# Impact of Present and Future HVDC Links on the Nordic Power Grid

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## Abstract

This article presents preliminary results from ongoing work on establishing a simulation model for R&D activities on the impact of the increasing number of HVDC links in the Nordic power grid. The total HVDC power capacity will be 13100 MW (excluding some smaller systems) by 2021. This study addresses a future scenario with additional 7400 MW of HVDC interconnection capacity for power exchange. The scenario is analysed numerically using the simulation tool "DIgSILENT PowerFactory", considering an aggregated representation of the future power grid. The preliminary power flow results indicate that capacity and voltage constraints within the Nordic power grid will be a limiting factor for the power exchange. The first dynamic results indicate that future high import scenarios can give more oscillations after disturbances compared to scenarios with less import, considering generic converter controllers that are not tuned to damp these oscillations.

## 1 Introduction

The Energiewende causes a steadily increasing share of non-dispatchable sustainable electric power sources in Europe. This calls for increased power balancing capabilities, where large scale energy storage is one of the key measures for balancing. The Norwegian hydropower stations with large reservoir have ideal characteristics for providing balancing resources and added flexibility to the power system. However, larger power exchange capacity between the Nordic region and Northern Europe is needed [1].

The Nordic power grid has already today one of the highest concentrations of HVDC installations in the world. The most prominent HVDC installation within the Nordic grid is the Fenno-Skan1+2 HVDC link (1300 MW). However, most of the HVDC installations are connections between the Nordic power grid and surrounding power grids (total of 8600 MW). There are also smaller HVDC links connecting offshore island grids, like Gotland island (260 MW), Valhall oil&gas platform (78 MW) and Troll-A oil&gas platform (188 MW). These HVDC links have not been included in this study, because their power rating is rather small. The total HVDC power included in this study is 9900 MW.

The interconnection capacity between e.g. Norway and the UK and continental Europe for power exchange is increasing and new HVDC converters in the southern part of Norway are planned [2]. The total HVDC power in the Nordic grid will increase by another 4500 MW by 2021. The share of HVDC power (ratio between total HVDC power and average system power) will increase from roughly 20% to 25%. Among these new HVDC installations, the South(-West) Link (1200 MW) and Ål-Link (100 MW) are not included in this study yet.

The vision of an integrated pan-European electricity market will most likely lead to even more HVDC links by 2030. This study addresses a 2030 scenario with additional 7400 MW HVDC interconnection capacity for power exchange. These hypothetical HVDC interconnectors result in a total of 20500 MW of HVDC capacity for the 2030 scenario applied here. The share of HVDC power will then increase from roughly 25% to around 35%.

The high concentration of HVDC links puts the HVDC systems into a crucially important role for power system operation and control. In a case with low load and large import to the Nordic system, few generators will be running, especially in the southern part of Norway. This is a critical scenario, which is investigated in this study.

The goal for the ongoing work is to establish a simplified, representative PowerFactory simulation model of the future Nordic electric power transmission system, including existing and new connections to adjacent import/export markets. The idea is to develop and maintain the model for use in different national and international research projects, as well as for educational purposes (PhD) without any restrictions due to intellectual property rights. Consequently, it is not aimed for an accurate and exact replication of the real systems. The model is intended for investigation of phenomena as well as test and verification of general ideas. It is not intended detailed engineering and verification of the actual transmission system.

## 2 Model Description

The established Nordic grid model is shown in Figure 1. An overview of the modelling is given in this section of the article. More details on the models and specific parameters can be found in [3].

### 2.1 The AC system

A 33-node equivalent model of the Nordic grid has been built in PowerFactory (with one or more AC busses per node). The model is an aggregated model; generators and loads in an area are added together to one power station representing total production and one load representing total load in that area. The model is somewhat based on an older 23-bus PSSE model [4], but it contains significantly more modelling details.

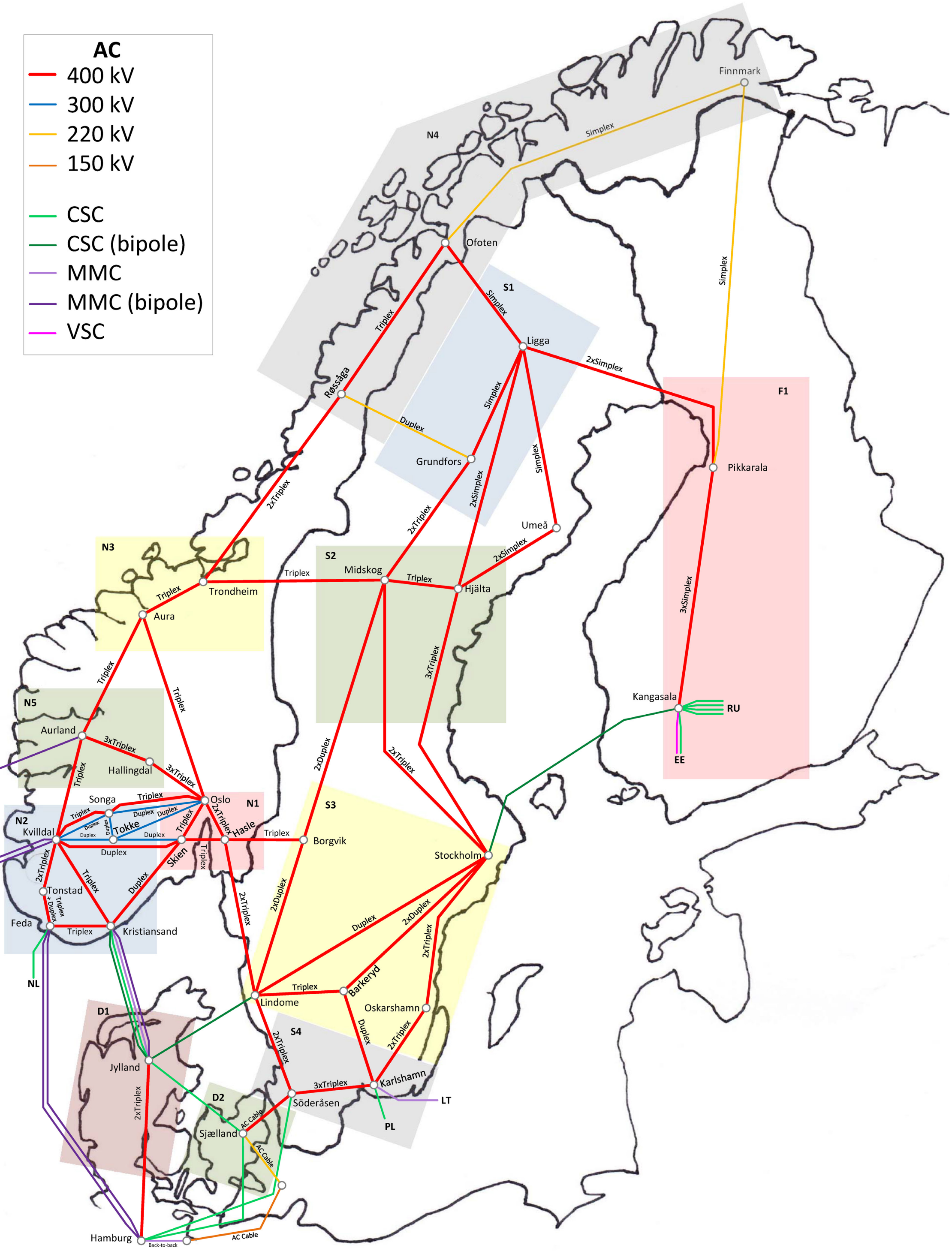


Figure 1: The aggregated model of the foreseen Nordic grid in 2030

***Generators***

The generator model used here is a 250 MVA salient pole synchronous machine with a hydropower turbine. The specific data (documented in [3]) is not reflecting a specific machine or turbine or power station, but is rather designed to represent a generic standard generator. All generation in the developed grid model is represented by this generic hydropower station.

PowerFactory generator models are scalable. This makes it easy to use the model to investigate cases where only some of the generators in a specific aggregated group are running, by simply specifying a representative scale factor.

It has been considered to include various types of generation technologies, especially larger thermal power stations and wind power plants, but this has not been realised at the time of writing. Potential future pumped hydropower stations in Norway have not been included in the model yet.

The governor, which is applied to the hydropower generators, is based on the model "pcu_HYGOV" from the PSSE model library. The parameters are chosen to represent a typical Norwegian hydropower turbine.

The excitation system is static, since all Norwegian generators at 25 MVA or more should have a static excitation system [5]. The implemented excitation system model is the Type ST1A [6].

The modelled hydropower stations also have a power system stabiliser (PSS) that has the function to enhance damping of power system oscillations by controlling the excitation of the generator. The power system stabiliser model IEEE PSS2B is normative for the Norwegian grid [5], and therefore the PowerFactory model "pss_PSS2B" is applied for all power stations in the grid model. The tuning of the PSSs is performed as stated in [5]. Both power and shaft speed is used as input; shaft speed for low frequencies and power for higher frequencies in order to increase the bandwidth. Parameters from the sample data for a type ST1A excitation system with type PSS2A power system stabilizer in [6] is used as a basis when tuning the PSSs. Eigenvalue and mode phasor plot in PowerFactory have been used to tune the PSS parameters in order to increase the damping of the system.

***Loads***

The loads are represented by the *ZIP*-model (impedance *Z*, current *I*, power *P*), with the coefficients being set to:

- 30% constant impedance loads
- 30% constant current loads
- 40% constant power loads

PowerFactory load models are scalable. This makes it easy to use the model to investigate cases where only some of the loads in a specific aggregated group are active, by simply specifying a representative scale factor.

***AC Network***

The network model (shown in Figure 1) represents the Nordic grid in 2030. The Norwegian grid is updated with the planned expansions towards 2030 [2]. It is assumed, that by 2030 most Norwegian transmission lines will be upgraded to 400 kV, with only a few 300 kV lines remaining in operation.

Western Denmark is connected to the continental European grid by an AC overhead line to northern Germany. The continental European power system is modelled as an equivalent external grid model (from the PowerFactory library) connected to the bus in northern Germany. This external grid is designed to be stiff enough to prevent significant influence on the results.

### 2.2 The HVDC systems

An overview of the HVDC systems is given in Table 1.

| Name | Power [MW] | Grid Connection | Project Status | Type | Configuration | Modelling | Reference |
|---|---|---|---|---|---|---|---|
| EstLink1 | 350 | Eastern | Operational | VSC | Monopole | One side | [7] |
| EstLink2 | 650 | Eastern | Operational | CSC | Monopole | One side | [8] |
| Fenno-Skan1+2 | 1300 | Internal | Operational | CSC | Bipole | Both sides | [9] |
| NorNed | 700 | Continental | Operational | CSC | Monopole | One side | [10] |
| KontiSkan1+2 | 760 | Continental | Operational | CSC | Bipole | Both sides | [11] |
| Storebælt | 600 | Continental | Operational | CSC | Monopole | Both sides | [12] |
| Kontek | 600 | Continental | Operational | CSC | Monopole | Both sides | [13] |
| BalticCable | 600 | Continental | Operational | CSC | Monopole | Both sides | [14] |
| SwePol | 600 | Continental | Operational | CSC | Monopole | One side | [15] |
| Vyborg1 | 350 | Eastern | Operational | CSC | Monopole | One side | [16] |
| Vyborg2 | 350 | Eastern | Operational | CSC | Monopole | One side | [16] |
| Vyborg3 | 350 | Eastern | Operational | CSC | Monopole | One side | [16] |
| Vyborg4 | 350 | Eastern | Operational | CSC | Monopole | One side | [16] |
| Skagerrak1+2 | 500 | Continental | Operational | CSC | Bipole | Both sides | [17] |
| Skagerrak3 | 440 | Continental | Operational | CSC | Monopole | Both sides | [17] |
| Skagerrak4 | 700 | Continental | Operational | MMC | Monopole | Both sides | [18] |
| NordBalt | 700 | Eastern | Operational | MMC | Monopole | One side | [19] |
| KriegersFlak | 400 | Continental | by 2019 | MMC | Monopole | Both sides | [20] |
| NordLink | 1400 | Continental | by 2020 | MMC | Bipole | Both sides | [21],[22] |
| NSN-Link | 1400 | UK | by 2021 | MMC | Bipole | One side | [23] |
| NorthConnect | 1400 | UK | by 2030 | MMC | Bipole | One side | [24] |
| Skagerrak5* | 2000 | Continental | by 2030 | MMC | Bipole | Both sides | ----------- |
| NordLink2* | 2000 | Continental | by 2030 | MMC | Bipole | Both sides | ----------- |
| NSN-Link2* | 2000 | UK | by 2030 | MMC | Bipole | One side | ----------- |

* Hypothetical systems

Table 1: The included HVDC systems

***CSC HVDC Links***

The grid model contains 14 CSC HVDC transmission systems with a total of 27 current source converters, placed in 21 converter stations (6 bipole, 15 monopole). The total CSC HVDC transmission capacity modelled is 8150 MW.

***VSC HVDC Links***

The grid model contains only one classical two-level VSC HVDC system, which is EstLink1, with a power capacity of 350 MW.

***MMC HVDC Links***

The grid model contains 9 MMC HVDC transmission systems with a total of 23 MMC converters, placed in 14 converter stations (9 bipole, 5 monopole). The total MMC HVDC transmission capacity modelled is 12000 MW.

***Modelling of one side or both sides***

Regarding some of the HVDC systems, only the Nordic converter station is modelled, since the other terminal of these links is connected to AC nodes that are not part of the model. It is assumed that these converter stations are connected to a stiff grid. These partly modelled HVDC links consist of a single converter station connected by a HVDC cable to a DC voltage source. Considering the CSCs, the DC voltage source has to be replaced by a DC current source, depending on the operational mode of the CSC (rectification or inversion).

***Specifications of the future MMC links***

The ratings of the three hypothetical VSC HVDC bipoles (Skagerrak5, NordLink2 and NSN-Link2) are set based on the maxima ratings from existing projects (shown in Table 2). This conservative estimation assures that no unrealistic technology development is assumed. The NorthConnect HVDC link is modelled the same way as NSN-Link, as this technical similarity can be assumed from the project proposal [24].

| Parameter | Value | Unit | Reference |
|---|---|---|---|
| Voltage | ± 525 | kV | NordLink [21] |
| Current | 1,9 | kA | Caithness-Moray [25] |
| Power | 2*1000 | MW | Calculation V*I |

Table 2: Ratings of hypothetical future MMC HVDC bipoles

## 3 Preliminary Results

The results presented here are based on ongoing work, and should not be considered as accurate forecast of the future dynamic system behaviour. However, they can indicate what kind of phenomena will appear in the future, when the Nordic power grid is subject to larger power flows while a reduced number of synchronous generators are online. Even though the model is an aggregated model, and it is not complete yet (South-West HVDC Link still missing), some interesting phenomena can be observed.

### 3.1 Contingency Analysis

To test the power flow analysis capabilities of the simulation model, a high-wind low-load scenario has been addressed. In this scenario, strong winds in the North Sea region lead to high power output of the coastal and offshore wind power plants, which in turn leads to very low power market prices. Scandinavia tries to benefit from the situation by importing as much cheap electricity as possible and thereby being able to reduce the output from its hydropower stations.

Considering the HVDC interconnectors of 2021 together with the 2030 AC grid, no serious problems appear. It is then tested how much power can be imported through the additional hypothetical HVDC links of 2030 (additional 7400 MW), before problems like current bottlenecks (based on thermal line rating) and voltage issues (minimum 0,93 p.u. [26]) in the power grid of southern Norway appear.

In the following two figures (Figure 2 and Figure 3), purple lines shows HVDC transmissions with fixed power flow, dark green are transmissions with low load. Transmissions with higher loads are indicated by lighter green, yellow and finally red which indicates close to maximum capacity. Green circles indicates voltage close to rated, blue are low voltage and black is even lower. High voltage is indicated by yellow and red for high and very high voltage respectively.

***Case 1: All power lines in service***

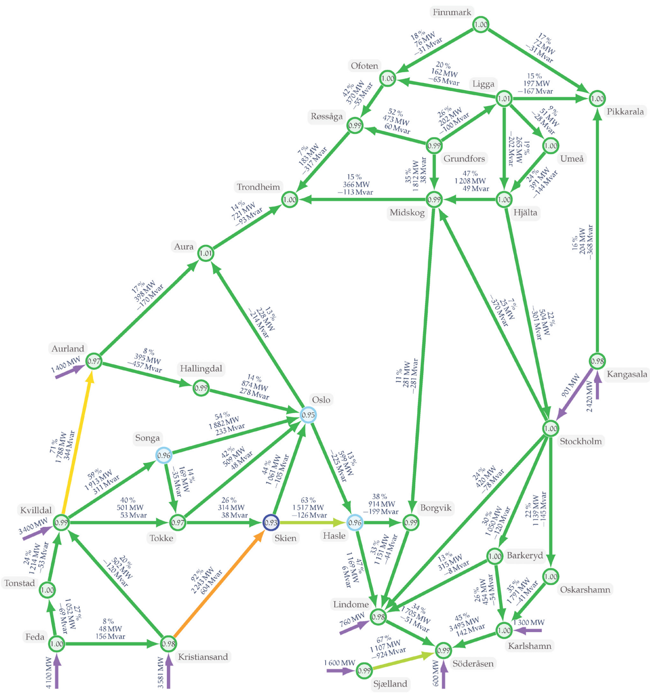


Figure 2: Power flow and bus voltages (N-0)

Case 1 is the base case with all power lines in service. The power flow and bus voltages are shown in Figure 2. The HVDC import can almost reach the maximum without violation of the lower voltage level. A slight reduction of the power import through the Skagerrak HVDC links is although necessary to avoid under-voltages around Skien.

Since the import to southern Norway is large, the power flow will go from Kristiansand to the Oslo area and further on to Sweden. The line between Kristiansand and Skien is the most critical since it is only a single circuit duplex line and since it is the shortest way to the Oslo area and Sweden.

*Case 2: Power line Kvilldal-Aurland out of service*

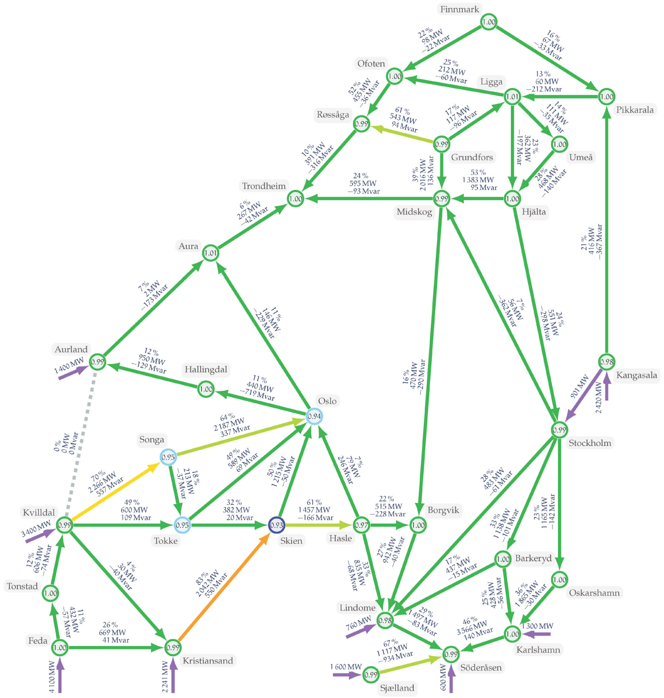


Figure 3: Power flow and bus voltages (N-1)

Case 2 is the worst-case single component outage, which has been identified with N-1 contingency analysis. The analysis has shown that removing the line between Kvilldal and Aurland results in the most severe problems. The highest over-loading appears on the critical line between Kristiansand and Skien, similar to the base case. Voltages around Skien become unacceptably low.

A possible measure to avoid these voltage limit violations is to limit the maximal imported power through the new Skagerrak5 HVDC system to only 600 MW (out of 2000 MW). The other Skagerrak Links 1-4 can operate as normal. The power flow for this case with reduced power transmission on Skagerrak5 is shown in Figure 3. As this severe limitation on the capabilities of Skagerrak5 is undesirable, a reinforcement of the critical line Kristiansand-Skien would be recommended if Skagerrak5 were to be built.

### 3.2 Dynamic RMS analysis

The main reason to develop the simulation model was to be able to perform dynamic simulations of the Nordic power system. The power flow calculations presented in the previous section could also have been achieved with less advanced tools.

For the dynamic RMS simulations, the earlier mentioned high-wind low-load scenario has been selected, as it represents a critical system state for the Nordic power system. In this system state, a critical loss-of-load event (1400 MW) at the 400 kV bus in Oslo has been simulated. Such a large loss of load event is not realistic to happen. The hypothetical event has been chosen to trigger the system response. More realistic system disturbances have not been studied yet.

The fault event is simulated for the two different network expansion stages:

- The 2021 stage, with an import of 11800 MW
- The 2030 stage, with an import of 19200 MW

The Kristiansand bus is one of the most critical busses in the system, as it is connected to the critical Kristiansand-Skien line and as there is many HVDC stations present. The grid voltage measurement at the 400 kV bus in Kristiansand is displayed for both stage simulations, 2021 in Figure 4 and 2030 in Figure 5.

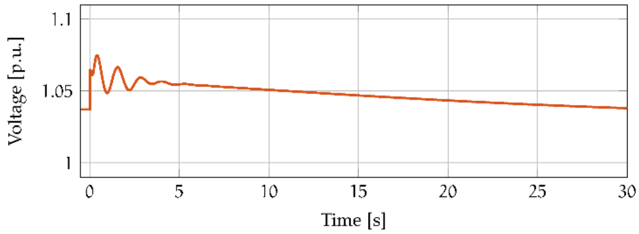


Figure 4: Grid voltage in Kristiansand (2021)

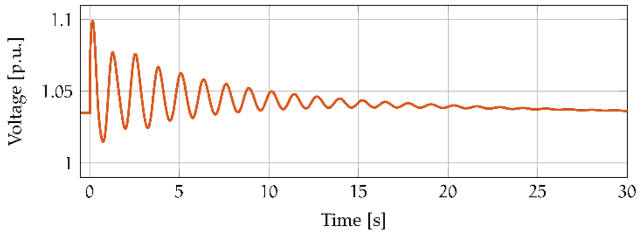


Figure 5: Grid voltage in Kristiansand (2030)

It can be clearly observed how the shift of power sources, from synchronous machines towards HVDC converter imports, affects the power system affinity to oscillations. In this model, the HVDC converter control does not include dedicated power system stabilising functionality. How this generic controller with the simplified converter model compares to a real HVDC station with regards to stability could not be evaluated, since the control schemes of the HVDC links are not publicly available.

Deploying these HVDC stations with the simple generic control seems to be acceptable only up to a certain limit. With the large amount of HVDC power in 2030, features like oscillation damping capability will become very important.

## 4 Conclusion

The large-scale deployment of wind power plants in the North Sea region significantly influences the Nordic power grid, even though it does not have a large share of wind power itself. This is generally caused by market coupling, and specifically by Norway's role as Europe's "green battery". The main bottleneck between the North Sea wind power plants and the Norwegian hydropower stations is often considered to be the HVDC transmission capacity, which couples the Nordic and the continental grids. However, this is only one part of the truth. Increasing the HVDC capacity (removing that bottleneck) will lead to new bottlenecks and voltage profile issues, especially in the southern Norwegian power grid.

The Nordic power grid model under development is a valuable tool, to assess the implications of the increasing power exchange in a general and generic way. The aggregation of regions into single nodes significantly reduces the computational efforts, while still maintaining an acceptable geographic resolution. It also increases the possibility of the user to have an overview over the system and "understand" it, which can be really challenging when simulating real grid topologies with hundreds or thousands of nodes.

The degree of detail of the HVDC links cannot keep up to HVDC models in EMT-tools like PSCAD, which are the typical HVDC simulation environments. However, simulations of the CIGRE HVDC Test Grid [27] with EMT software have proven to be challenging and rather slow. The simulation of the Nordic grid model with an EMT-tool would probably be possible, but it would be facing the same problems. This simplified approach makes the model fast and "user-friendly", as not all converter details might be important to see the "big picture" in the Nordic power grid. The PowerFactory software also offers the possibility for EMT-type simulation, but this has not been attempted yet. It is planned for the future.

## Acknowledgements

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## References

[1] D. Huertas-Hernando, H. Farahmand, S. Jaehnert, S. Voeller, and O. Wolfgang, "Nordic hydro power flexibility and North European wind power: A transmission expansion study", *EWEA conference,* 2013.

[2] Statnett, "Nettutviklingsplan 2013 - Nasjonal plan for neste generasjon kraftnett", 2013.

[3] E. S. Aas, "Simulation Model of the Future Nordic Power Grid Considering the Impact of HVDC Links", *NTNU Master Thesis,* 2016.

[4] E. Hagstrøm, I. Norheim, and K. Uhlen, "Large-scale Wind Power Integration in Norway and Impact on Damping in the Nordic Grid", *Wind Energy,* 2005.

[5] Statnett, "Funksjonskrav i kraftsystemet (in Norwegian)", 2012.

[6] I. s. 421.5, "Recommended Practice for Excitation System Models for Power System Stability Studies", 2005.

[7] L. Ronström, M. L. Hoffstein, R. Pajo, and M. Lahtinen, "The Estlink HVDC Light Transmission System", in *CIGRE Regional Meeting*, Tallinn, Estonia, 2007.

[8] Fingrid and Elering, "EstLink 2 - EstLink 2 is a high voltage direct current (HVDC) interconnection between Estonia and Finland".

[9] T. D. Ingemansson, T. Kiiveri, H. Nurminen, B. L. Pääjärvi, and K.-G. Danielsson, "New Fenno-Skan 2 HVDC pole with an upgrade of the existing Fenno-Skan 1 pole", presented at the CIGRE, Paris, 2012.

[10] J.-E. Skog, K. Koreman, B. Paeaejaervi, T. Worzyk, and T. Andersroed. (2007, The NorNed HVDC Cable Link - a Power Transmission Highway between Norway and the Netherlands.

[11] A. Grid, "Konti-Skan 1 - HVDC Renocation Project", 2010.

[12] ABB, "Connecting Denmark's eastern and western power grids - Storebaelt HVDC submarine and underground cable link", 2011.

[13] C. Wolff and T. Elberling, "The Kontek HVDC link between Denmark and Germany", *IEEE PES Winter Meeting,* 2000.

[14] ABB Power Technologies. (1994, Submarine Cable Link - The Baltic Cable HVDC Connection Sweden / Germany.

[15] ABB Power Technologies, "The Kontek HVDC link between Denmark and Germany".

[16] G. Tsfasman, A. .Mazurenko, A. Mordcovich, A. Tarasov, E. Zmaznov, A. Bastunsky, D. Lubarsky, E. Rossovsky, G. Prochan, and A. Popov, "New Integrated Control and Protection System for Vyborg Back-to-Back HVDC Link", *CIGRE Session Paris,* 2008.

[17] ABB - HVDC, "HVDC References", 2015.

[18] ABB Grid Systems - HVDC, "Skagerrak 4 - Excellent benefits through interconnections ", ed, 2014.

[19] ABB's high voltage cable unit in Sweden, "The world's longest HVDC Light cable - BordBalt HVDC Light connection, Sweden-Lithuania", 2011.

[20] ABB press releases, "ABB wins $140 million order to boost integration of renewables in Europe", 2016.

[21] M. Callavik, P. Lundberg, and O. Hansson, "NORDLINK - Pioneering VSC-HVDC interconnector between Norway and Germany", *ABB White Paper,* 2015.

[22] Nexans, "NordLink HVDC interconnector between Norway and Germany will use Nexans' subsea power cables".

[23] ABB press releases, "ABB wins $450 million order for Norway-UK HVDC interconnection", 2015.

[24] 4C Offshore, "Offshore HVDC Converter & HVDC Grid Collector Database", http://www.4coffshore.com, 2014-10-23 2014.

[25] ABB news releases, "Creating Scotland's Caithness Moray subsea HVDC power link ", 2014.

[26] A. G. Endegnanew, E. Tedeschi, J. I. Marvik, R. E. Torres-Olguin, and S. d'Arco, "MARINET Deliverable 2.26 - Collation of European grid codes", 2013.

[27] T. K. Vrana, S. Dennetiere, Y. Yang, J. Jardini, D. Jovcic, and H. Saad, "The CIGRE B4 DC Grid Test System", *Electra,* vol. 270, 2013.