameters used for calculation of e.g. power flow and allows the user to create graphs and figures specific to that study case. It also sets activated operation scenarios, variations, etc.

VARIATION allows the user to test changing project parameters (which are considered constant) or grid structure without making the changes permanent. Instead, the alterations are saved in a variation and will only be active while that variation is enabled. Multiple variations can be enabled at a time. Whenever a variation is active, all changes to the fixed project data, except for library items, are saved in the variation.

OPERATION SCENARIO concerns the values of grid components that can change depending on the situation being analysed, such as values of loads, generator dispatch, out of service components and other set points. Note: parameters saved in the operation scenario are easily identified by having their parameter name coloured in blue.

The method used for implementing a scenario with sub-cases is:

1. Create a new *Study Case* by copying an existing one. This is done to make sure the same parameters are used for calculation of power flow and initial conditions in every analysis. The study case is used as the main container for one of the studied scenarios and activates the relevant operation scenario and variations.

2. Create a new *Variation* to be used for the current study case. Variations are used because the scaling of generators is done by adjusting the number of *parallel generators*, which is considered a constant project parameter. The variation allows saving the currently used number of active generators without affecting the project data. The same is true for the simplified CSC-HVDC links utilising a DC current source, whose *nominal current* is also a fixed project parameter.

3. Create a new *Operation Scenario* by copying an existing one. An operation scenario is created for each sub-case of a studied scenario. Multiple scenarios are created if needed, to analyse different cases. This is done to maintain the same setpoint for all values. Specific settings for the newly created scenario can then be altered, such as load scaling or HVDC converter power.

6.4 CONTINGENCY ANALYSIS

In this section, contingency analysis is performed to make sure the grid has *n-1* security, i.e., the system can withstand the outage of any one component. Several lines are described and indicated, which can all be observed in the accompanying figures.

6.4.1 Limiting Factors

All lines have a rated current determining their loadability. This is determined primarily due to thermal constraints. If the line current is above the rated current, thermal expansion of the conductor material will cause the line to sag, possibly leading to short-circuit if the sag is becomes large. Lines can normally operate above their rated values for short periods of time, but the continuous current, or loading, should never be above 100 % of the rated value. This limit is also called the *thermal limit* of the line [31].

Low voltages decrease the stability of the system by limiting the margin left until voltage collapse. In addition, low or high voltages can damage utility and customer equipment. Statnett operates with a minimum continuous system voltage of 0.93 p.u.(related to 420 kV and 300 kV base) [31].

The Transmission System Operators (TSOs) in the different countries have their own rules, but use similar limits. Since the primary focus of the simulation model and this thesis is on the Norwegian power grid, the limits used by Statnett are used as limits during the analysis.

In summary, two limits are considered in this analysis:

LINE LOADING should not be above 100 % for any lines.

NODE VOLTAGE should not be under 0.93 p.u. for any 400 kV, 300 kV or 220 kV nodes.

6.4.2 Method

The *Contingency Analysis* function in PowerFactory is used to assist in the analysis, where contingencies are defined for all lines and transformers. Generator outages are not considered because of the complexity caused by the large aggregation. For lines where multiple parallel lines are specified, the analysis tool cannot be used to a satisfactory degree in all cases. In cases where the automatic outage of a multi-circuit line causes non-convergence or violations, the analysis is done manually, i.e., reducing the number of lines by one and recalculating the power flow.

6.4.3 Scenario 1: 2021 High Import

6.4.3.1 *Case 1.1: No contingencies*

Power import on the HVDC links available in 2021 is increased to the maximum 11 820 MW without any violations of the limiting factors occurring, when all power lines are in service (n-0). Generation and load for this scenario is shown in Table 6.2.

The power flow and voltages in the Nordic grid for this case is shown in Figure 6.1, when all lines are in service. The figure is a simplified version of Figure 4.1 and contains all relevant information. Arrows indicate the direction of active power, line loadings are presented in % along with the sending end active and reactive power, and voltages are shown in p.u. for each node, where 420 kV is used as base value for 400 kV buses. HVDC flows are shown as purple arrows. They are referred to the connecting bus in the Nordic grid, except Fenno-Skan which is always referred to Sweden with a positive value indicating import. Contingencies will be shown as dotted, grey lines.

Table 6.2: Generation and load for scenario 1

Group	Area	Generation [MW]		Load [MW]
		Initial	Actual	
Norway	N1	1 200	1 039	5 439
	N2	1 810	1 581	4 219
	N3	1 520	1 316	1 919
	N4	3 640	3 152	2 327
	N5	3 280	2 840	3 243
	Total	11 450	9 928	17 147
Sweden	S1	5 460	4 728	1 450
	S2	2 220	1 922	2 700
	S3	11 300	9 785	7 690
	S4	3 600	3 117	9 850
Finland	Total	6 480	5 611	7 100
East Denmark	Total	600	520	1 000
Nordic	Total	41 110	35 611	46 937

6.4.3.2 *Case 1.2: N-1 with no upgrades*

When performing *n-1* contingency analysis, there are only two major line overloading issues occurring. These cannot be avoided even if the power import is low and have to be upgraded to before any further analysis is performed.

Røssåga–Grundfors becomes slightly overloaded when the line between Midskog and Trondheim (106 %) or one of the parallel lines between Grundfors and Midskog (109 %) are out of service. Both of these connections are between Norway and Sweden. The line overloaded is a 220 kV *simplex* line, and is possibly higher rated in the real system. It shows a tendency for the flow to go from Sweden to Norway. The line will likely be upgraded if it is indeed a weakness, but could also be a modelling error. Therefore, it is upgraded to a *duplex* line in this, as well as all other scenarios.

Söderåsen–Karlshamn will always be overloaded (137 %) if one of its two parallel lines are out of service. This is primarily because of a very large load on the Söderåsen bus and will occur even when the power import is low. Reducing import on the Baltic Cable even worsens the issue. The cause of this is probably lack of detail in the aggregation of the Swedish power grid. Nevertheless, it proves the line is very important and has to have sufficient capacity in the future grid. Therefore, it is upgraded with a third parallel *triplex* line in this, as well as all other scenarios.

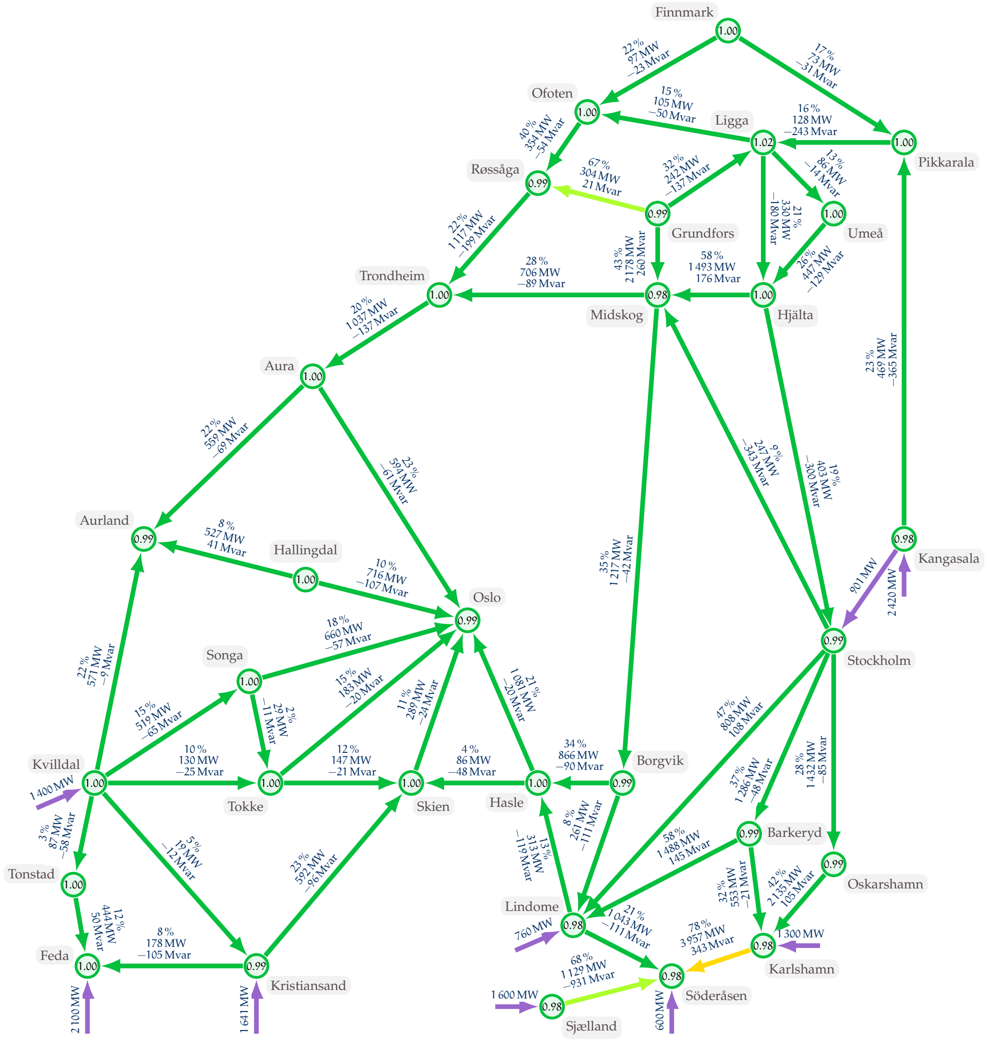


Figure 6.1: Case 1.1: All lines in service

The upgrades are listed in Table 6.3.

6.4.3.3 *Case 1.3: N-1 with upgrades*

After the two weaknesses are upgraded, no other violations occur when importing the maximum available power of 11 820 MW.

6.4.4 Scenario 2: 2030 Very High Import

6.4.4.1 *Case 2.1: No contingencies*

Power import on the HVDC links is increased as much as possible until violations of the limiting factors occur with all power lines in service (n-0). It is clear from the start that the higher power transfer causes voltage issues in the southern Norwegian grid, mainly in the

Table 6.3: New upgrades introduced after Case 1.2

Element	Name	Upgrade
Line	Røssåga–Grundfors	Simplex → Duplex
Line	Söderåsen–Karlshamn	1 x Triplex

Table 6.4: Generation and load for scenario 2

Group	Area	Generation [MW]		Load [MW]
		Initial	Actual	
Norway	N1	1 200	980	5 439
	N2	1 080	900	4 219
	N3	950	776	1 919
	N4	2 440	1 992	2 327
	N5	1 640	1 339	3 243
	Total	7 310	5 987	17 147
Sweden	S1	5 880	4 801	1 450
	S2	1 770	1 445	2 700
	S3	8 900	7 267	7 690
	S4	3 600	2 939	9 850
	Total	20 150	16 452	21 690
Finland	Total	6 480	5 291	7 100
East Denmark	Total	600	500	1 000
Nordic	Total	34 540	28 230	46 937

Oslo area. The maximum level is almost reached before voltage reaches 0.93 p.u. in Skien, at an import of 19 160 MW. In addition several lines are very highly loaded. Generation and load for the scenario is shown in Table 6.4. The power flow for this case is shown in Figure 6.2.

6.4.4.2 *Case 2.2: N-1 with no new upgrades*

When considering *n-1* contingencies, the import power has to be reduced to a lower level where no violations occur. Import is reduced on Skagerrak 5 to 600 MW, making the total import 17 820 MW. At that point, the outage of *Kvilldal–Aurland* gives low voltages in 300 kV grid between Kvilldal and Oslo; mainly Songa, Tokke and Skien are affected. The power flow for the worst contingency *Kvilldal–Aurland* without any additional upgrades is shown in Figure 6.3.

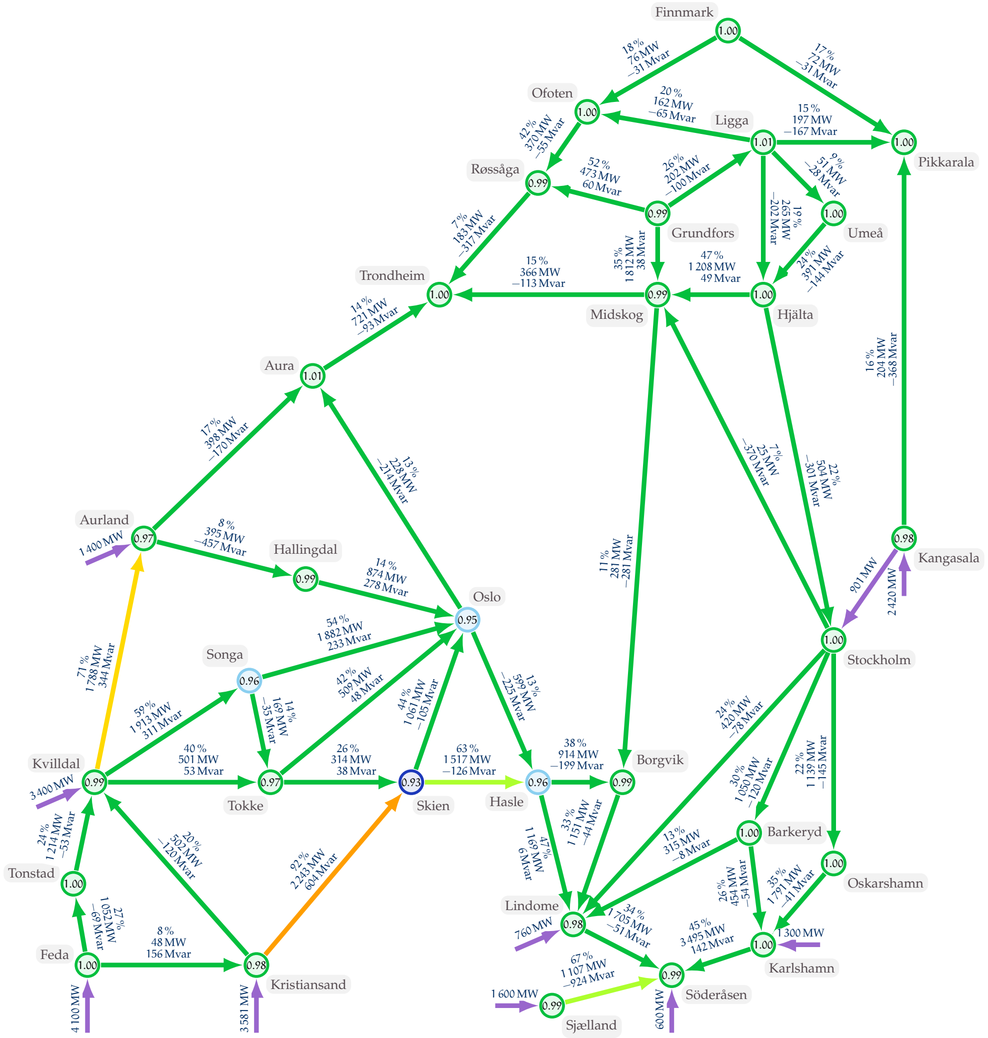


Figure 6.2: Case 2.1: All lines in service

6.4.4.3 *Case 2.3: N-1 With new upgrades*

Adding reactive power compensation at the affected buses removes the low voltage issue, but it does not really increase the import capacity since line loadings are quite high. When the power import is 18 260 MW, the outage of *Kvilldal–Aurland* causes *Kristiansand–Skien* to be loaded above 100 %. This shows that to be able to maximise imported power, new lines have to be added.

A suggested solution is adding one new parallel triplex line on *Kristiansand–Skien* and one new line *Skien–Oslo*, which is also very highly loaded. Adding an SVC with 1 000 Mvar capacitive reactive power at the Oslo 400 kV bus and upgrading the Skien SVC to 1 000 Mvar (from 200 Mvar) allows maximum power import, without any violations. The upgrades are listed in Table 6.5. The power flow for the worst case con-

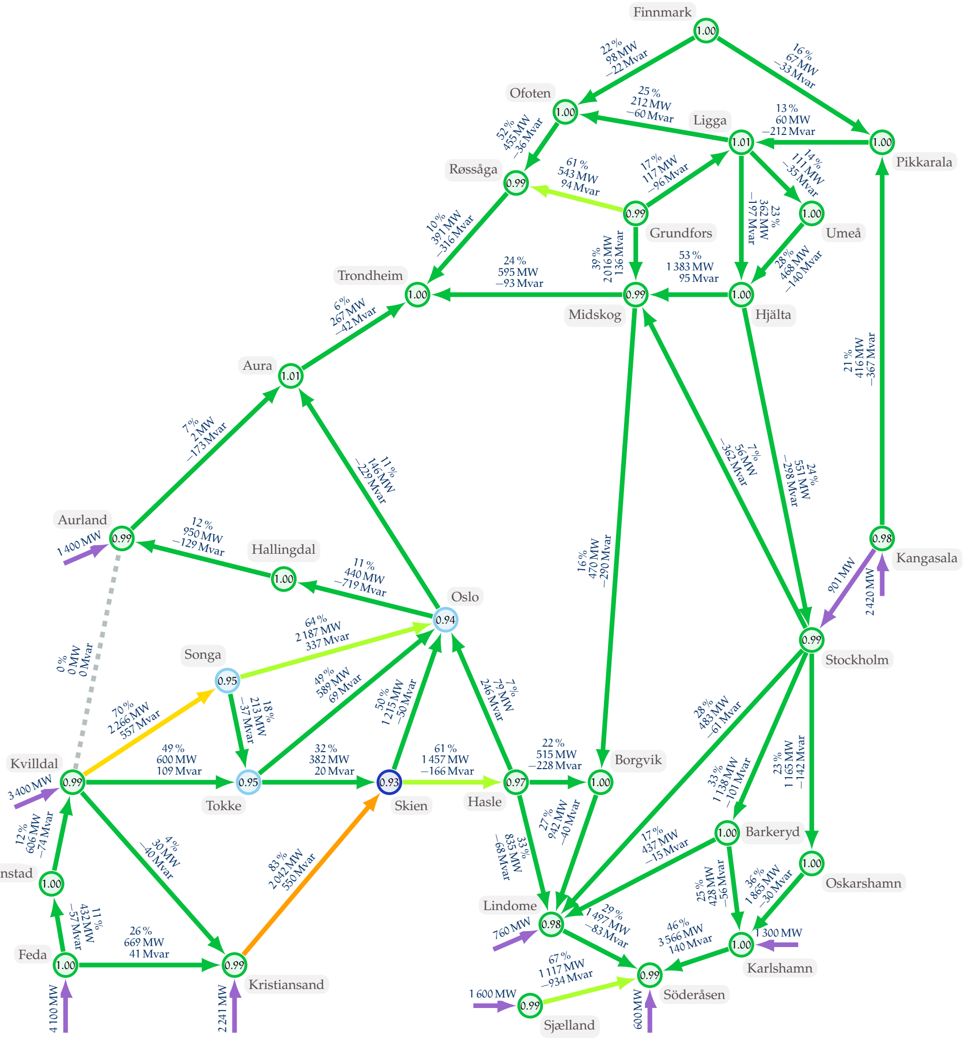


Figure 6.3: Case 2.2: Worst case *n-1* without new upgrades

tingency *Kvilldal–Aurland* with upgraded lines and SVCs is shown in Figure 6.4.

6.4.5 Scenario 3: 2021 High Export

6.4.5.1 *Case 3.1: No contingencies*

With load reduced evenly throughout the grid, but most in areas with high HVDC penetration, the maximum export of 11 000 MW can be reached. The number is a bit higher than the expected 10 755 MW because the sending end power is higher to account for link losses. Central Sweden is troubled with low voltages, but do not reach below the limit for the current situation. This is only true as long as the

Table 6.5: New upgrades introduced for Case 2.3

Element	Name	Upgrade
Bus	Oslo	1 000 Mvar SVC
Bus	Skien	+ 800 Mvar SVC
Line	Kristiansand–Skien	1 x Triplex
Line	Skien–Oslo	1 x Triplex

Table 6.6: Generation and load for scenario 3

Group	Area	Generation [MW]		Load [MW]
		Initial	Actual	
Norway	N1	2 400	2 201	3 807
	N2	6 120	5 621	2 532
	N3	1 520	1 394	1 727
	N4	3 640	3 338	2 327
	N5	4 920	4 512	2 594
	Total	18 600	17 067	12 987
Sweden	S1	6 300	5 778	1 450
	S2	4 420	4 054	2 430
	S3	11 300	10 363	5 383
	S4	3 600	3 302	6 895
	Total	25 620	23 497	16 158
Finland	Total	6 480	5 943	5 680
East Denmark	Total	960	880	400
Nordic	Total	51 660	47 387	35 225

Fenno-Skan connection is offline, which otherwise causes very low voltage at the Midskog node.

The upgrades in *case 2.3* have not been included, but the required changes from *case 1.1* are implemented. Generation and load for this scenario is shown in Table 6.6. The power flow is shown in Figure 6.5

6.4.5.2 *Case 3.2: N-1 With no new upgrades*

In this case, the system is clearly constrained by the Swedish grid. Sweden has a lot of generation in the Nordic part, specifically at the Hjälta node, while almost all Swedish load is in the south. Combined with very long transmission lines that, this lead to voltage problems in the Northern part. Grundfors is affected the most, since it is a connecting point to Norway from Hjälta.

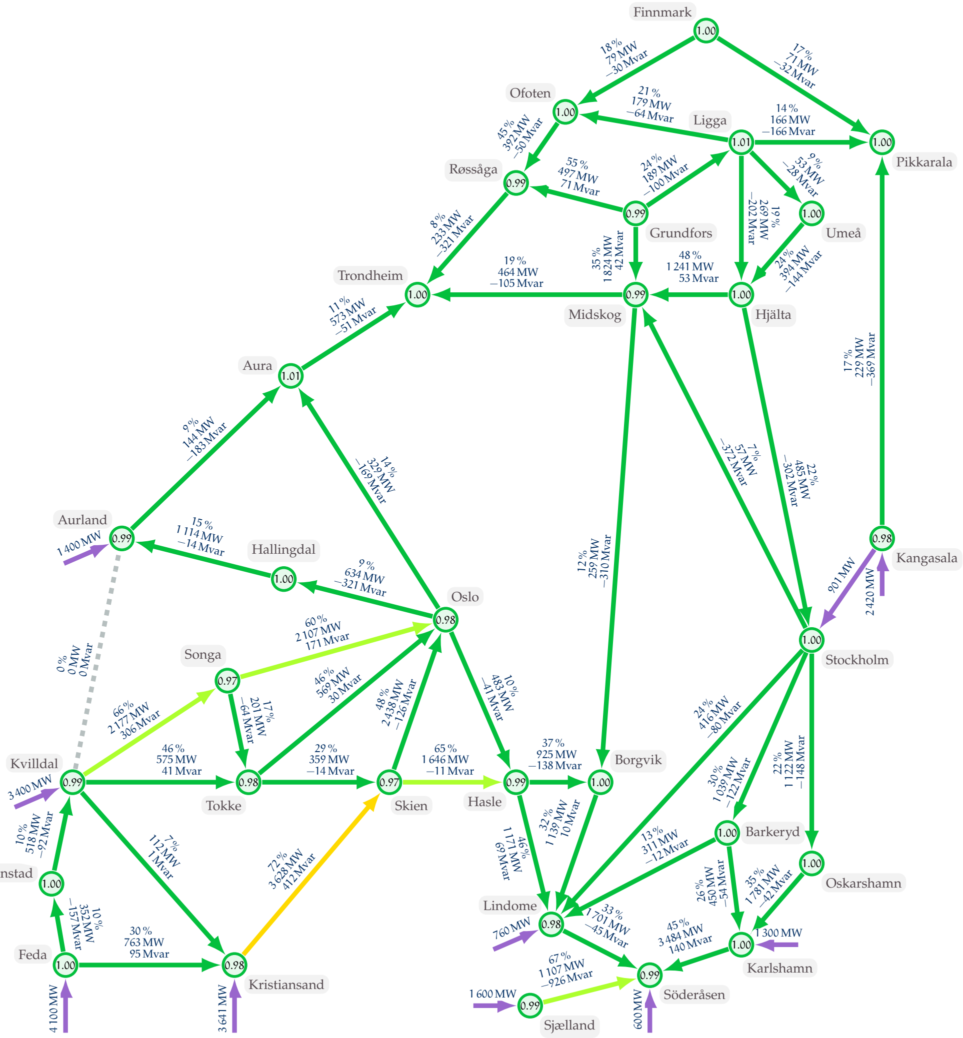


Figure 6.4: Case 2.3: Worst case *n-1* with new upgrades

The case requires several considerations. First of all, Fenno-Skan has to transmit power to Finland to prevent the line *Ligga–Pikkarala* from being overloaded. At the same time, the voltage in Grundfors decreases to very low voltages, down to 0.90 p.u. Since a lot of power is transmitted straight south trough the Swedish grid, the central lines will be highly loaded. Already in Case 3.1 it could be seen that Hjälta–Midskog was highly loaded. In order for no lines to become overloaded or the Grundfors voltage too low, Swedish export has to be reduced significantly, to the point where only Konti-Skan, Storebælt and partly Kriegers Flak are active. The Western Norwegian grid is also affected to some extent, primarily the duplex line Tonstad–Feda becomes overloaded when its parallel triplex line is out of service. NorNed is turned off and power on NordLink is reduced.

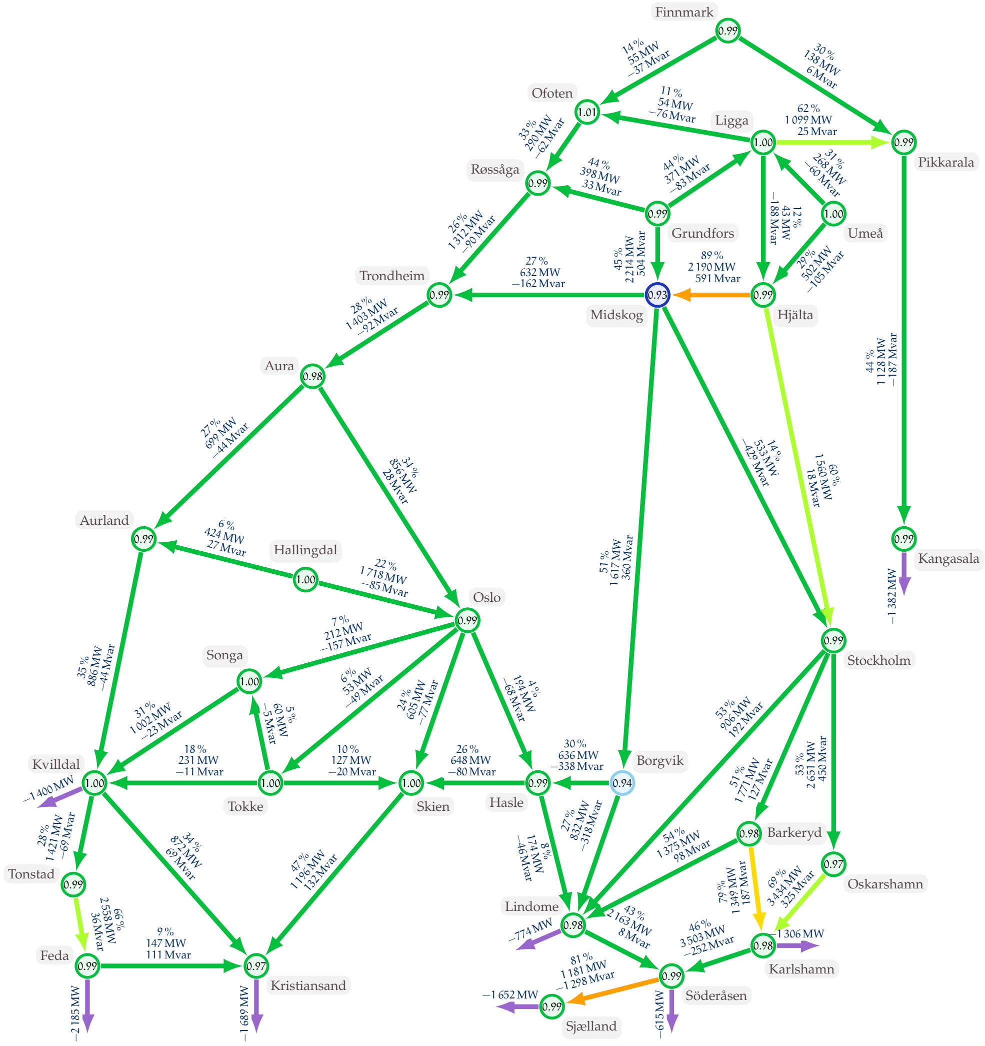


Figure 6.5: Case 3.1: No contingencies

The best case that can be achieved is a total power export of 7 170 MW, where the worst *n-1* case is the outage of Hjälta–Midskog causing Hjälta–Stockholm to reach 100 %. The power flow for this case is shown in Figure 6.6. This shows that significant upgrades are required to achieve a higher export capacity.

6.4.5.3 *Case 3.3: N-1 with new upgrades*

Hjälta–Midskog is clearly a large inhibitor for increased power transfer, and is immediately upgraded with another parallel *triplex* line. An 1 000 Mvar capacitive SVC is placed at Midskog to remove the voltage problem. An additional *duplex* line is added between Feda and Tonstad in Norway. An additional *triplex* line is added between Oskarshamn and Karlshamn due to it being overloaded when one of the two parallel lines being put out of service.

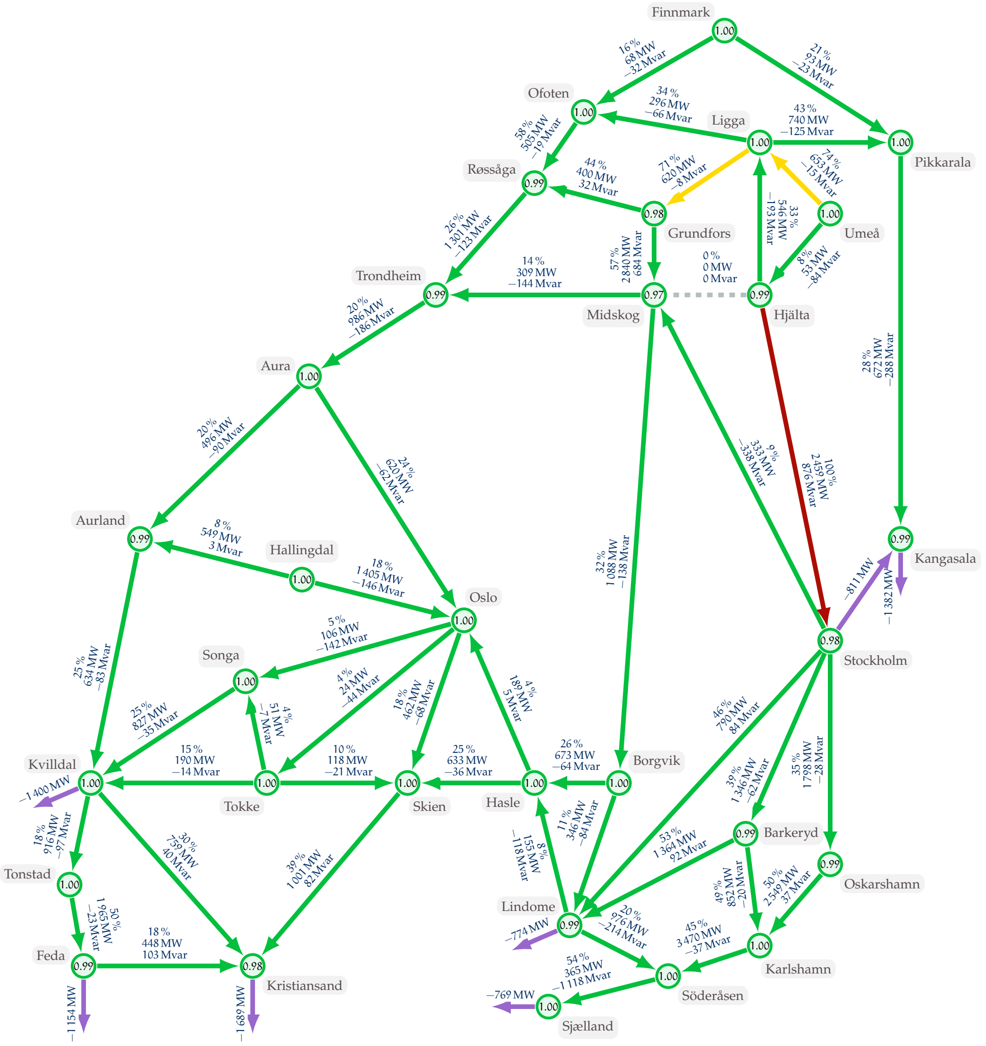


Figure 6.6: Case 3.2: Worst case *n-1* without new upgrades

After these upgrades, the grid can almost handle export of the full 2021 power. However, as is seen in the previous case, Borgvik also suffers from low voltages. In most cases, it stays above the limit, but when the line Lindome–Barkeryd is out of service, the voltage at Borgvik drops to 0.91 p.u.. Borgvik has noe generator, i.e., no local reactive power abilities whatsoever. Therefore, a smaller, but still large SVC of 500 Mvar is placed there. The same outage also causes an overloading of Barkeryd–Karlshamn (110 %). It is a *duplex* line and is upgraded with another in parallel. All the upgrades introduced for this case are listed in Table 6.7.

Then, finally, no problems appear for any contingency at the maximal HVDC export 11 000 MW. Now, the worst case is the outage of Skien–Kristiansand in Southern Norway, causing a low voltage of 0.95 p.u..

Table 6.7: New upgrades introduced in Case 3.3

Element	Name	Upgrade
Bus	Midskog	1 000 Mvar
Bus	Borgvik	500 Mvar
Line	Hjälta–Midskog	1 x Triplex
Line	Oskarshamn–Karlshamn	1 x Triplex
Line	Barkeryd–Karlshamn	1 x Duplex
Line	Feda–Tonstad	1 x Duplex

This is because the suggested line from *case 2.3* has not been implemented in this case. The power flow is shown in Figure 6.7.

6.4.6 Scenario 4: 2030 Very high export

This scenario is the one causing the most strain on the grid. *Case 2.3* proved that there was significant need for reactive power compensation in Southern Norway when the new HVDC links are active. The same problems, both reactive power requirements and overloading of Skien–Kristiansand arise in this scenario. Therefore, the upgrades made for *case 2.3* are implemented in this scenario as well. This makes sense, since they will be there anyway if the grid is to have maximum flexibility in both directions. In addition, the upgrades from *case 3.3* for the 2021 export scenario are implemented.

6.4.6.1 *Case 4.1: No contingencies*

A lot more power can be exported through the new hypothetical links. For this load situation, Aura in Western Norway, is the node first reaching down to 0.93 p.u. This happens at a total export of 15 400 MW, where Skagerrak 5 is not used and NSN-Link 2 is not used to its full capacity. Generation and load for this scenario is shown in Table 6.8 and the power flow is shown in Figure 6.8.

6.4.6.2 *Case 4.2: N-1 with no new upgrades*

This time, outage of Hasle–Borgvik, on the southern border of Norway and Sweden, causes the lowest voltage, again at Aura. Power export is reduced to 14 200 MW. The resulting power flow is shown in Figure 6.9.

6.4.6.3 *Case 4.3: N-1 with new upgrades*

Considering all the previous upgrades, any further additions are unlikely, but it is tested what is needed for full power export to be possible.

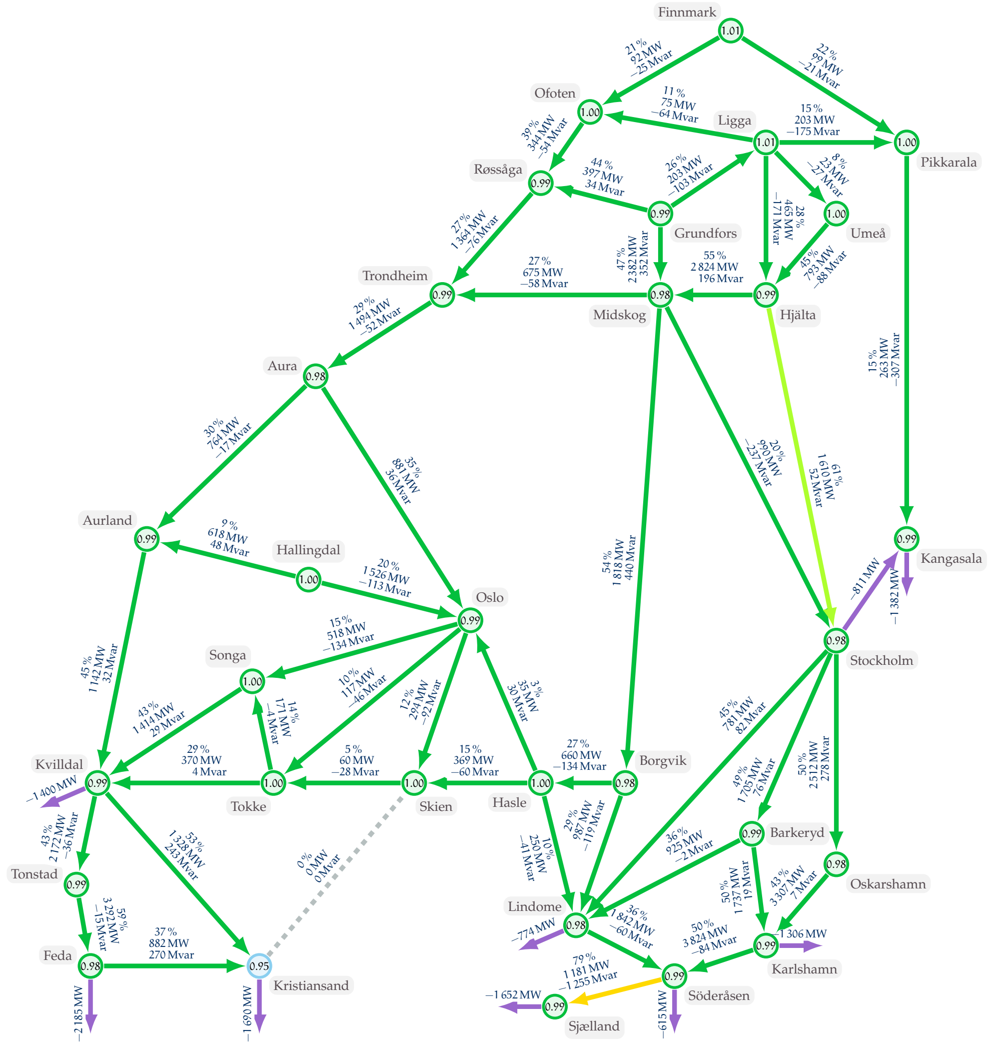


Figure 6.7: Case 3.3: Worst case *n-1* with new upgrades

First, the voltage issues at Aura are mitigated by implementing a 1 000 Mvar SVC and a new parallel triplex line Hasle–Borgvik. At higher export power, low voltages reappear at Borgvik and the SVC has to be upgraded to 1 000 Mvar. When all links are operating at maximum, except for Skagerrak 5 at 600 MW, the SVC at Midskog in North Sweden has maxed out and the voltages reach down to the limit. Therefore, it is doubled to 2 000 Mvar. To reach the maximum level, an increasing amount of reactive power is needed. By adding an additional 500 Mvar in Kristiansand and 1 000 Mvar in Aura, Trondheim, and Borgvik, the maximum export power can be reached. The result is a heavily loaded system with a power flow as shown in Figure 6.10 when all lines are still in service.

Achieving *n-1* security for this level of export requires an infeasible amount of upgrades. *Case 4.2* is therefore taken as the limit for this sce-

Table 6.8: Generation and load for scenario 4

Group	Area	Generation [MW]		Load [MW]
		Initial	Actual	
Norway	N1	2 400	2 142	2 720
	N2	6 120	5 473	2 110
	N3	1 520	1 357	1 575
	N4	3 640	3 249	2 327
	N5	4 920	4 391	1 622
	Total	18 600	16 610	10 353
Sweden	S1	6 300	5 622	1 450
	S2	4 420	3 945	1 890
	S3	11 300	10 085	3 845
	S4	3 600	3 213	5 910
	Total	25 620	22 865	13 095
Finland	Total	6 480	5 783	5 680
East Denmark	Total	960	857	400
Nordic	Total	51 660	46 115	29 528

nario, since it already includes upgrades required for the high import scenario in 2030.

6.4.7 Summary of the Contingency Analysis

In summary, all the required upgrades for each scenario is shown in Table 6.9. These are rough estimates which could be optimised by a more detailed analysis.

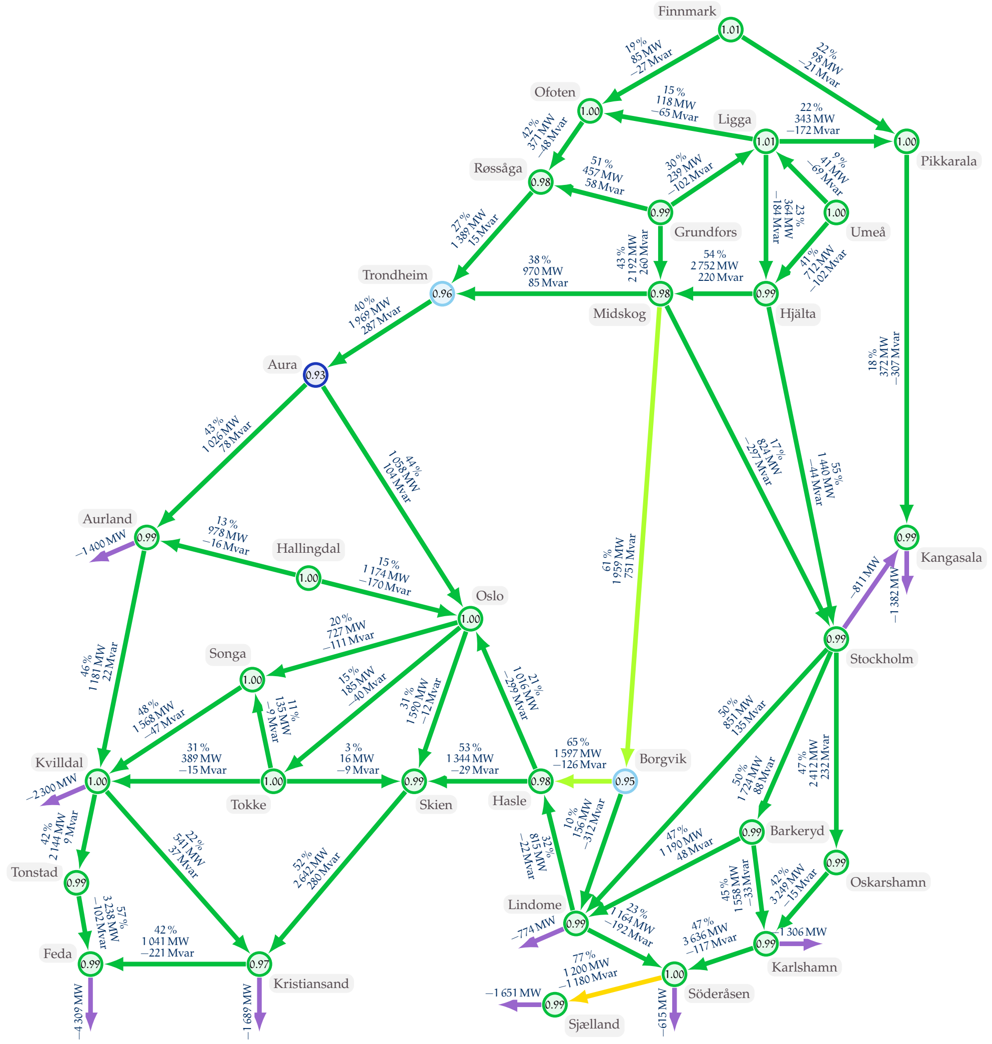


Figure 6.8: Case 4.1: No contingencies

Table 6.9: Summary of all upgrades needed for each scenario

Element	Name	Upgrade	Scenario 1	2	3	4
Bus	Oslo	1 000 Mvar		✓		✓
Bus	Skien	+ 800 Mvar		✓		✓
Bus	Midskog	1 000 Mvar			✓	✓
Bus	Borgvik	500 Mvar			✓	✓
Line	Kristiansand–Skien	1 x Triplex		✓		✓
Line	Skien–Oslo	1 x Triplex		✓		✓
Line	Hjälta–Midskog	1 x Triplex			✓	✓
Line	Oskarshamn–Karlshamn	1 x Triplex			✓	✓
Line	Barkeryd–Karlshamn	1 x Duplex			✓	✓
Line	Feda–Tonstad	1 x Duplex			✓	✓

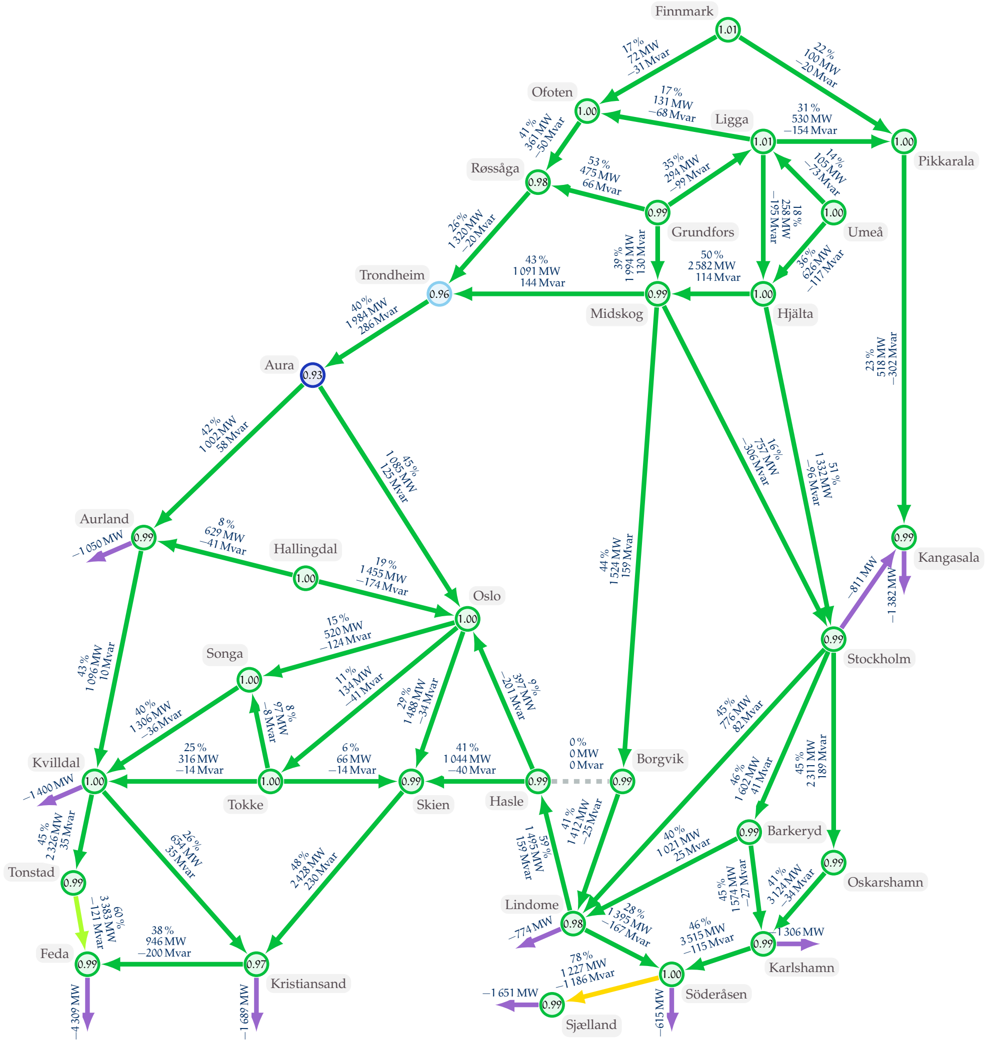


Figure 6.9: Case 4.2: Worst case *n-1* without upgrades

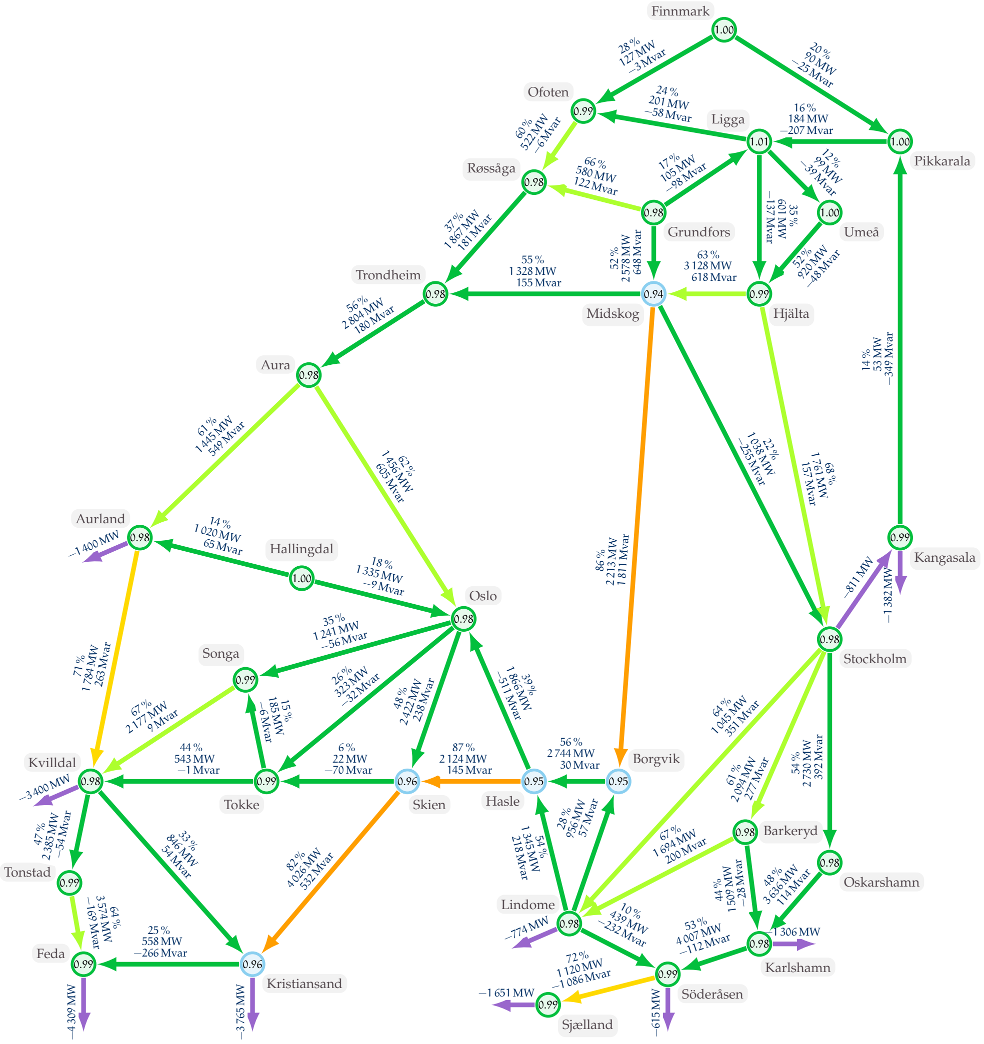


Figure 6.10: Case 4.3: N-0 with upgrades

6.5 DYNAMIC ANALYSIS

In this section, the best cases from each scenario in the contingency analysis are chosen for further evaluation of their dynamic performance. The response and stability of the system is considered, following a load or generation event.

6.5.1 Method

The nominal frequency in the Nordic power system is 50 Hz. The frequency is allowed to be in the range 49.9 Hz to 50.1 Hz in the normal state [37]. Frequency Restoration Reserves (FRR) are controlled by the TSOs to keep the frequency stable in the given range. There is no FRR scheme implemented in the model, and so the result may differ from reality. The active generators will act according to their governor controllers to keep the frequency at the desired level.

The dimensioning fault is the worst fault that the power system has to be able to handle and still remain operational. In 2021, the dimensional fault in Norway is the loss of 1 400 MW generation or load [38], which is used as a basis for simulated events.

Simulations are run for the best case of each scenario, i.e., the case with highest power. A generation outage of about 1 400 MW is analysed for the export scenarios. This is done by a *switch event* for the Oslo generator, which has a dispatch of about 1 400 MW. A loss of load of about 1 400 MW is analysed for the import scenario. This is done by a *load event* causing a 34 % reduction of the Oslo load, which has a value of 4 210 MW at the nominal voltage. Since load and generation changes in each scenario, Oslo was found to be the most fitting node for the occurrence of both events, enabling it to be the reference node in all scenarios. Frequency and voltage is measured at the Kristiansand 400 kV bus which is heavily influenced by HVDC converters. Voltage is referred to a 400 kV base for per unit values, giving a nominal value of 1.05 p.u. If the frequency settles outside the allowed range after the event, power is reduced on the HVDC links until an acceptable operating point is achieved.

6.5.2 Scenario 1: 2021 High Import

The grid from *Case 1.3* is the basis for this analysis. No upgrades from the existing grid are implemented except for the small changes that are required in the base case. Total import to the Nordic grid is initially 11 820 MW. At $t = 0$, the load event occurs, resulting in frequency and voltage as shown in Figure 6.11 for time ranges of 30 s and 150 s.

The event causes the frequency to rise since the generation becomes higher than the load. This sudden event causes an oscillation that eventually finally settles at 50.095 Hz. This is inside the allowed frequency operating range, but not desirable. The voltage suffers the same kind of oscillation and settles at 1.038 p.u. which is not far from the initial voltage of 1.037 p.u.

The fast oscillations at about 1.6 Hz are completely damped after 5 s, but the slow oscillation is finished after 150 s. The frequency reaches a peak of 50.20 Hz at 24.7 s.

6.5.3 Scenario 2: 2030 Very High import

The grid from *case 2.3* is the basis for this analysis. Required upgrades from the existing grid to reach the desired import are implemented. Total import to the Nordic grid is initially 19 220 MW. At $t = 0$, the load event occurs, resulting in frequency and voltage as shown in Figure 6.12 for time ranges of 30 s and 150 s.

Considering the frequency, the fast oscillations at about 1.6 Hz are mostly damped out after 30 s, but not fully. During the first five seconds, there are some spikes appearing at the oscillation peaks. The cause of this is unknown, but might be due to HVDC converters reaching their operational limits. The slow oscillation is finished after about 150 s, after reaching the peak of 50.20 Hz at 25.8 s. Finally, the frequency settles at 50.095 Hz.

The voltage has the same pattern in the fast oscillation, but the slow oscillation is not as significant. It finally settles at 1.038 p.u., not far from the initial voltage at 1.035 p.u.

6.5.4 Scenario 3: 2021 High Export

The grid from *case 3.3* is the basis for this analysis. Required upgrades from the existing grid to reach the desired export are implemented. Total export to the Nordic grid is initially 11 000 MW. At $t = 0$, the Oslo generator is taken out of service, resulting in frequency and voltage as shown in Figure 6.13 for time ranges of 30 s and 150 s. The generator has a dispatch of 1 465 MW before the event.

In this case, there is also a quick oscillation at the beginning, that is damped out after 10 s. There is a distortion in the first swing of the frequency measurement. The case of this is not clear.

Finally, the frequency settles at 49.92 Hz, which is in the allowed operating range, but not desirable.

After about 100 s, the voltage has recovered to the initial voltage of 1.02 p.u.. From 10 s to 23 s, a linear characteristic is noticed in the voltage. This is possibly caused by SVCs or VSCs, that eventually reaches their reactive power limit.

6.5.5 Scenario 4: 2030 Very High Export

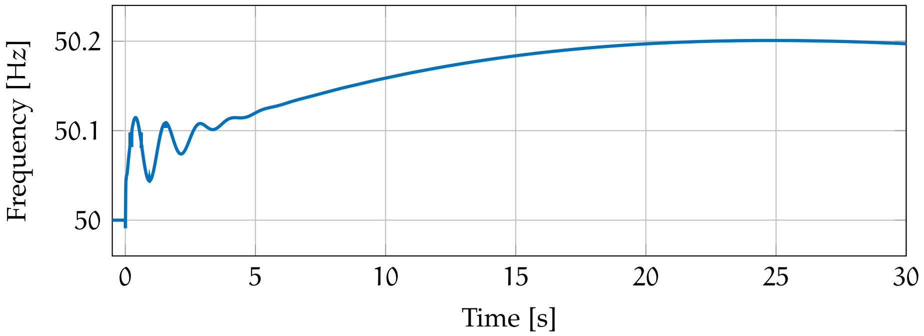
The grid from *case 4.2* is the basis for this analysis. Required upgrades from the existing grid to reach the desired export are implemented. Total export to the Nordic grid is initially 14 200 MW. At $t = 0$, the Oslo generator is taken out of service, resulting in frequency and voltage as shown in Figure 6.14 for time ranges of 30 s and 150 s. The generator has a dispatch of 1 392 MW before the event.

The response for both voltage and frequency is in this case quite similar to *scenario 3*. In the voltage, there is a much larger initial drop. This is possibly because the grid requires more reactive power than in *scenario 3*. In the frequency, a strange shape can be noticed for the first swings. This is a possible sign of generators starting to lose synchronisation with the grid frequency. In the end, frequency and voltage also in this case settles at 49.92 Hz and 1.02 p.u.

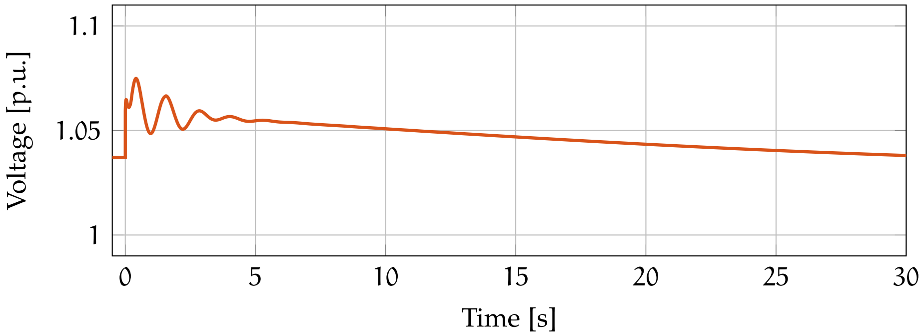
6.5.6 Comparison

Figures 6.15a and 6.15c shows the frequency for the high import scenarios of 2021 and 2030. It is clear that the 7 400 MW additional imported power in 2030 is a more unstable situation, causing a much stronger and longer-lasting oscillation. In the 2021 scenario, 81 % of the available generators are active, while in the 2030 scenario, only 68 % are active. This lower number also means lower amount of inertia in the system. An effect of this is that the slow oscillation quicker to reach the final value and does not reach as large maximum and minimum values.

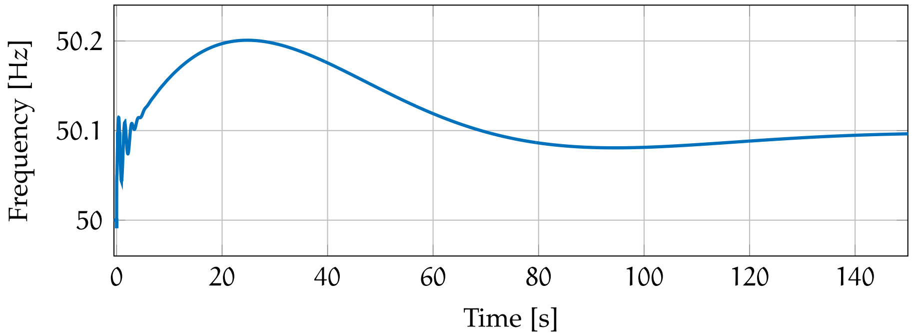
Figures 6.15b and 6.15d shows the frequency for the high export scenarios of 2021 and 2030. The difference between these two is not as large as for the import scenarios, being only 3 200 MW. This is still a significant amount, causing the system to be become more unstable.



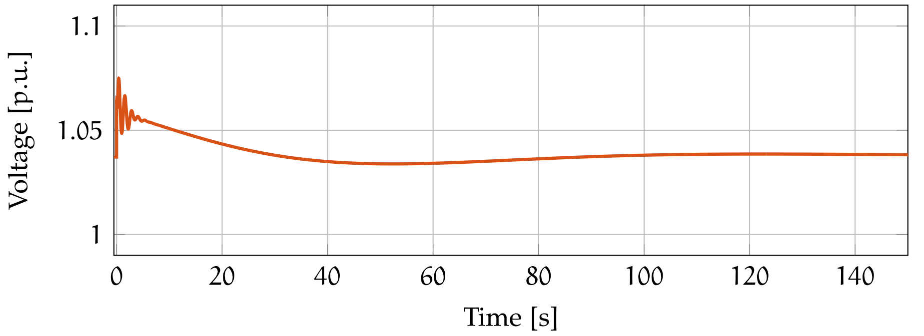
(a) Frequency for scenario 1: Import, 30sec



(b) Voltage for scenario 1: Import, 30sec

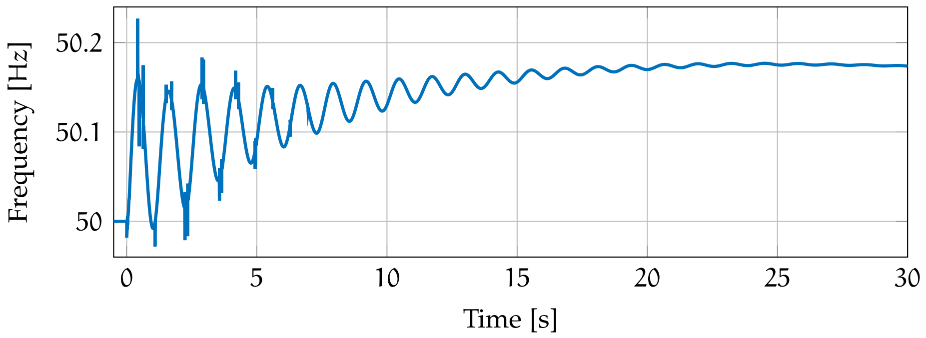


(c) Frequency for scenario 1: Import, 150sec

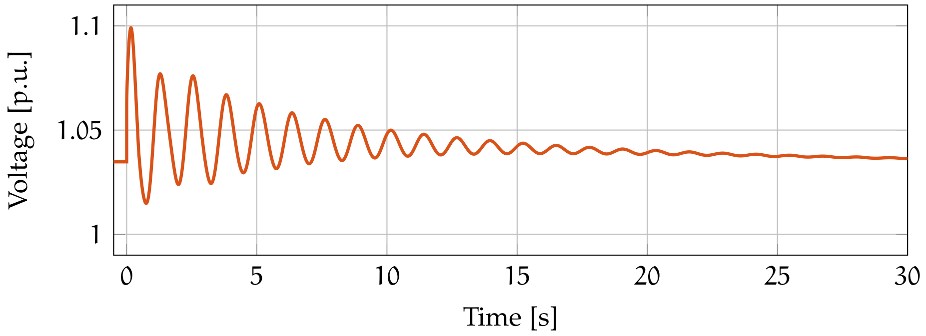


(d) Voltage for scenario 1: Import, 150sec

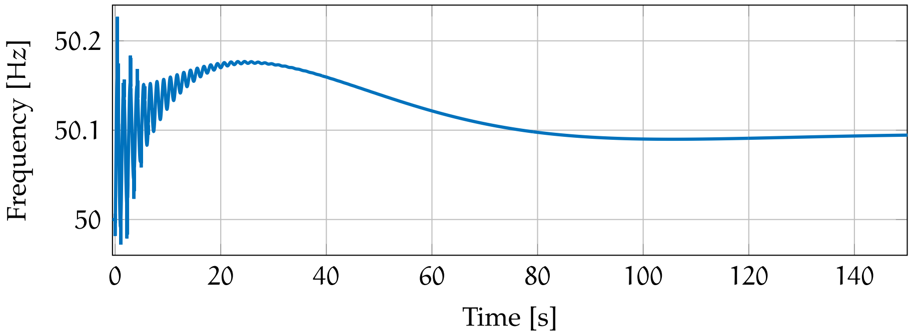
Figure 6.11: Scenario 1: Frequency and voltage in Kristiansand at loss of 1 400 *MW* load in Oslo when the import is 11 820 *MW*.



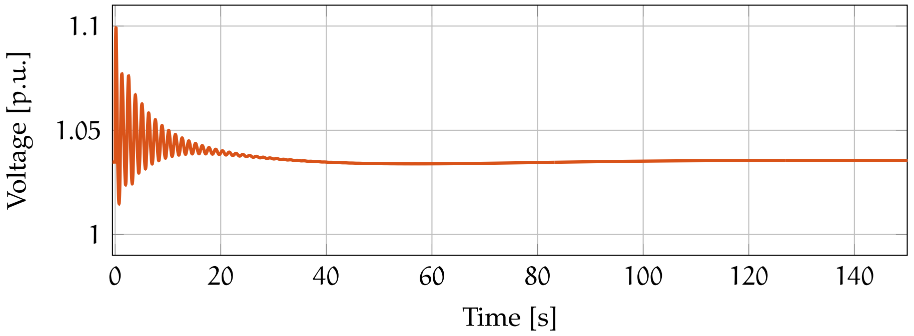
(a) Frequency for scenario 2: Import, 30sec



(b) Voltage for scenario 2: Import, 30sec

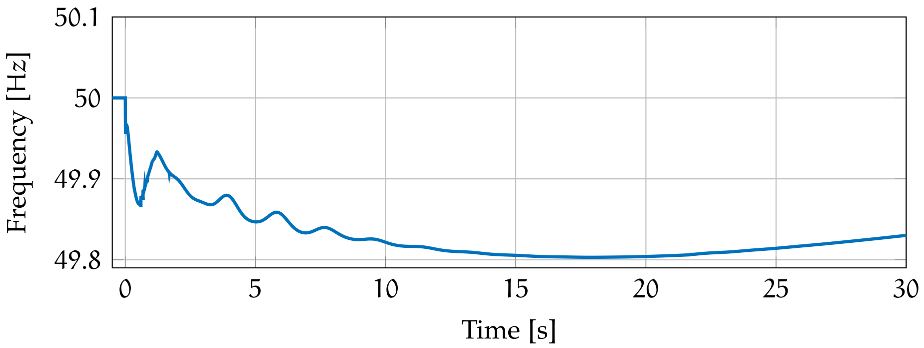


(c) Frequency for scenario 2: Import, 150sec

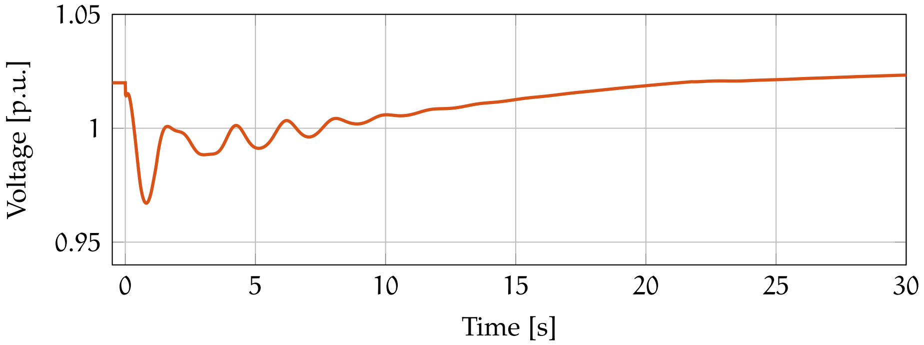


(d) Voltage for scenario 2: Import, 150sec

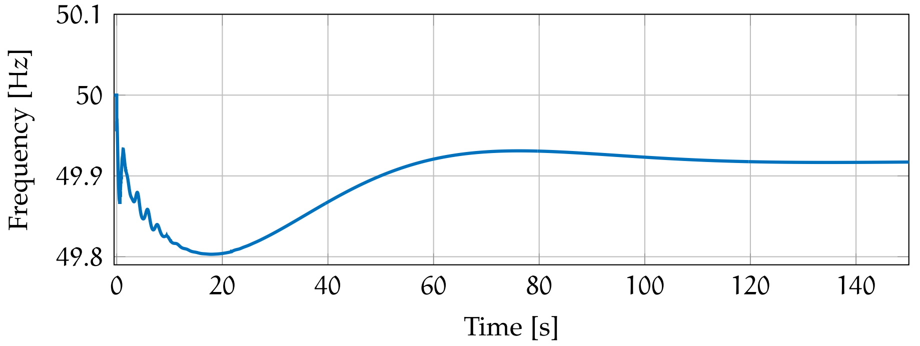
Figure 6.12: Scenario 2: Frequency and voltage in Kristiansand at loss of 1 400 *MW* load in Oslo when the import is 19 220 *MW*.



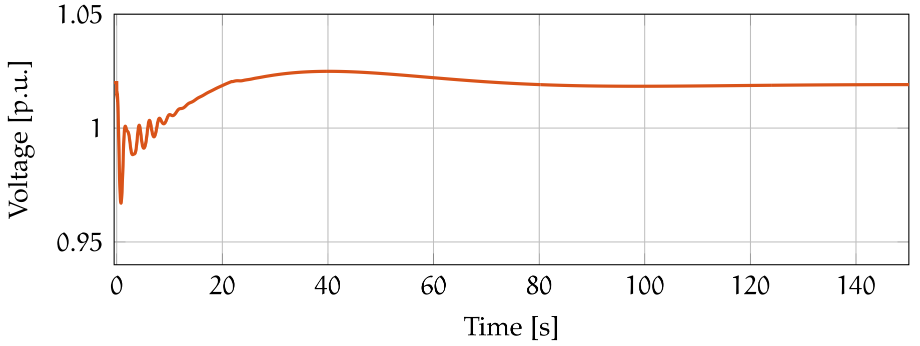
(a) Frequency for scenario 3: Export, 30sec



(b) Voltage for scenario 3: Export, 30sec

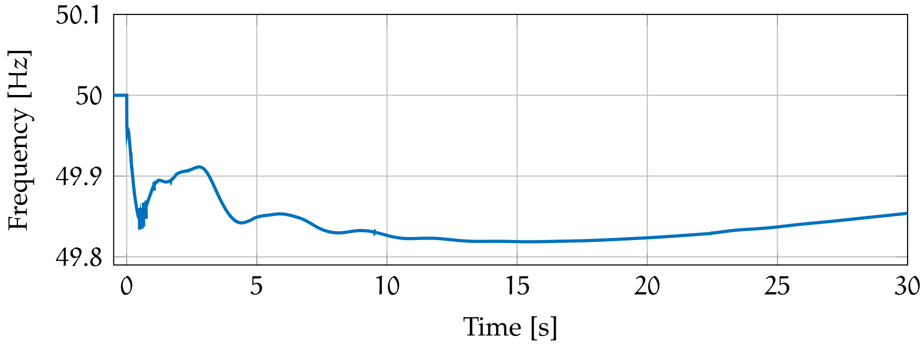


(c) Frequency for scenario 3: Export, 150sec

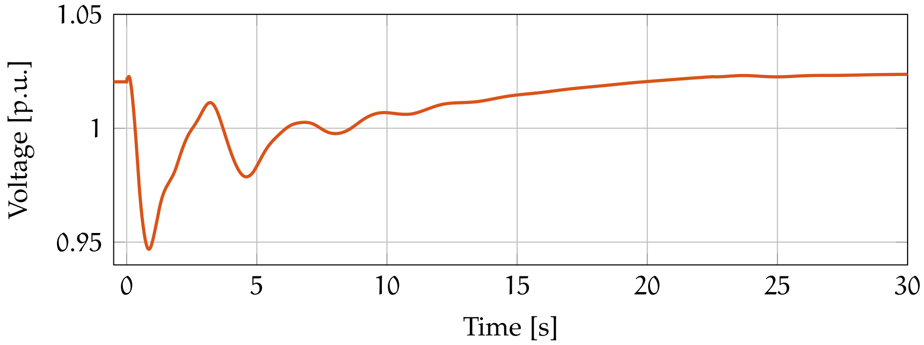


(d) Voltage for scenario 3: Export, 150sec

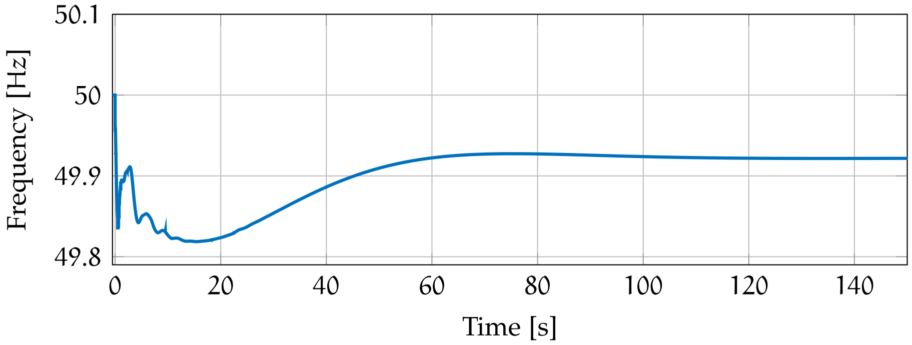
Figure 6.13: Scenario 3: Frequency and voltage in Kristiansand at loss of 1 400 MW generation in Oslo when the export is 11 000 MW



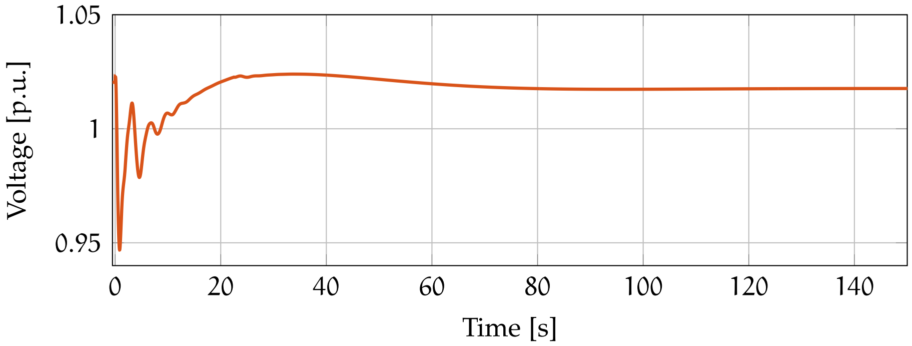
(a) Frequency for scenario 4: Export, 30sec



(b) Voltage for scenario 4: Export, 30sec

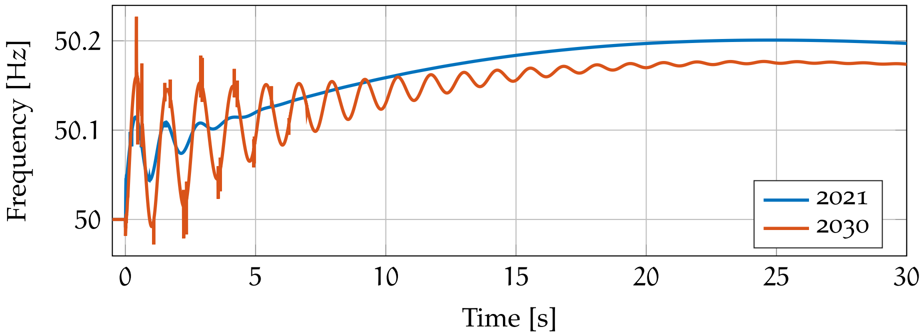


(c) Frequency for scenario 4: Export, 150sec

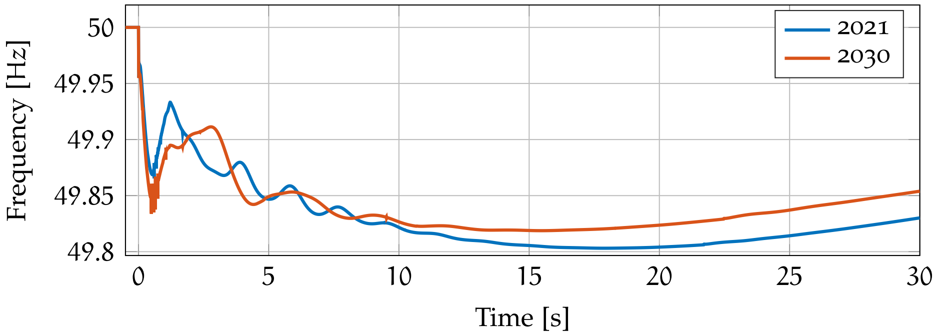


(d) Voltage for scenario 4: Export, 150sec

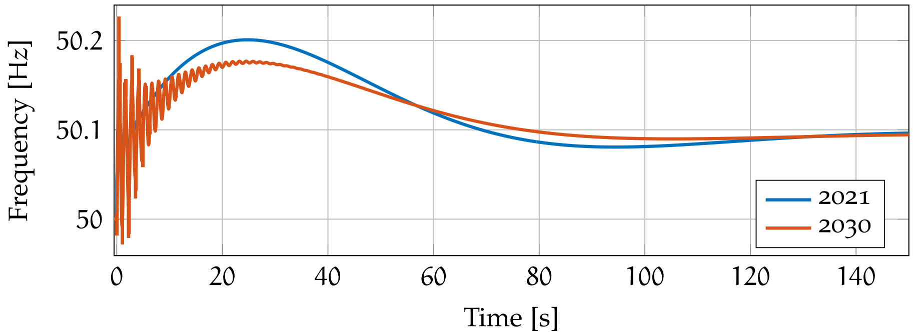
Figure 6.14: Scenario 4: Frequency and voltage in Kristiansand at loss of 1 400 MW generation in Oslo when the export is 14 200 MW



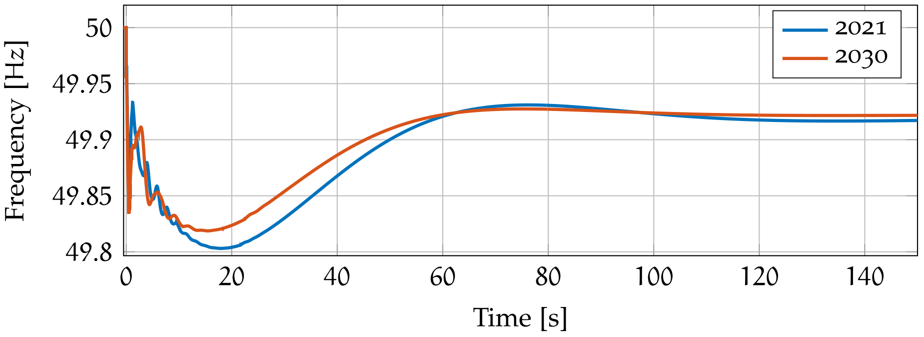
(a) Frequency for scenario 1-2: Import 2021 vs 2030, 30 sec



(b) Frequency for scenario 3-4: Import 2021 vs 2030, 30 sec



(c) Frequency for scenario 1-2: Import 2021 vs 2030, 150 sec



(d) Frequency for scenario 3-4: Import 2021 vs 2030, 150 sec

Figure 6.15: Scenario 4: Comparion of frequency for scenario 1-4

7 DISCUSSION AND CONCLUSION

7.1 DISCUSSION

The first task was to include the missing HVDC links required for a complete integration of all the Nordic HVDC links in the simulation model. These were SwePol, Kontek, Baltic Cable, NordBalt, EstLink, Vyborg, Kriegers Flak and NorthConnect. All of the links have voltage and power ratings, as well their configuration collected from available literature. Each link has received the necessary attention and has been found to perform well under testing.

All included VSC-HVHDC links, except for EstLink1, have been modified to use the modern MMC topology instead of the traditional two-level topology. Since no readily available parameters could be found, general parameters based on the expected number of converter levels and ratings have been calculated using a method found in literature. The validity of this has not been sufficiently tested, but the performance of the converters has been good.

The new AC system buses Tokke, Songa, Finnmark, Oskarshamn and Umeå gives more flexibility for a future user of the model, since load and generation can be more distributed when combining the model with market data. With the change of nominal voltage level from 420 kV to 400 kV, the nominal per unit voltage is now 1.05 p.u. for the main grid. During this change of nominal voltage, some unforeseen problems might have surfaced due to incorrect voltage ratings. Great care has been taken to make sure this has been done correctly.

Scenarios developed for testing of the future HVDC exchange capacity are highly dependent on the power flow situation they are created for. The assumption that load is constant, while generation is reduced for import might be slightly false since generation might also be increased. The same is true for development of the export scenarios where generation is constant and load is reduced. Artificial or incorrect power flow situations might have been created during the reduction of load and generation. The placement of power generation and loads highly affects the performed studies. Balancing by synchronous generators, used in the power flow calculation, gives some flexibility for the final solution, but without correct values for generation and load, an entirely correct system condition can never be achieved.

The method used for contingency analysis is quite simple and does to give entirely conclusive results. For a more correct analysis, voltage stability should be investigated in a more detailed way. Nevertheless, the method has given a clear indication of where problems appear and what can be done to mitigate them. Analysis showed that the lines Røssåga-Grundfors, and Söderåsen-Karlshamn were prohibiting the system from having *n-1* security even during low or no HVDC power exchange. The assumption that these lines are modelling errors or will be upgraded underlines the results for all the other scenarios.

Finally, it shoud be mentioned that many of the issues appearing during the contingency analysis might be in part due to the aggregation of the model. A system with more distributed load and generation, might give other results, but the analysis performed does give indicate overall problems that can be the subject of further, more detailed studies.

Analysis of the simulated events might not give sufficient results to determine the system stability, but is has proven that the system is able to withstand a significant change in power during a high power flow situation.

7.2 CONCLUSION

A simulation of the Nordic Power grid considering a large number of Nordic HVDC links has been further developed in the work of this master's thesis. The model has been improved in several areas and now include all present and planned HVDC links, with a total exchange capacity of 11 820 *MW* by 2021. Additionally, the model includes four possible HVDC links for a 2030 scenario with a total capacity of 7 400 *MW*. Four scenarios have been studied attempting to maximising import and export on the HVDC links in 2021 and 2030. The analysis has proven that the model is flexible and can handle a large variation of power flow situations.

For a 2021 high import scenario with reduced load, it is indicated that the full HVDC exchange of 11 820 *MW* can be utilised, provided that some minor grid upgrades are implemented. Without any further significant upgrades, 17 280 *MW* is possible in the 2030 scenario. If the grid in Southern Norway is strengthened with a line and reactive power compensation, the maximum available exchange capacity of 19 220 *MW* is possible.

Export from the Nordic power grid proved to have much larger difficulties. Only export of 7 170 *MW* was possible in the 2021 scenario, primarily limited by the Swedish grid. Export of 11 000 *MW* was only made possible by assuming several grid upgrades to the Swedish could be made. Combining the required upgrades for the high export scenario with the upgrades needed for the highest import in the 2030 scenario showed that $14\,200\,MW$ can be exported from the Nordic grid in the 2030 scenario. Simulations performed showed that the stability of the system was not the limiting factor determining the possible exchange capacities.

7.3 FURTHER WORK

Now that all HVDC links are included in the model, it can be used for a range of further studies, but there is still some development that should be addressed:

- The control system for VSCs should be reviewed and possible updated to improve its capability with MMC-based HVDC links
- MMC converters as a replacement for VSCs in the grid should be studied further.
- Linking the model with data from future market models will give more realistic scenarios. It can be interesting to see how this compares to the scenarios studied in this thesis and to verify the feasibility of these new scenarios.
- A more comprehensive stability analysis of the system should be investigated.
- Studying the use of the HVDC links for balancing resources is an interesting topic and will likely be very important in the future.
- It could be interesting to see the effect of frequency restoration controls in the model and how the results would differ.
- EMT simulations have not been a focus at this time. Preliminary tests indicate that the model is vulnerable to analysis of short-circuits. Currently, CSC-HVDC links are very sensitive to short-circuits and are not able to recover from a commutation failure.

BIBLIOGRAPHY

[1] C. Kim, *HVDC transmission power conversion applications in power systems*. Singapore; Hoboken, NJ: IEEE, 2009.

[2] D. A. Woodford, *HVDC transmission*, 1998.

[3] Alstom, *HVDC for beginners and beyond*, 2010.

[4] N. Mohan, T. M. Undeland, and W. P. Robbins, *Power electronics: Converters, applications, and design*, 3rd ed. Hoboken, NJ: John Wiley & Sons, 2003.

[5] ABB, *Thyristors*, Dec. 2015. [Online]. Available: `http://new.abb.com/semiconductors/thyristors/phase-controlled-pct`.

[6] ABB, *It's time to connect*, 2013.

[7] D. Jovcic and K. Ahmed, *High voltage direct current transmission: Converters, systems and DC grids*. Hoboken: John Wiley & Sons Ltd, 2015.

[8] E. S. Aas, "Simulation model for power system stability studies of the future nordic power grid," Project report, 2015.

[9] DIgSILENT, *DC current source*, 2016.

[10] P. L. Sorensen, B. Franzén, J. D. Wheeler, R. E. Bonchang, C. D. Barker, R. M. Preedy, and M. H. Baker, "Konti-Skan 1 HVDC pole replacement," in *B4-207*, Cigré, 2004.

[11] N. Kirby, C. Horwill, N. Macleod, and D. Critchley, "Konti-Skan HVDC refurbishment and life extension methods for other HVDC projects," in *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*, Jul. 2008, pp. 1–5.

[12] G. Andersson and M. Hyttinen, "Skagerrak the next generation," in *HVDC and Power Electronic Technology*, Cigré, 2015.

[13] S. Teeuwsen, C. Rasmussen, and H. Abildgaard, "Dynamic performance of the new 400 kV storebaelt HVDC project," in *Power Systems Conference and Exposition, 2009. PSCE '09. IEEE/PES*, Mar. 2009, pp. 1–7.

[14] J. E. Skog, H. v. Asten, T. Worzyk, and T. Andersrød, "NorNed – world's longest power cable," Cigré, 2010.

[15] ABB, *Fenno-skan*, Feb. 2016. [Online]. Available: `http://new.abb.com/systems/hvdc/references/fenno-skan`.

[16] B. Abrahamsson, L. Soderberg, and K. Lozinski, "SwePol HVDC link," in *AC-DC Power Transmission, 2001. Seventh International Conference on (Conf. Publ. No. 485)*, Nov. 2001, pp. 211–213.

[17] ABB, *NordBalt*, Dec. 2015. [Online]. Available: http://new.abb.com/systems/hvdc/references/nordbalt.

[18] ——, *Baltic cable*, Mar. 2016. [Online]. Available: http://new.abb.com/systems/hvdc/references/baltic-cable.

[19] C. Wolff and T. Elberling, "The kontek HVDC link between denmark and germany," in *IEEE Power Engineering Society Winter Meeting, 2000*, vol. 1, 2000, 572–574 vol.1.

[20] V. N. Ivakin, V. D. Kovalev, N. S. Lazarev, R. A. Lyatev, A. K. Mazurenko, L. L. Balyberdin, Y. S. Kraichik, and A. A. Smirnov, "Experience of reconstruction and expansion of vyborg Back-to-Back HVDC link," 2002.

[21] Fingrid, *Electricity exported commercially to russia for the first time on 7 june 2015*, Feb. 2016. [Online]. Available: http://www.fingrid.fi/en/news/announcements/Pages/First-time-ever-electricity-transmission-from-Finland-to-Russia-7th-June-2015.aspx.

[22] L. Ronström, M. L. Hoffstein, R. Pajo, and M. Lahtien, "The estlink HVDC light transmission system," 2007.

[23] Elering, *Estlink 2 information leaflet*. [Online]. Available: http://estlink2.elering.ee/public/Dokumendid/EL2_teabeleht_A4_eng.pdf.

[24] Statnett, *NSN link*, Dec. 2015. [Online]. Available: http://www.statnett.no/Nettutvikling/Kabel-til-england/.

[25] Energinet.dk, *Elforbindelser til utlandet*, 2016. [Online]. Available: http://www.energinet.dk/DA/ANLAEG-OG-PROJEKTER/Generelt-om-elanlaeg/Sider/Elforbindelser-til-udlandet.aspx.

[26] ABB, *Kriegers flak combined grid solutions*, Apr. 2016. [Online]. Available: http://new.abb.com/systems/hvdc/references/kriegers-flak-combined-grid-solutions-(fk-cgs)-hvdc.

[27] NorthConnect, *NorthConnect*, May 2016. [Online]. Available: http://www.northconnect.no/.

[28] ABB, *Caithness moray HVDC link*, Apr. 2016. [Online]. Available: http://new.abb.com/systems/hvdc/references/caithness-moray-hvdc-link.

[29] DIgSILENT, *General load*, 2016.

[30] T. I. Reigstad, T. K. Vrana, and O. Mo, *PowerFactory model description - nordic electric power grid*, 2015.

[31] Statnett, *Funkjsonskrav i kraftsystemet*, 2012. [Online]. Available: `http://www.statnett.no/Global/Dokumenter/Kraftsystemet/Systemansvar/FIKS%202012.pdf`.

[32] Å. M. H. Kjørholt, "HVDC transmission using a bipolar configuration composed of an LCC and MMC," Master Thesis, 2014.

[33] ENTSOE, *Nordic HVDC utilization and unavailability statistics 2013*, 2014.

[34] ——, *Nordic and baltic HVDC utilisation and unavailability statistics 2014*, 2015.

[35] N. Pool, *Historical market data*, May 2016. [Online]. Available: `http://www.nordpoolspot.com/historical-market-data/`.

[36] DIgSILENT, *PowerFactory user manual*, 2016.

[37] ENTSOE, *System operation agreement*, 2006. [Online]. Available: `https://www.entsoe.eu/Documents/Publications/SOC/Nordic/System_Operation_Agreement_2014.pdf`.

[38] Statnett, *Utvikling av systemtjenester 2016-2021*. [Online]. Available: `http://www.statnett.no/Documents/Kraftsystemet/Utvikling%20av%20kraftsystemet/Utvikling%20av%20systemtjenester%202016-2021.pdf`.

APPENDIX

A PARAMETERS

A.1 LOADS

Table A.1: Load Type Parameters

Technology	3PH-'D'
Coefficient aP	0.4
Exponent e_{aP}	0
Coefficient bP	0.3
Exponent e_{bP}	1
Coefficient cP	0.3
Exponent e_{cP}	2
Coefficient aQ	0.4
Exponent e_{aQ}	0
Coefficient bQ	0.3
Exponent e_{bQ}	1
Coefficient cQ	0.3
Exponent e_{cQ}	2
Static (const Z)	0 %
Dynamic	100 %
Dynamic Load Time Constant	0.1 s
Frequency Dependence, kpf	0
Frequency Dependence, kqf	0
Frequency Time Constant, tpf	0 s
Frequency Time Constant, tqf	0 s
Voltage Time Constant, tpu	0 s
Voltage Time Constant, tqu	0 s
Upper Voltage Limit	1.2 pu
Lower Voltage Limit	0.8 pu

A.2 LINES AND CABLES

A.2.1 AC grid

In addition, there is a:

- 220 kV simplex line with the same parameters as the 400 kV.

Table A.2: Parameters for AC power lines and cables

		Triplex 400 kV	Duplex 400 kV	Simplex 400 kV	Duplex 300 kV	Cable 400 kV
Rated current	[kA]	3.555	2.422	1.211	2.422	1.000
R′ AC-Resistance	$[\frac{\Omega}{km}]$	0.02	0.028	0.055	0.028	0.05
R0′ AC-Resistance	$[\frac{\Omega}{km}]$	0.16	0.224	0.44	0.224	0.05
X′ Reactance	$[\frac{\Omega}{km}]$	0.268	0.328	0.438	0.315	0.079
X0′ Reactance	$[\frac{\Omega}{km}]$	0.697	0.853	1.139	0.819	0.079
C′ Capacitance	$[\frac{\mu F}{km}]$	0.013	0.011	0.008	0.011	0.15
B0′ Susceptance	$[\frac{\mu S}{km}]$	2.45	2.059	1.508	2.145	47.124
G′ Conductance	$[\frac{\mu S}{km}]$	0.004	0.004	0.004	0.004	0.04
G0′ Conductance	$[\frac{\mu S}{km}]$	0.004	0.004	0.004	0.004	0.04

- 200 kV AC cable with the same parameters as the 400 kV.
- 150 kV AC cable with the same parameters as the 400 kV.

A.2.2 HVDC links

A.3 TRANSFORMERS

In this section, all parameters for transformers are listed. The *SHC-Voltage* u_{kr} is representing the copper loss, given percent of the total power rating. Most parameters are the same for all transformers and some are equal to the default PowerFactory values. Mainly the *Power Rating*, *Rated Voltage, HV*, *Rated Voltage, LV*, *Short-Circuit Voltage* u_k and *SHC-Voltage* u_{kr} differs.

A.3.1 Grid

A.3.2 HVDC

The values are common for all CSC- and VSC-HVDC transformers

Table A.3: Parameters for AC grid transformers

		Standard		Generator
Parameter		400/22	400/300	400/22
Nominal Frequency	[Hz]	50	50	50
Power Rating	[MVA]	1 000	1 000	250
Rated Voltage, HV	[kV]	400	400	400
Rated Voltage, LV	[kV]	22	300	22
Vector Group, HV		YN	YN	YN
Vector Group, LV		YN	YN	YN
Phase Shift	[°]	0	0	0
Short-Circuit Voltage u_k	[%]	6	4	6
SHC-Voltage u_{kr}	[%]	0.5	0.3	
Short-Circuit Voltage u_{k0}	[%]	3	3	
SHC-Voltage u_{k0r}	[%]	0	0	
No Load Current	[%]	0	0	
No Load Losses	[kW]	0	0	
x, Pos. Sequence, HV	[p.u.]	0.5	0.5	
x, Pos. Sequence, LV	[p.u.]	0.5	0.5	
r, Pos. Sequence, HV	[p.u.]	0.5	0.5	
r, Pos. Sequence, LV	[p.u.]	0.5	0.5	
z, Zero Sequence, HV	[p.u.]	0.9	0.9	
z, Zero Sequence, LV	[p.u.]	0.1	0.1	
Mag. Impedance/u_{k0}		100	100	
Mag. R/X		0	0	

Table A.4: General parameters for HVDC link transformers

		CSC	VSC
Technology		3-ph	3-Ph
Nominal Frequency	[Hz]	50	50
Vector Group, HV		YN	YN
Vector Group, LV		YN	YN
Phase Shift	[°]	0	0
Short-Circuit Voltage u_k	[%]	15	18
SHC-Voltage u_{kr}	[%]	0.375	0.375
Short-Circuit Voltage u_{k0}	[%]	3	3
SHC-Voltage u_{k0r}	[%]	0	0
No Load Current	[%]	0	0
No Load Losses	[kW]	0	0
x, Pos. Sequence, HV	[p.u.]	0.5	0.5
x, Pos. Sequence, LV	[p.u.]	0.5	0.5
r, Pos. Sequence, HV	[p.u.]	0.5	0.5
r, Pos. Sequence, LV	[p.u.]	0.5	0.5
z, Zero Sequence, HV	[p.u.]	0.9	0.9
z, Zero Sequence, LV	[p.u.]	0.1	0.1
Mag. Impedance/u_{k0}		100	100
Mag. R/X		0	0

Table A.5: Specific parameters for HVDC link transformers

Link		Type	Power Rating [MVA]	Rated Voltage		Copper Losses [MW]
				LV [kV]	HV [kV]	
Skagerrak	1 + 2	CSC	400	400	218	1.5
Skagerrak	3	CSC	600	288	400	2.25
Skagerrak	4	MMC	800	272	400	3
Storebælt		CSC	800	348	400	3
VyborgLink		CSC	500	148	400	1.875
Konti-Skan	1 + 2	CSC	600	244	400	2.25
VyborgLink		CSC	500	148	400	1.875
NorNed		CSC	900	400	780	3.375
Baltic Cable		CSC	800	400	392	3
EstLink	1	VSC	400	163	400	1.5
EstLink	2	CSC	800	391	400	3
Fenno-Skan	1	CSC	700	348	400	2.625
Fenno-Skan	2	CSC	1 100	400	435	4.125
NordLink	1	MMC	800	280	400	3
NordLink	2	MMC	1 150	280	400	4.312
KriegersFlak		MMC	500	155	400	1.875
KriegersFlak		MMC	500	155	162	1.875

A.4 GENERATORS

A.4.1 Synchronous Machine

All generators utilise the same type, whose parameters are shown in Table A.6

Table A.6: Parameters for synchronous generators

	Load Flow tab		
xd	Synchronous Reactance	[p.u.]	1.2
xq	Synchronous Reactance	[p.u.]	0.8
	Reactive Power Limits, min	[p.u.]	−0.3
	Reactive Power Limits, max	[p.u.]	0.5
x0	Zero Sequence Data	[p.u.]	0.1
x0	Zero Sequence Data	[p.u.]	0.001
x2	Negative Sequence Data	[p.u.]	0.2
r2	Negative Sequence Data	[p.u.]	0.001
	RMS-simulation tab		
	Model		Detailed
	Acceleration Time Const, rated to Pgn	[s]	10
rstr	Stator Resistance	[p.u.]	0.001
xl	Stator Leakage Reactance	[p.u.]	0.14
xrld	Stator Leakage Reactance, d	[p.u.]	0.01
xrlq	Stator Leakage Reactance, q	[p.u.]	0.01
	Rotor Type		Salient pole
Td′	Transient Time Constant, d	[s]	1
xd′	Transient Reactance, d	[p.u.]	0.3
Td″	Subtransient Time Constant, d	[s]	0.05
Tq″	Subtransient Time Constant, q	[s]	0.05
xd″	Subtransient Reactance, d	[p.u.]	0.25
xq″	Subtransient Reactance, q	[p.u.]	0.25
x0	Zero Sequence Reactance	[p.u.]	0.1
r0	Zero Sequence Reactance	[p.u.]	0.001
x2	Negative Sequence Reactance	[p.u.]	0.2
r2	Negative Sequence Reactance	[p.u.]	0.001
	Saturation		No saturation
	Mechanical Damping	[p.u.]	0
	Additional Damping	[p.u.]	0
	Effect of Speed Variation		Partially neglected

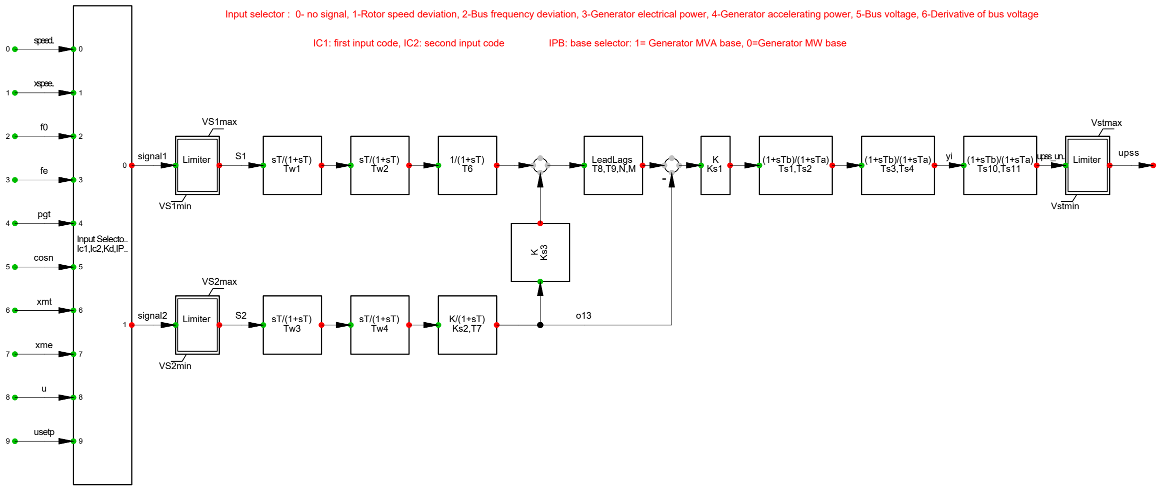
A.4.2 Power System Stabilizer (PSS)

Table A.7: PSS parameters

T_{w1}	1st Washout 1th Time Constant	[s]	10
T_{w2}	1st Washout 2th Time Constant	[s]	10
T_6	1st Signal Transducer Time Constant	[s]	0
T_{w3}	2nd Washout 1th Time Constant	[s]	10
T_{w4}	2nd Washout 2th Time Constant	[s]	0
k_{Ks2}	2nd Signal Transducer Factor	[p.u.]	1
T_7	2nd Signal Transducer Time Constant	[s]	10
K_{s3}	Washouts Coupling Factor	[p.u.]	1
K_{s1}	PSS Gain	[p.u.]	20
T_{s1}	1st Lead-Lag Derivative Time Constant	[s]	0
T_{s2}	1st Lead-Lag Delay Time Constant	[s]	0
T_{s3}	2nd Lead-Lag Derivative Time Constant	[s]	0
T_{s4}	2nd Lead-Lag Delay Time Constant	[s]	0
T_8	Ramp Tracking Filter Deriv. Time Constant	[s]	0.3
T_9	Ramp Tracking Filter Deriv. Time Constant	[s]	0.15
N	Ramp Tracking Filter		4
M	Ramp Tracking Filter		2
I_{c1}	1st Input Selector		1
I_{c2}	2nd Input Selector		3
K_d	Derivator Factor	[p.u.]	0
I_{PB}	PSS base selector		0
T_{s10}	3rd Lead-Lag Derivate Time Constant	[s]	0
T_{s11}	3rd Lead-Lag Delay Time Constant	[s]	0
$V_{st_{min}}$	Controller Minimum Output	[p.u.]	-0.066
$V_{S1_{min}}$	Input Signal 1 Minimum Limit	[p.u.]	-1
$V_{S2_{min}}$	Input Signal 2 Minimum Limit	[p.u.]	-1
$V_{st_{max}}$	Controller Maimum Output	[p.u.]	0.2
$V_{S1_{max}}$	Input Signal 1 Maximum Limit	[p.u.]	1
$V_{S2_{max}}$	Input Signal 2 Maximum Limit	[p.u.]	1

Table A.8: Specially tuned pss parameters

		Default	Grundfors	Stockholm
T_7	[s]	10	8	8
K_{s1}	[p.u.]	20	40	30



Input selector : 0- no signal, 1-Rotor speed deviation, 2-Bus frequency deviation, 3-Generator electrical power, 4-Generator accelerating power, 5-Bus voltage, 6-Derivative of bus voltage

IC1: first input code, IC2: second input code

IPB: base selector: 1= Generator MVA base, 0=Generator MW base

Figure A.1: PSS2B

A.4.3 Governor

Table A.9: Governor parameters

R	Permanent Droop	[p.u.]	0.08
	Temporary Droop	[p.u.]	0.5
	Governor Time Constant	[s]	7.5
	Filter Time Constant	[s]	0.05
	Servo Time Constant	[s]	0.5
Tw	Water Starting Time	[s]	1
At	Turbine Gain	[p.u.]	1.15
Pturb	Turbine Rated Power	[MW]	0
Dturb	Frictional losses factor	[p.u.]	0
qnl	No Load Flow	[p.u.]	0.08
Gmin	Minimum Gate Limit	[p.u.]	0
Qnl	No Load Flow	[p.u.]	0
Velm	Gate Velocity Limit	[p.u.]	0.2
Gmax	Maximum Gate Limit	[p.u.]	1

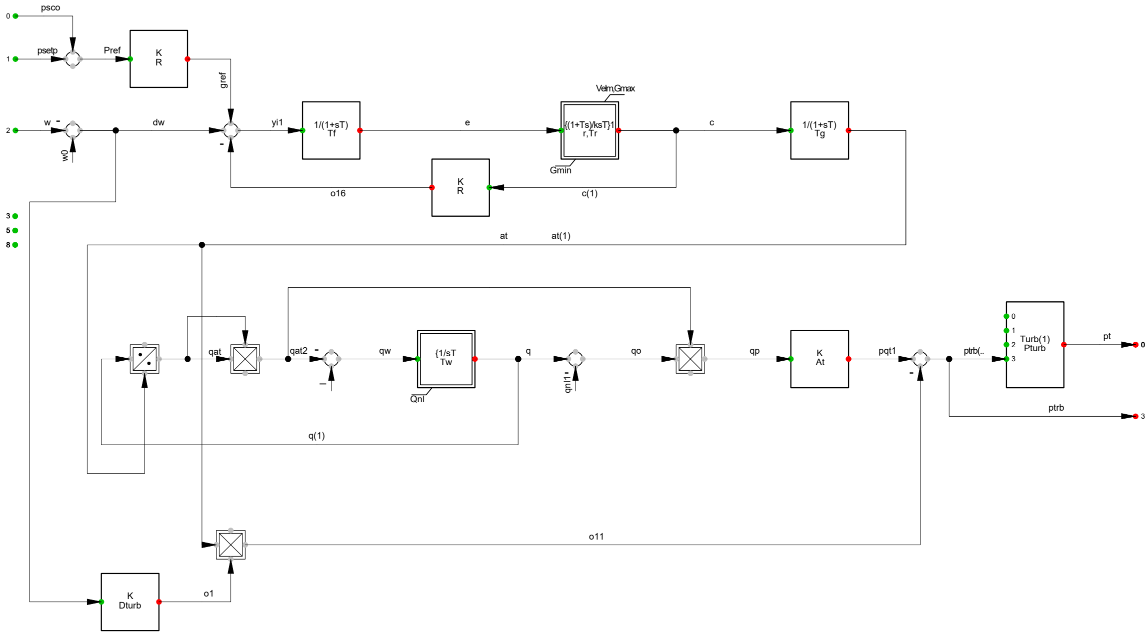


Figure A.2: Hygov

A.4.4 Exciter

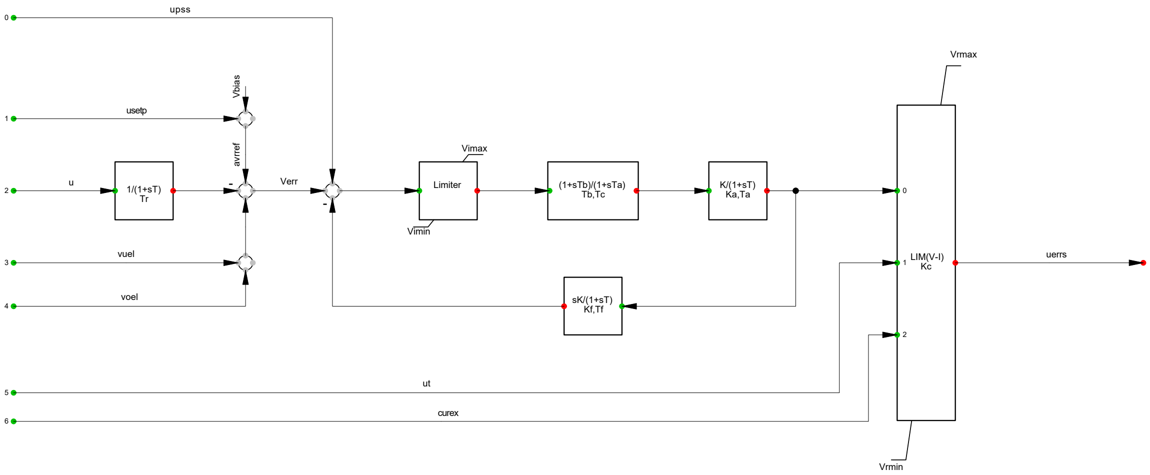


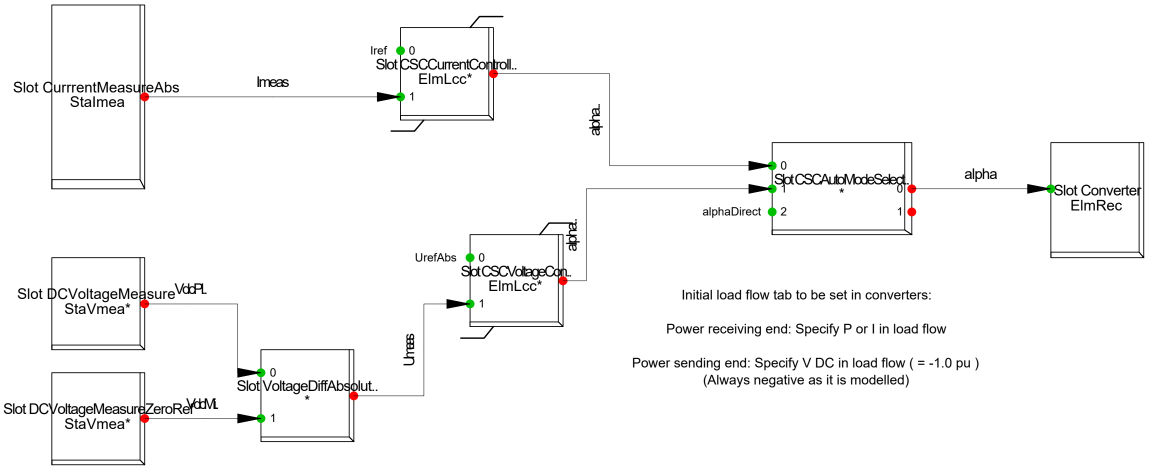
Figure A.3: AVR EXST1

Table A.10: Exciter parameters

T_r	Measurement Delay	[s]	0
T_b	Filter Delay Time	[s]	10
T_c	Filter Derivative Time Constant	[s]	1
K_a	Controller Gain	[p.u.]	200
T_a	Controller Time Constant	[s]	0.015
K_c	Exciter Current Compensation Factor	[p.u.]	0.04
K_f	Stabilization Path Gain	[p.u.]	0
T_f	Stabilization Path Delay Time	[s]	0.001
$V_{i_{min}}$	Controller Minimum Input	[p.u.]	-10
$V_{r_{min}}$	Controller Minimum Output	[p.u.]	-4.5
$V_{i_{max}}$	Controller Maximum Input	[p.u.]	10
$V_{r_{max}}$	Controller Maximum Output	[p.u.]	5.6

A.5 HVDC CONTROLLERS

A.5.1 CSC

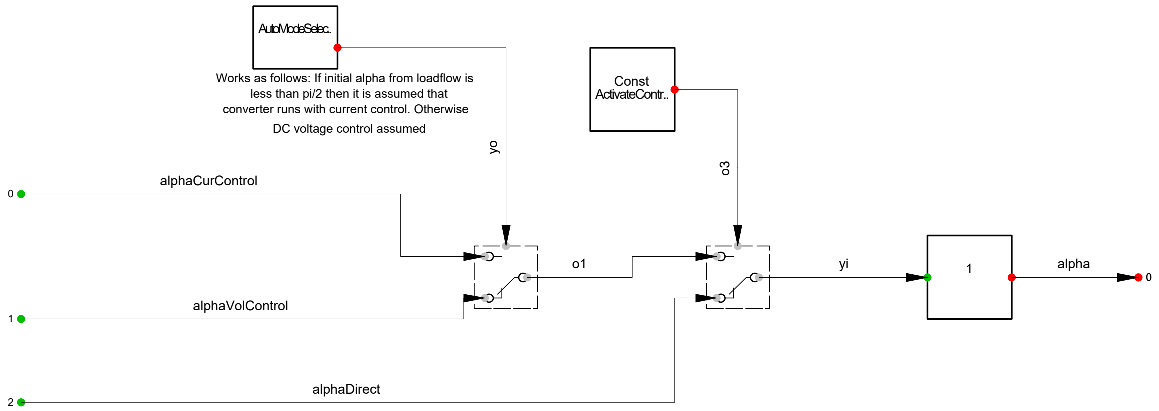


Initial load flow tab to be set in converters:

Power receiving end: Specify P or I in load flow

Power sending end: Specify V DC in load flow (= -1.0 pu)
(Always negative as it is modelled)

Figure A.4: Block diagram for CSC control frame



Works as follows: If initial alpha from loadflow is less than pi/2 then it is assumed that converter runs with current control. Otherwise DC voltage control assumed

Figure A.5: Block diagram for CSC control selector

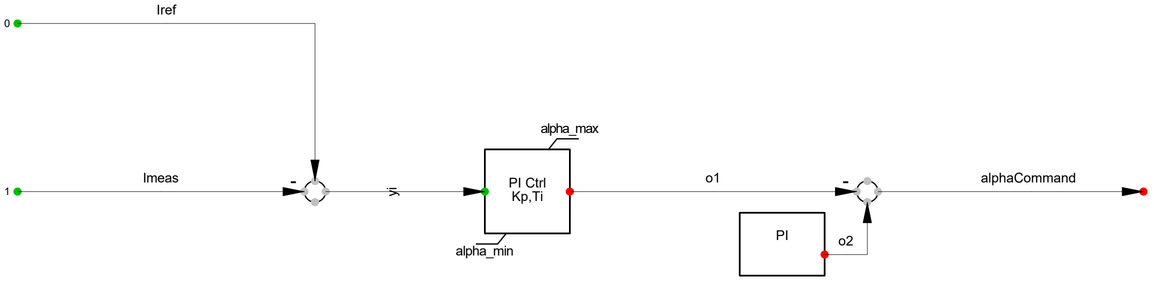


Figure A.6: Block diagram for CSC current controller

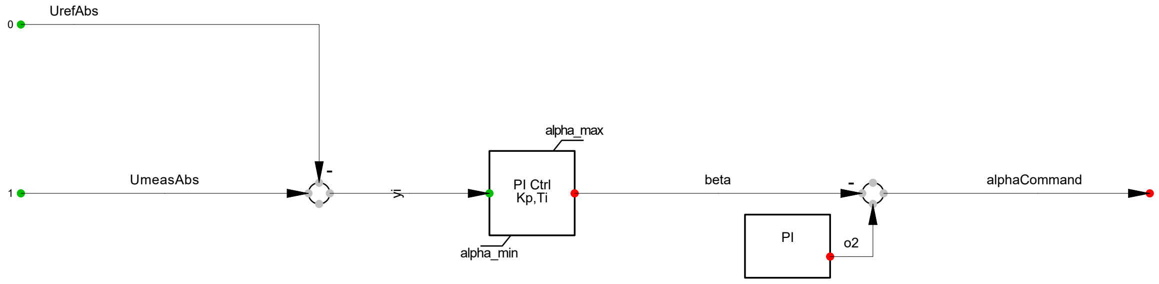


Figure A.7: Block diagram for CSC voltage controller

B | MODEL OVERVIEW

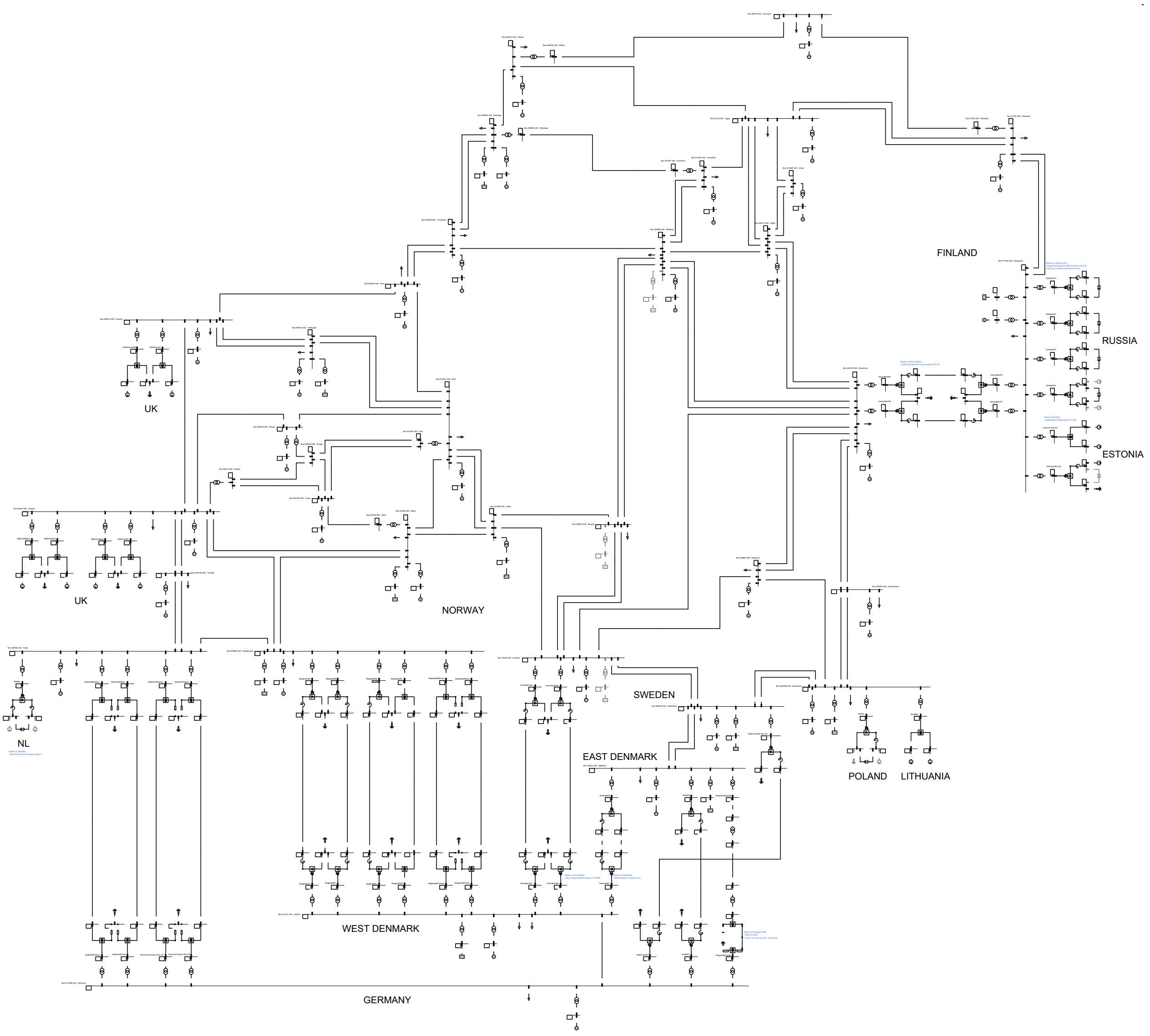


Figure B.1: Overview of the full grid in PowerFactory

C PYTHON SCRIPTS

C.1 BASE POWERFACTORY SCRIPT

```
import powerfactory
import re
from datetime import datetime

class Application:
    def __init__(self):
        self.app = powerfactory.GetApplication()
        self.prj = self.app.GetActiveProject()
        self.ops = self.app.GetActiveScenario()
        self.script = self.app.GetCurrentScript()
        self.Ldf = self.app.GetFromStudyCase("ComLdf")
        self.Ini = self.app.GetFromStudyCase(’ComInc’)
        self.Sim = self.app.GetFromStudyCase(’ComSim’)
        self.evt = self.app.GetFromStudyCase(’IntEvt’);
        self.vsc = self.app.GetCalcRelevantObjects(’ElmVsc’)
        self.csc = self.app.GetCalcRelevantObjects(’ElmRec’)
        self.tr2 = self.app.GetCalcRelevantObjects(’ElmTr2’)
        self.sym = self.app.GetCalcRelevantObjects(’ElmSym’)
        self.svc = self.app.GetCalcRelevantObjects(’ElmSvs’)
        self.bus = self.app.GetCalcRelevantObjects(’ElmTerm’)
        self.load = self.app.GetCalcRelevantObjects(’ElmLod’)
        self.line = self.app.GetCalcRelevantObjects(’ElmLne’)

    def calculateTotalImport(self):
        P = [0, 0, 0, 0, 0]
        areas = [’UK’,’Baltic’,’Russia’,’Europe’,’All’]
        # Go trough all transformers
        for tr in self.tr2:
            name=tr.loc_name
            # Do not select grid transformers or out of service transformers.
            if not re.match(’Trafo’, name) and not tr.outserv:
                if re.match(’NorNed’, name):
                    # NorNed has the LV side connected to the grid
                    attribute = ’m:Psum:buslv’
                else:
                     # Others have the HV side connected to the grid
                    attribute = ’m:Psum:bushv’
                try:
                    P_tr = round(tr.GetAttribute(attribute),0)
                except:
                    self.Ldf.Execute()
                    P_tr = round(tr.GetAttribute(attribute),0)

                # Only select HVDC transformers in the Nordic grid.
                # Disregard Fenno-Skan and KriegersFlak sea transformer
                if not re.search(’(D1)|(Z4)|(Fenno-Skan)’, name):
                    # Positive value is import, negative is export.
                    if re.match(’(NSN)|(NorthConnect)’, name):
                        P[0] -= P_tr
                    elif re.match(’(NordBalt)|(EstLink)’, name):
                        P[1] -= P_tr
                    elif re.match(’Vyborg’, name):
                        P[2] -= P_tr
                    else:
```

```
                        P[3] -= P_tr
                    P[4] -= P_tr
        return P, areas

    def exportResults(self, pTot = None, eventName = 'ManualExport'):
        app = self.app

        if not pTot:
            P, areas = self.calculateTotalImport()
            pTot = P[4]

        savePath=self.script.savePath
        timeNow=datetime.strftime(datetime.now(), '%b%d-%H%M')
        prjVer=re.findall('\s(v.*)\s',self.prj.GetFullName())[0]
        saveFile="{0}\{1}-{2:.0f}MW-{3}-{4}.csv".format(savePath, prjVer, pTot, eventName, timeNow)

        res = app.GetFromStudyCase('ComRes');
        res.iopt_exp=6 #Export to csv
        res.iopt_csel = 0 # Variable selection, 0=All
        res.iopt_sep=0 #Use custom column separator and decimal operator
        res.col_Sep=';'
        res.dec_Sep='.'
        res.iopt_tsel = 0 # User defined interval, 0=no
        res.iopt_locn = 1 # Bus name, 0=No name, 1=Bus name, 2=Full path
        res.ciopt_head = 2 # Variable desc, 0= No Name, 1=varname, 2=short desc, 3=long desc
        res.pResult= app.GetFromStudyCase('All calculations.ElmRes')
        res.f_name = saveFile

        if res.Execute():
            app.PrintError('Results not saved to file')
        else:
            app.PrintInfo('Results saved to file: ' + savePath)

        infoFile=savePath + '\\' + 'last_sim_results.txt'
        with open(infoFile,'w') as f:
            f.write(saveFile)
```

C.2 SET HVDC POWER

```
# Set the Power transfer on an HVDC link
# - Parameters for the converters are automatically changed in both ends of the link
# - If the power is set to 0 MW, all link items are set out-of-service
#
# Instruction:
# 1. Create a new Python Script object (.ComPython) in PowerFactory and link it to this file.
#
# 2. Create an Input Parameter for the power transfer in MW of each link the script should modify.
#    - Give it a short, suitable variable name.
#    - Examples: Type: Name: Value: Unit: Description
#               int   sk12  500    MW    Skagerrak1+2 bipole link
#
#               int   nsn1  1400   MW    NSN-Link1 bipole link
#
#               int   nor   500    MW    NorNed monopole link
#
# 3. Create an External object for each converter in the link and link it to the relevant converter.
#    - The name is required to be of the following syntax:
#       TYPE_LINKCOMPLETE{LINKEND}_NAME{_UNIT}
#           The parts in brackets are optional
#           TYPE can be either "VSC" or "CSC"
#           LINKCOMPLETE is 1 if the link is modelled in both ends, 0 if only in one end
#           LINKEND is A or B. This has to be set if LINKCOMPLETE is 1. Positive power means A <- B
#           NAME has to be the same name as the corresponding parameter name.
```

```
#           UNIT has to be specified if the link is a bipole and the power is specified as a combined value. Can be any name
#       Examples: Name:             Object:                         Description:
#                 CSC_1A_sk12_1     Skagerrak1N2 converter          Skagerrak1N2 converter
#                 CSC_1A_sk12_2     Skagerrak2N2 converter          Skagerrak2N2 converter
#                 CSC_1B_sk12_1     Skagerrak1D1 converter          Skagerrak1D1 converter
#                 CSC_1B_sk12_2     Skagerrak2D1 converter          Skagerrak2D1 converter
#
#                 VSC_1_nsn1_min    NSN-Link1N2Minus converter      NSN-LinkN2Minus converter
#                 VSC_1_nsn1_plus   NSN-Link1N2Plus converter       NSN-LinkN2Plus converter
#
#                 CSC_0_nor         NorNedN2 converter          NorNedN2 converter
#
# 4. If the link is a CSC and only modelled in one end, an additional external object has to be created for all of the three
#   - The name has the same syntax as in #3, except for:
#           TYPE can only be "Src"
#           UNIT has to be specified and be "cs", "vlow", or "vhigh".
#       Examples: Name:             Object:                         Description:
#                 Src_0_nor_cs      NorNed DC Source Import         NorNed current source
#                 Src_0_nor_vlow    NorNed DC Source Export Minus   NorNed low voltage source
#                 Src_0_nor_vhigh   NorNed DC Source Export Plus    NorNed high voltage source
#
# 5. If there is a need to change Vdc/Q-control and its value, that has to be changed manually.

import myPowerfactory
import re
import math
pf = myPowerfactory.Application()

def setLinkOutserv(obj, outserv): # Requires that all the link items are in a separate folder
    items = obj.GetParent().GetContents()
    for item in items:
        item.outserv = outserv

def getCscIRP(obj, Psetp, linkComplete):
    converterName = re.findall('(.*)[A-Z][0-9]', obj.loc_name)[0]
    sources = obj.GetParent().GetContents(converterName + '*.ElmDcu')
    lines = obj.GetParent().GetContents(converterName + '*.ElmLne')

    Tr = obj.GetParent().GetContents(converterName + '*.ElmTr2')[0]
    rk = Tr.typ_id.uktrr/100
    Unom = obj.typ_id.Unomdc

    if linkComplete:
        R_line = lines[0].dline * lines[0].typ_id.rline
        if len(sources) == 2 and not len(sources[0].loc_name.split('+')) > 1: # Not Skagerrak 3+4
            R = R_line + 2 * sources[0].Ri # One line, two DC ground sources with resistance
        else:
            if len(lines) == 1:
                R = R_line # One line per converter, bipole
            elif len(lines) == 2:
                R = 2 * R_line # Two lines, bipole
            else:
                pf.app.PrintError("Error finding line")
                return False
        Pinv = Psetp/(1-rk)
    else:
        R = 2 * sources[0].Ri
        Pinv = Psetp

    I = (Unom - math.sqrt(Unom**2 - 4*R*Pinv))/(2*R)
    Prec = Pinv + R * I**2
    return I, R, Pinv, Prec

def setCscVdc(obj, Psetp_in, linkComplete):
    # Calculate voltage at the inverter
    if linkComplete:
        Unom = obj.typ_id.Unomdc
```

```
        I, R, Pinv, Prec = getCscIRP(obj, Psetp, linkComplete)
        I = Prec/Unom
        Uinv = 1.0 - (R * I**2)/Unom
        Usetp = -round(Uinv, 3)
        obj.uset = Usetp

    setLinkOutserv(obj, 0)
    obj.ntrcn = 2 # Gamma control tap changer
    obj.bstp = ’Vdc’ # Vdc control

def setCscP(obj, Psetp_in, linkComplete):
    if Psetp_in < 0:
        Psetp = -Psetp_in
    else:
        Psetp = Psetp_in

    I, R, Pinv, Prec = getCscIRP(obj, Psetp, linkComplete)
    Psetp = round(Prec,2)

    Pmax = int(obj.typ_id.Pnom)
    if Psetp > Pmax:
        pf.app.PrintPlain(’Power setpoint ({0} MW) for {1} is higher than maximum ({2} MW). Setting to {2} MW.’.for
        Psetp = Pmax
    setLinkOutserv(obj, 0)
    obj.bstp = ’P’ # P control
    obj.ntrcn = 1 # Alpha control tap changer
    obj.Pset = Psetp

def setVscP(obj, Psetp_in, linkComplete):
    if linkComplete:
        if Psetp_in < 0:
            Psetp = Psetp_in # Specified as negative out from inverter
        else:
            Psetp = -Psetp_in
    else:
        Psetp = -Psetp_in

    Smax = obj.Snom
    if abs(Psetp) > Smax:
        oldPsetp = Psetp
        Psetp = Smax * math.sqrt(1-0.35**2)
        pf.app.PrintPlain(’Power setpoint ({0} MW) for {1} is higher than maximum ({2} MVA). Setting to sqrt(1-0.35
    setLinkOutserv(obj, 0)
    obj.i_acdc = 4 # Control mode P-Vac
    obj.psetp = Psetp

objectNames = pf.script.obj_name
objectIds = pf.script.obj_id
converters = {}
for i, objName in enumerate(objectNames):
    obj = objectIds[i]
    objInfo = objName.split(’_’) #VSC_0_nsn1_min -> [VSC, 0, nsn1, min] --- CSC_1A_sk12_1 -> [CSC, 1A, sk12, 1]
    objType = objInfo[0]
    linkComplete = int(objInfo[1][0]) # 0 or 1, If it is modelled in both ends or not
    linkName = objInfo[2] # e.g. nsn1, same as input parameter
    Psetp = getattr(pf.script, linkName)

    if objType == ’VSC’:
        if len(objInfo) > 3: # A bipole link
            Psetp = Psetp/2

        converters[linkName] = obj

        if not linkComplete: # Only modelled in one end
            if Psetp == 0:
                setLinkOutserv(obj, 1)
            else:
```

```
            setVscP(obj, Psetp, linkComplete)
    else:               # modelled in both end
        linkEnd = objInfo[1][1] # A or B
        if Psetp > 0 and linkEnd == ’A’ or Psetp < 0 and linkEnd == ’B’: # Power is defined at inverter
            setVscP(obj, Psetp, linkComplete)
        elif Psetp == 0:
            setLinkOutserv(obj, 1)
        else:
            obj.i_acdc = 6 # Control mode Vdc-Vac

elif objType == ’CSC’:
    if len(objInfo) > 3: # A bipole link
        Psetp = Psetp/2

    converters[linkName] = obj

    if not linkComplete: # Only modelled in one end
        if Psetp < 0:
            setCscP(obj, Psetp, linkComplete)
        elif Psetp == 0:
            setLinkOutserv(obj, 1)
        else:
            setCscVdc(obj, Psetp, linkComplete)
    else:                # modelled in both ends
        linkEnd = objInfo[1][1] # A or B
        if Psetp > 0 and linkEnd == ’B’ or Psetp < 0 and linkEnd == ’A’: # Power is defined at rectifier
            setCscP(obj, Psetp, linkComplete)
        elif Psetp == 0:
            setLinkOutserv(obj, 1)
        else:
            setCscVdc(obj, Psetp, linkComplete)

elif objType == ’Src’: # For simple CSC links. Used for modifying the extra sources
    objVar = objInfo[3]
    converterName = obj.loc_name.split()[0]
    Tr = obj.GetParent().GetContents(converterName + ’*.ElmTr2’)[0]
    rk = Tr.typ_id.uktrr/100
    Pinv = Psetp/(1-rk)
    if objVar == ’cs’:
        if Pinv > 0:
            Vnom = converters[linkName].typ_id.Unomdc
            obj.Inom = (Pinv/Vnom + obj.Gi*Vnom)*1000 # Set the nominal current for the current source
            obj.outserv = 0
        else:
            obj.outserv = 1
    elif objVar == ’vlow’ or objVar == ’vhigh’:
        if Psetp < 0:
            obj.outserv = 0
            R = obj.Ri
            Unom = obj.Unom
            if Unom > 1:
                I = (Unom - math.sqrt(Unom**2 - 4*R*Pinv))/(2*R)
                Uinv = round(1.0 - (0.5 * R * I**2)/Unom,3)
                if obj.uset < 0:
                    obj.uset = -Uinv
                else:
                    obj.uset = Uinv
            else:
                obj.uset = 0
        else:
            obj.outserv = 1
else:
    pf.app.PrintError(’The object type is not of a valid type’)
```