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Frequency Quality in the Nordic Power System: Wind Variability, Hydro Power Pump Storage and Usage of HVDC Links

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Abstract

This work investigates the effect that variable power production from offshore wind farms in the North Sea will have together with the use of pumped storage facilities at hydropower stations in Norway, on the Nordic frequency. Two different pumped storage cases are investigated for a power exchange situation between Norway and Continental Europe, which illustrates the effect of wind power variability. The performance of primary and secondary controllers to restore frequency quality is analyzed.

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Keywords: Offshore wind variability; hydro power flexibility; balancing power; frequency quality; pump storage; HVDC links; LFC

1. Introduction

Ambitious targets have been set by the European renewable Directive 2009/28/EC, which establish an overall quota of a 20% share of Renewable Energy Sources (RES) in gross consumption of energy by 2020 [1]. The willingness of the European Union to cut greenhouse gas emissions was underpinned by the introduction of the “Energy Roadmap 2050” (EU directive 2009/29/EC) aiming to reduce greenhouse gas emissions to 80-95% below 1990 levels by 2050 [2]. These targets will have a profound impact on transmission planning and system operation.

Wind energy is expected to contribute a large share of the future Renewable Energy Sources (RES) in Northern Europe [3]. Due to the variable generation from wind energy, increased production flexibility

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will be required for the operation of the future power system. The Nordic hydro power has ideal characteristics to provide such balancing resources and add flexibility to the continental European power system. In order to effectively exploit these resources, sufficient transmission capacity must be available between the Nordic region and Continental Europe.

This paper studies how the flexible usage of hydro power plants in the Nordic region to balance wind farm production from facilities around the North Sea will impact the Nordic frequency. Flexible hydropower usage refers to a more varying hydropower production than the present practice, as well as the usage of pumped storage in the system. The objective of this paper is the study how this change in production units and loads affects the frequency of Nordic power system. The power system simulation tool PSS/E is used in this study.

The interplay between variable power production from offshore wind farms, load from pumped storage facilities at hydropower stations and more volatile power flows across HVDC links between Norway and Continental Europe is expected to have an effect on the Nordic frequency. We have analyzed how primary and secondary controllers will work towards improving the frequency quality.

2. Offshore wind vs. Pumped storage

In this work, the focus is on the interplay between offshore wind farms in the North Sea and the Norwegian hydro pumped storage possibilities. Increased production flexibility will be needed for the operation of a future power system with more uncertainty due to an increased share of uncontrollable generation from renewable sources; especially wind power. Introduction of pump storage in Norway might be able to effectively increase the production flexibility in the power system. While offering the possibility to store excessive power production from large wind power production in the North Sea during times of high wind production, stored energy can be fed back into the grid and support the power system during periods of low wind production.

According to the estimations made by the European Wind Energy association (EWEA) [3], the installed wind power capacity in Europe might accumulate up to 210 GW in 2020, of which more than 35 GW will be installed in the North Sea. This number increases to 96 GW offshore by the year 2030. This much penetration of wind power in the system results in highly variable generation, and therefore, the need for balancing power becomes cardinal.

Stronger interconnections combined with a large-scale development of wind power in neighboring countries connected with Norway will increase the demand for flexible hydropower production, *e.g.,* to provide balancing services. Increased hydro peaking will have an impact on the local ecosystem due to increased variations of the hydro reservoir level and river regulations. Tougher restrictions on the running of hydro power stations based on local environmental impacts may lead to a more limited utilization of the hydro reservoirs. The CEDREN[b] report [4] includes 19 specific power plants in southern Norway and analyses the potential of hydro power production expansion. The study carried out includes three different scenarios ranging from a capacity expansion of 11.2 GW to 18.2 GW. The report concludes that it is technically feasible to increase the power production of the Norwegian hydroelectric power stations by 18.2 GW without violating the existing environmental restrictions including limits for the highest and lowest regulated water level.

One of the large reservoirs in Norway is located in Tonstad and is expected to serve as a host for new pump storage unit. Tonstad is expected to be directly connected to the planned HVDC cable to Germany (NorGer). The NorGer HVDC link is expected to link the Southern Norway to Northern Germany.

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[b] http://www.cedren.no/

Furthermore, a future scenario is considered where two planned offshore wind production facilities in Germany, DanTysk and NordseeOst, will be connected to the same grid point as the end point of NorGer [5].

Fig 1 illustrates the correlation between the Tonstad pumping pattern and the German offshore wind production at wind facilities connected to NorGer HVDC cable, as found in [5]. The figure shows that pumping at the Tonstad hydropower station is correlated with the variation in wind production at DanTysk and NordseeOst. These results indicate that in the future power system with a large penetration of wind energy, the pumping strategy in the Nordic region will not only be influenced by seasonal inflows but also by the variability of wind production around the North Sea.

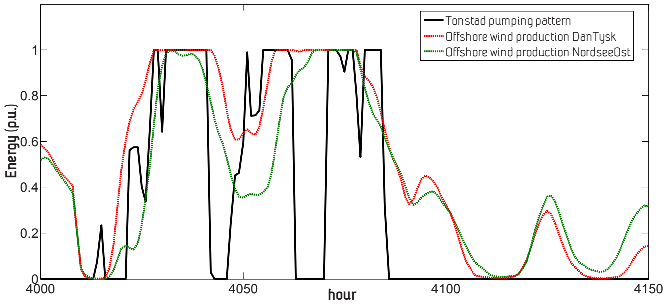


Fig 1. Production of German offshore facilities connected to the NorGer HVDC cable *vs.* pumping pattern in Tonstad (from [5])

3. Simulation model

The power system simulation model includes the Nordic and Continental European synchronous systems. The Nordic synchronous system consists of power systems of Norway, Sweden, Eastern Denmark and Finland; whereas the Continental European synchronous system consists of Western Denmark and the rest of UCTE. The four existing HVDC links that connect the two synchronous systems, *i.e.* Skagerrak 1&2, Skagerrak 3, Konti-Skan and Storebælt, are also included in the simulation model. In addition, the power flow on the NorGer, planned HVDC link between Norway and Germany, is also considered. Simplified representation of the Nordic synchronous system is used where each bus denotes one area with aggregated load and generation. The Western Danish power system, which is part of the European synchronous system, is modeled in detail while the rest of the continental European power system is represented by a large single bus such that system frequency deviation will remain within a ±0.2 Hz band if there is a sudden power imbalance of 3 GW[6] .

As a primary control 6% droop was used in all aggregated generators in the Nordic synchronous system and in the three largest thermal units in the western Danish power system. The rest of the generators in the simulation model have primary control with fixed dead-band frequency of ± 0.2 Hz.

Load Following Controller (LFC) on generators and Ramp Following Controller (RFC) on HVDC links were used as a secondary control. The three largest thermal generators participate in the LFC in Western Denmark which monitors the AC-connections between Denmark and Germany. According to the bilateral cross-border trade agreement between the two countries [7], every imbalance in the flow has to be compensated by national reserves. The LFC in Denmark has a total capacity of ±90 MW. Furthermore, LFC is also assumed in Norway. Its assumed capacity is ±375 MW and monitors the power flows on the AC-connections with Sweden and HVDC connection with west Denmark. The three largest aggregated hydro power plants located in the southern part of Norway are assumed to participate in the Norwegian LFC.

A power station with pump storage unit is included in the simulation model. It is located in the southern part of Norway and it corresponds to the Tonstad hydropower station in our model. It is therefore close to the connection point of the NorGer HVDC link. The pump storage station is modeled as a time varying positive or negative load, where positive load means water is being pumped back to the reservoir and therefore, the station is drawing power from the system, and negative load means the power station is generating power. It is assumed that there is a 2 minutes delay before generation begins after pumping is shutdown.

Initial power flow data for the all HVDC links except NorGer are taken from NordPool data from 11th November 2010, where a large storm passing through western coast of Denmark caused shutdown of offshore wind farm, Horns Rev 2 [8]. The initial data flow on the NorGer link and details for the Tonstad pumping station are taken from the market-grid analysis done in [5].

4. Controllers

Three different types of user defined controllers are used in the simulation study. They are Storm controller, Ramp Following Controller on HVDC (RFC-HVDC) and Load Following Controller (LFC). Each type of controller is described in detail in [8], but summaries on their main functionalities are presented here.

Storm controllers in wind turbines gradually ramp down power production when the wind speed reaches the threshold wind speed (~25 m/s). The power output variation is characterized by a smooth change of power ΔP within a time span of ΔT around the threshold wind speed. In this study work, it is assumed that a large storm causes shutdown of six offshore wind farms located in the western coast of Denmark that have a combined generation capacity of 2000 MW. It is assumed that wind turbines with storm controller, ramp down their production to total shutdown within 15 minutes.

RFC-HVDC controller follows the power change in offshore wind farm outputs and compensates the power variation by dynamically changing the power flow on the HVDC cables. RFC takes as an input the Area Control Error (ACE) created by wind power production and frequency variation and generates as an output the total demand of power change (ΔP_{TOT}) on the power flow through HVDC links. Power flows on Skagerrak 1&2, Skagerrak 3, Konti-Skan and Storebælt HVDC links are changed according to outputs RFC-HVDC controller attached to each of them.

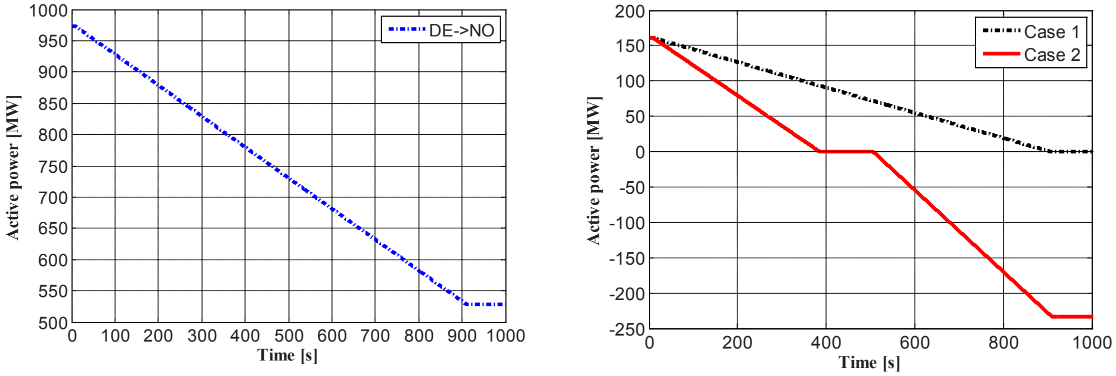
The LFC has the same control structure as the RFC-HVDC except that the input signal for power flow change, comes from deviations in power flows at control area borders. In addition, the total demand of power change (ΔP_{TOT}) is divided among "n" number of generators that participate in the LFC. In western Danish LFC, the area control error due to power flow is measured at the border connections between Germany and Denmark and the three largest thermal power plants are involved in the LFC. Similarly, the area control error at the border flows between Norway and Sweden, and between Norway and Denmark are handled by the Norwegian LFC by adjusting the output of the three largest aggregated hydro power plants in southern Norway. Initial power flows before the wind farm shut down occurs are used as reference (planned) power flow on the transmission lines at the control area borders.

5. Studied cases and simulation results

5.1. Case description

In the initial steady state, active power is flowing into the Nordic synchronous system from the Continental European synchronous area through all the HVDC links due to the high wind power production in the later power system. Skagerrak 1,2&3, NorGer, Storebælt and Konti-Skan cables carry 240 MW, 970MW, 590 MW and 100 MW, respectively. The power station with pumped storage unit in Norway is pumping water into the reservoir and consuming 160 MW.

Two different cases, Case 1 and Case 2, were studied. In both cases, wind farm shutdown due to storm passage causes a loss of 2000 MW generation in Western Denmark. The RFC-HVDC controllers dynamically change the power flows on the HVDC links to compensate for the lost wind power production in western Denmark. The LFC in Norway and western Denmark change the production of the generators attached to them to counteract the changes in control area border flows. At the same time, a 440MW reduction occurs in power flowing through NorGer due to wind power production change in Germany. See Fig 6 (a). Consequently, the pumping station, which is located close to the termination point of NorGer link, reduces pumping load and stops pumping. Two different rates of pumping are investigated in this study. In Case 1, the power station with pumping unit gradually stops pumping within 15 minutes. In Case 2, pumping is shut down and after 2 minutes power production begins and reaches 230 MW at the end of the 15 minutes studied period. See Fig 6 (b). Positive value implies load and negative value implies generation.



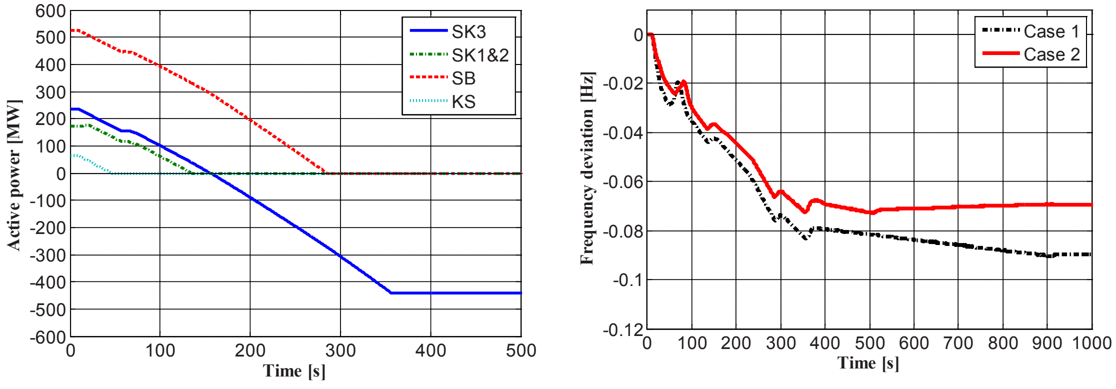
(a) (b)

Fig 2: (a) NorGer power flow; (b) Pumping load for Case1 and Case2

The effect on Nordic frequency quality as a consequence of combined effect of loss of large amount of offshore wind power due to storm, change in HVDC power flow and variation in pumping load is investigated in the simulations.

5.2. Simulation results

When a storm causes shutdown of wind farms in western Denmark, the RFC-HVDC controllers follow the change and try to counteract the imbalance by changing the power flow on the HVDC cables that connect the Nordic power system and the western Denmark power system. This causes the power being exported from West Denmark to the Nordic power system to decrease. Fig 3 (a) below shows the change in power flow on the HVDC cables that are controlled by RFC-HVDC controllers. Positive values indicate power flow from West Denmark to Nordic power system and negative values indicate vice-versa. Power export from West Denmark to Norway on Skagerrak1&2, Storebælt and Konti-Skan is reduced to zero, while power transmission on Skagerrak3 is reversed and at around 350s, SK3 is transferring its maximum capacity of 440 MW from Norway to West Denmark.



(a) (b)

Fig 3: (a) Power flow on HVDC links Skagerrak 1&2, Skagerrak 3, Storebælt and Kont-Skan; (b) Frequency deviation in Nordic power system

The LFC in Norway reacts to the power flow reduction on the Skagerrak links and the flow changes in AC-connection with Sweden, and increases the power production on the participating generators. However, the capacity of the primary droop controllers on the generators in the Nordic synchronous system and the Norwegian LFC (±375 MW) are smaller than the loss in production and change power flow in the HVDCs. Therefore, the frequency in the Nordic power system drops. The frequency deviation in the Nordic synchronous system for the two studied cases is presented in Fig 3(b). In both studied cases, the Nordic frequency has deviated from the desired frequency 50Hz. Case1, which has a slower rate of pumping shutdown, results in higher deviation than Case2, where the rate of pumping is relatively higher and power generation is started. Even though the frequency deviations found in the studied cases are significant, they are still within allowed limits of ±1Hz.

6. Conclusion

Future large offshore wind production variations in North Sea are likely to correlate with variable power flows between Continental Europe and Nordic region and water pumping storage periods [5]. Based on these results, analysis of two different pump storage situations is performed for a scenario with large wind power variations due to a storm shutdown of wind farms in the North Sea and change in the NorGer HVDC power flow between Continental European and the Nordic system. The effect on frequency quality for the Nordic region is investigated in these situations. RFC-HVDC control together with LFC in the Nordic region contributes to power system balance restoration. However, they will have an impact on the Nordic frequency quality. In addition, the rate of change of pumped storage in hydropower stations will introduce an additional load, which also affects the Nordic frequency.

In this paper it is shown how the relative rate of change in pumping stations with respect to the variations of wind power and flows between the Nordic and Continental Europe system / North Sea will affect the frequency quality in the Nordic region. In this sense, pumping can be used as a variable load in the Nordic system.

A representative case of offshore wind variability, pumped storage loads and power flow on the HVDC links connecting the Continental and Nordic power systems was used. Frequency deviations found the studied cases, although significant, are still within the allowed operational limits.

Acknowledgements

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