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Coordinated Control between Wind and Hydro Power Systems through HVDC Links

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Abstract

The main objective of this paper is to show how the control systems on wind farm turbines, HVDC cables and power generating units can be coordinated to improve power system balance in the event of a wind farm shut down due to a storm passing. The paper considers offshore wind farms located in West Denmark and HVDC cables connecting West Denmark with the Nordic system, where high shares of controllable balancing power are potentially available. The control systems investigated include turbine storm control, HVDC control and Load Following Control (LFC) in Denmark and Norway. The HVDC controller follows the ramp down of wind farm(s) production to compensate for the lost wind production, while the LFCs in Norway and West Denmark try to remove the area control error. Two cases were studied: A) Shut down of Horns Rev 2 (209 MW); B) Shut down of six planned offshore wind farms in West Denmark with combined capacity of 2000 MW. It is found that in both cases the coordination between the controllers either removes (Case A) or significantly reduces (Case B) the power imbalance, created in the Western Danish power system due to the shut down of the wind farm(s), by using hydro power generation in Norway, while keeping the frequency deviations in both power systems within acceptable levels. Such coordinated control will impact the current operation conditions in the region as well as require reservation of capacity on HVDCs and hydro power units.

Keywords: Storm control; Balancing power; LFC; Reservation of capacity on HVDCs; Offshore wind

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1. Introduction

There are ambitious plans for large scale deployment of offshore wind in Europe between 2020 and 2050 [1]. A high concentration of offshore wind power is expected around the North and Baltic seas [2]. Most of the planned wind farms will be connected to countries in North Europe *e.g.* Germany, The

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Netherlands, Belgium, UK and the Nordic countries. In Denmark, there is already ~3.8GW installed wind power today [3] and there are extensive plans for more wind power installation [2]. This will result in increasingly higher shares of variable and less controllable generation in the region. On the other hand, the Nordic power system has a high share of controllable hydro power units [4]. The eastern part of the Danish power system is part of the Nordic synchronous power system, while the western Danish power system, which has larger share of wind power, is not synchronously connected to the Nordic power system. The trend is, therefore, to investigate how to connect the northern Continental European synchronous system, likely to have increasing shares of variable generation in the future, with the Nordic system where comparable high shares of controllable balancing power are potentially available [4].

The main objective of this paper is to show how the control systems on wind farm turbines, HVDC cables and power generation units can be coordinated to improve power system balance in the event of a wind farm shut down due to a storm passing. The paper considers offshore wind farms located in West Denmark and HVDC cables connecting West Denmark with the Nordic system. This paper is organized in the following way: The studied power systems are described in Section 2. Section 3 illustrates the different types of controllers used in the simulations. The studied cases are introduced in Section 4. Simulation results and discussions are presented in Section 5, and the conclusions of the paper work are stated in Section 6.

2. Model description (Studied power system)

The studied power system comprises of the Nordic and the Continental European power systems including the HVDC links between the two regions. The Nordic synchronous system consists of simplified models of the power systems in Norway, Sweden, Eastern Denmark and Finland [5]. A 6% droop for each generating unit is used as primary control. The Western Danish power system, synchronously connected to the Continental European synchronous power system, is modeled in detail. The primary control is implemented by setting the three largest thermal power plants in West Denmark with a droop of 6 %, while the rest of the power generating units in the area have a dead band of ±0.2 Hz. The rest of the Continental European synchronous power system is represented by a single large aggregated 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].

Even though the Western Danish power system is part of the Continental European synchronous system, the system balancing is handled locally. The primary control is supported by the droop controllers and by importing/exporting the necessary primary reserve through the AC-connections to Germany that creates an Area Control Error (ACE) on the German-Danish border. The bilateral agreement regarding the trade over this border states that every imbalance in the flow has to be compensated by national reserves [7]. A central Load-Frequency control (LFC) system, which can counteract the border power imbalance up to ±90 MW, is currently in use in West Denmark. In the simulation model, the ±90 MW LFC is evenly distributed among the three largest thermal power plants in West Denmark. However, when large disturbances occur in the system, this ±90 MW LFC balancing capacity is insufficient. In such cases, the imbalance is removed by manual tertiary control in collaboration with the Nordic synchronous system through the NOIS-cooperation (Nordic Operation Information System) [8], so tertiary actions regulate either power plants in West Denmark or HVDC-connections to Norway, Sweden or East Denmark [9].

Today, there are three HVDC interconnections between West Denmark and the Nordic power system: 300 MW Konti-Skan link between Sweden and West Denmark, the 600 MW Storebælt link between East and West Denmark and three Skagerrak –links of totally 1000 MW between Norway and West Denmark. There is a plan to have a fourth HVDC connection between Norway and Denmark, Skagerrak 4, with a power rating of 700 MW [10].

The power system analysis simulation tool PSS/E [11] was used to run the simulations.

3. Control systems used in the simulations

Three control systems are implemented and simulated to analyze the response of the system in an event of wind farm shut down in West Denmark. These control systems are applied on different parts of the power system. The first control system is storm control which is implemented in each wind turbine in offshore wind farm(s) in West Denmark. The second is power control of the HVDC cables which connect West Denmark to the Nordic synchronous power system. The third control system considered is Load Frequency Controllers (LFC) which controls the thermal power generating units in West Denmark and hydro power units in the southern part of Norway. Each control system is presented in the next subsections.

3.1. Storm control

A storm controller is implemented in each wind turbine to delay the ramping from rated to zero power production during wind farm shutdown. A wind farm is modeled as a negative load in the simulations. This is a reasonable assumption considering that the most important parameter for modeling the storm control is the wind farm generation ramp down due to storm passage. Such ramp is modeled with a time span ΔT and a wind farm power production change ΔP, under the assumption that when the wind farm shutdown occurs, each turbine in the wind farm experiences wind speeds that exceed its storm control shutdown threshold (~25 m/s). Consequently, the wind farm gradually decreases production and eventually stops during ΔT.

Two different ΔP are investigated in this study over the time span of ΔT=15 minutes. The first ΔP represents the full shutdown of the Horns Rev 2 wind farm, which means ΔP=209 MW (Case A). The second ΔP represents shutdown of six wind farms (including Horn Rev 2), that have combined production capacity of 2000 MW, all located along the western coast of West Denmark (Case B).

3.2. HVDC control

The HVDC links between West Denmark and the rest of the Nordic countries are currently handled by manually setting P_{ref} in Fig 1. This is called "*constant current control mode*" and keeps the power flow fixed without regarding sudden changes in the areas that the cables connect [7]. This control mode is used in day-ahead spot market schedule and manual tertiary control. In this paper, automatic HVDC control is investigated.

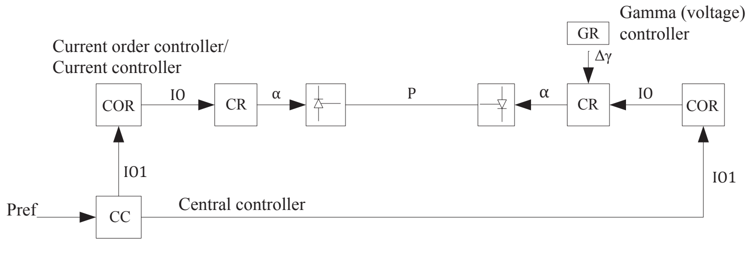

Fig 1: Constant current control mode [5]

The HVDC control system considered here is directly linked to the power output of wind farm(s). The block diagram for the dedicated HVDC control is identical to the one shown in Fig 1, but the input parameter P_{ref} is changed by a signal from a controller that measures the change in power production at the wind farm(s), and outputs a signal to the HVDC controller to counteract this power change. Such controller is based on earlier studies where a change in the governor set point can be adjusted as function of a ramp. We refer to such controller as Ramp Following Controller (RFC) [12].

3.3. Load Frequency Control (LFC) and Ramp Following Control (RFC)

In the Norwegian network model, standard hydro governor from PSS/E library (HYGOV) is used [11]. It compares measured generator speed with a reference speed and uses the error to decide gate opening of the turbine. Since this type of governor reacts to the speed measurements (and thus the system frequency), it is regarded as primary regulation. A more dedicated type hydro governor controller was used for Area Control Error (ACE): Automatic Load Frequency Controllers (LFC) [12]. The LFCs get their control signals from the ACE in two interconnected areas and regulate the production of the power generating unit(s) they are connected to, and make production follow the change in power flow in accordingly. Fig 2 shows the block diagram of the main controller used in this study [12] both for RFC and LFC controls.

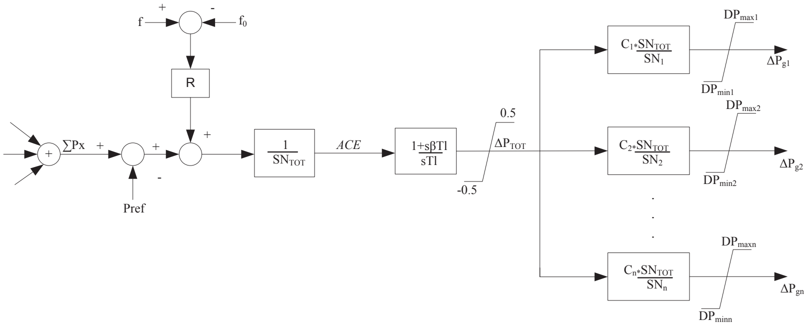

Fig 2: RFC & LFC block diagram [12]

The inputs to the controllers are twofold. The first input is power flow change in megawatts (ΣP_x). This signal is compared with the planned power flow in the transmission lines, and the difference is used as a control signal due to power flow imbalance. In the case of HVDC ramp following control, ΣP_x is related to the change in production for the wind farm(s). In the case of area LFC, ΣP_x is the power flow through HVDC links and/or control area borders. In general for the LFC, both frequency and power flow deviations will result in ACE. The second input is deviation from normal system frequency. For the RFC, this is implemented in order to avoid change in normal system frequency that may arise from following change in power flow, ΣP_x. The frequency bias setting R of the controllers do not have to correspond exactly to the power systems' power-frequency characteristics, as the integrator will ensure that the ACE is eventually returned to zero. However, it should not deviate too much from the power-frequency characteristics, as this might lead to undesirable controller movements [5].The control signals due to change in power and change in frequency are added to give the total control error which is fed to a PI controller to generate a total demand of power production change (ΔP_{TOT}). It is also possible to use an integral controller I, but this does not change the results significantly. The choice of integration time constant TI is not critical for the control function as long as it is kept within reasonable limits. However, the system performance, and even stability, is quite sensitive to the size of the proportional gain β which must always be kept less than 1. Changing TI does not improve the situation if β is given large value [5].

ΔP_{TOT} is then distributed amongst the attached “n” generating units according to their ratings. In the Western Danish system, the area control error between Germany and Denmark is handled by the Danish LFC by changing power production on the three largest power units. Correspondingly, three hydro generators in the southern part of Norway are used in the Norwegian LFC. In both power systems, initial power flows before wind farm shut down occurs are used as reference (planned) power flow on the transmission lines. In the Norwegian power system, the LFC is used to counter balance the change in flow in the Skagerrak cables. On the other hand, the flow on the HVDC links considered (Skagerrak 1&2-3, Konti-Skan, Storebælt) changes by following the changes in wind farm production. Note that the RFC controller shown in Fig.2 has been implemented for each HVDC individually rather than one single LFC for the whole area *i.e.* each link receives its own ΔP_{TOT}.

4. Studied cases

Two main cases are studied in the simulations. The first case, Case A, simulates shut down of an offshore wind farm located in West Denmark, Horns Rev 2 (HRB), which has a production capacity of 209 MW. The second case, Case B, is a hypothetical case with shut down of six (planned) offshore wind farms producing a total of 2000 MW. This case is particularly relevant considering the future plans for large scale offshore wind development.

In both simulated cases, it is assumed that the wind farm(s) come to a complete shut down after passage of a storm front. The initial power flow on the German-Danish border is 960 MW flowing from Germany to Denmark in Case A and ~ 800 MW flowing from Denmark to Germany in Case B. The initial power flow on all the HVDC links, in both cases, is from West Denmark to the Nordic system, representative of the typical export situation of West-Denmark due to high wind production under storm conditions. In Case A, both Skagerrak 1&2 and Skagerrak 3 cables carries 240 MW while Storebælt has 590 MW and Konti-Skan has 0 MW flow. The initial power flows on the HVDC links for Case B are the same as Case A except the flow on Konti-Skan is 100 MW. These flows are selected based on the data received from the Danish TSO Energinet.dk for HVDC power flows on 11th November 2010 before a storm hit Horns Rev 2. The LFC in Denmark has ±90 MW regulating capacity, while ±375 MW is reserved for the LFC in Norway. In both cases, identical controller settings, i.e. R, β and TI, were used for each LFC. However, larger β and TI were chosen for the LFC in Norway than the one in Denmark. Data received from Energinet.dk was used to select Danish LFC parameters.

For each case, it is investigated how the coordination between the different controllers can remove/improve the imbalance caused by the loss of offshore wind power production. The power flows on the HVDC links and the German-Danish border, which are used as an input to the LFCs in both regions, and the corresponding hydro and thermal generators in Norway and West Denmark involved in the LFC control are studied. In addition, the frequency deviation in the Nordic region is also studied.

5. Simulation results and discussions

5.1. Case A: Shut down of Horns Rev 2, ΔP=209 MW

The imbalance that is investigated in this case is a shutdown of the wind farm Horns Rev 2 during a storm. The wind farm shuts down when the mean wind speed at the wind turbine controller reaches the shut down threshold of 25 m/s or higher for a prolonged period of time. In the simulations, it is assumed that a storm controller is applied on each wind turbine in the wind farm, so the duration over which the wind farm shuts down is set to 15 minutes. This is the relevant time to provide automatic storm control within the range of secondary regulation.

Without regarding potential manual control due to forecasts, the ramping of Horns Rev 2 will generate an imbalance of power on the border between Germany and Denmark. The German-Danish border imbalance is the deviation of the power flow from the planned value. This imbalance has to be eliminated according to grid codes and international agreements [7]. It is used as an input signal for the LFC controller in West Denmark, which demands an increase in production from the generators connected to it. The dash-dot curve Fig 3(a) shows the power output of one of the three thermal power plants connected to the LFC controller. It has a ±30 MW band of regulating power for the LFC unit to utilize. The dash-dot curve in Fig 3(b) shows that the imbalance at the German-Danish border still remains even after production increase from the thermal units. This is because the power loss is greater than 90 MW, which is the maximal output of the Western Danish secondary LFC control unit. The remaining imbalance (around 110 MW) has to be handled manually by increasing production or importing (reducing export) power. Today storm forecasts and other tools are used in order to minimize border imbalances (planed versus actual production) before they occurs [9].

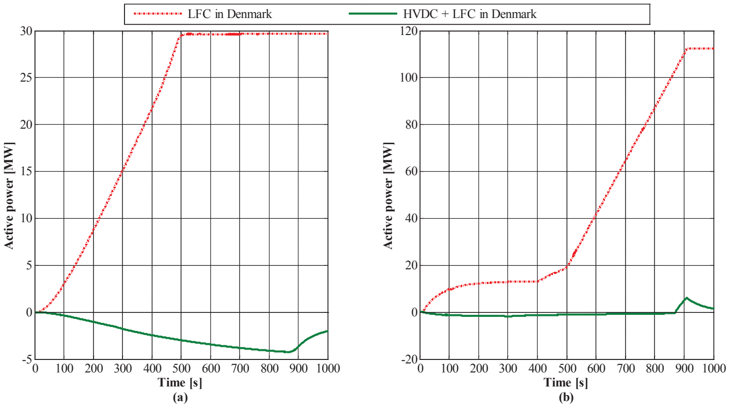

Fig 3: (a) Power production from one of the thermal units that are involved in LFC control in Denmark, and (b) Imbalance at the German-Danish boarder

The solid curve in Fig 3(a) shows the output of the thermal generating unit when an RFC-HVDC controller is implemented on Skagerrak 3 in addition to the Danish area LFC, allowing dynamic change of power flow on the cable to counteract the reduction in production from Horns Rev 2. The change of thermal power output is very small because the imbalance on the German-Danish border (see Fig 3(b)) is almost eliminated when RFC-HVDC-control and LFC in Denmark are used.

However, there are some negative implications of transferring imbalances (approximately 200 MW) from a huge system like the Continental European synchronous system, to a smaller system like the Nordic synchronous system where the frequency is a lot more sensitive to power imbalances. The solid curve in Fig 4(a) shows the frequency deviation of the Nordic synchronous system for the cases where the Danish power imbalances are transferred to this system, and when no countermeasures are applied other than primary regulation. This brings the Nordic frequency down by 0.015 Hz as shown in Fig 4(a). This deviation would today be handled manually in the balancing market. The solid curve Fig 4(b) shows the output of one of the Norwegian aggregated hydro power units increasing its output by 16 MW due to primary control. Each aggregated power plant in the Nordic synchronous region contributes with the same percentage of its rated power by following a droop of 6%.

The frequency deviations created in the Nordic power system due to using HVDC-control can be significantly improved by introducing automatic LFC control in addition to primary control. The dashed curve in Fig 4 (a) shows the frequency deviation in the Nordic system is very small when an LFC controller is used to change production outputs of three aggregated hydro units in southern Norway to counteract the change in power flow on Skagerrak 3. The dashed curve in Fig 4(b) shows an aggregated hydro power plant output changing its production by about 80 MW when it is used as one of the controlled units in the Norwegian LFC system.

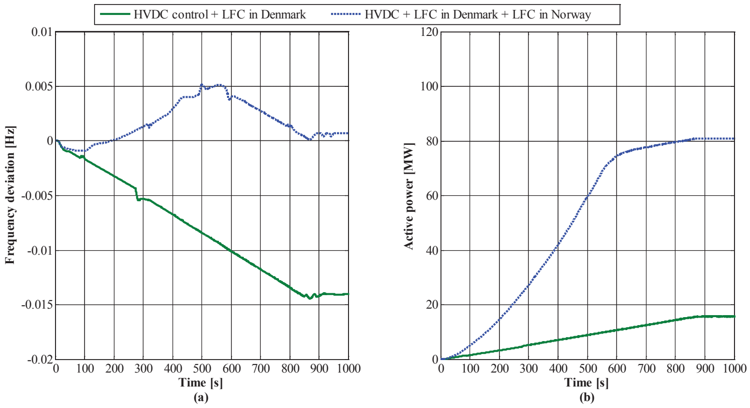

Fig 4: (a) Nordic frequency deviation; (b) Power production from one of the hydro power generation units that are involved in LFC control in Norway

5.2. Case B: Shut down of six offshore wind farms, ΔP=2000 MW

In this case a power imbalance caused by shut down of six offshore wind farms with combined total power production of 2000 MW is investigated. As in Case A, it is assumed that the wind farms shut down because of wind speed greater than 25 m/s and that a storm controller is applied on each wind turbine so the wind farm(s) shut down within 15 minutes.

Since the production loss due to wind farm shut downs is very large in this case, HVDC controllers are implemented on all four HVDC links that connect West Denmark with Nordic power system. The power flows on Skagerrak 1&2, Skagerrak 3, Konti-Skan and Storebælt are changed to counteract the reduction of power production at the six wind farms. Danish and Norwegian LFCs are used to regulate the power flow change on the German-Danish border and on Skagerrak 1, 2&3 cables, respectively.

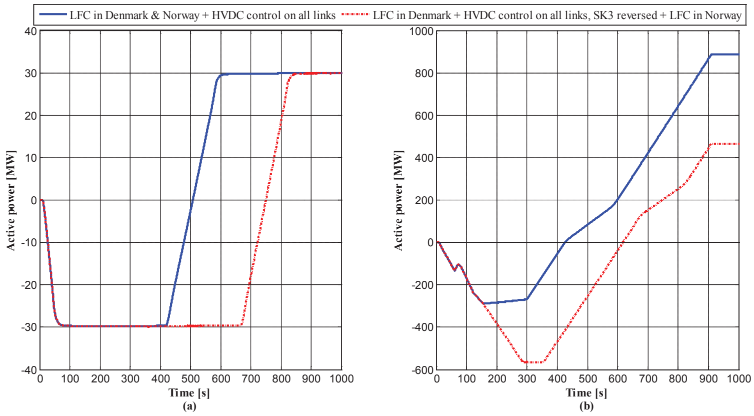

Fig 5: (a) Power production from one of the thermal units that are involved in LFC control in Denmark, and (b) Imbalance at the German-Danish border

Fig 5(a) shows power output from one of the thermal generating units in West Denmark connected to the LFC. The output of the generator decreases by 30 MW immediately after the wind farms' productions start ramping down. This is because the imbalance that is created at the German-Danish border (used as input to the Danish LFC) is negative. See Fig 5 (b). This means that there is more power in the Western Danish power system than planned and the result is less power following into West Denmark than planned via the border connections. The reason for the excess power observed in the Western Danish power system, even when the system is losing power due to wind farm ramp downs, is because the change in power flow in the HVDC-cables that counteract the reduction in power production is faster than the change in production itself. In other words, the HVDC-controllers are over compensating.

But as the HVDC cables stop ramping because they have reached zero power flow, the real imbalance at the German-Danish border becomes visible. This can be seen in Fig 5(b) after 400 and 600 seconds for the two curves as the imbalance becomes positive. In this the case, the LFC in Denmark orders the thermal generating units to increase their production by 30 MW, compared to the initial production level, in an effort to keep the imbalance to zero. The dash-dot curves in Fig 5 shows the effect of reversing power flow on the 450 MW Skagerrak 3 cable so that power flows from the Nordic to the West Denmark system. As can be seen from Fig 5(b), reversing the power flow on Skagerrak 3 reduces the steady state imbalance at the German-Danish border but it doesn't completely remove it.

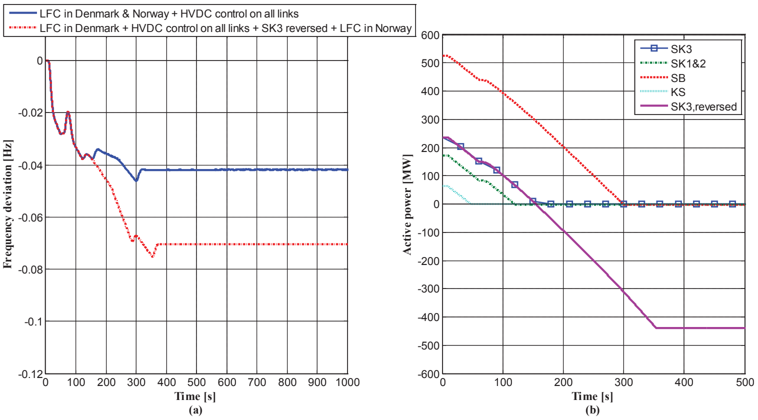

Fig 6: (a) Nordic frequency deviation; (b) Power flow on the four HVDC links that connect West Danish power system to the Nordic power system

The Nordic frequency deviation is shown in Fig 6(a). Changing the power flow on the HVDC links to reduce, and eventually stop, the power export from the Western Danish system to the Nordic system brings the Nordic system frequency down by a bit more than 0.04 Hz. This is because of the large amount of power that was being imported to the Nordic synchronous system before the wind farms' shut down occurred. The production increase in the Nordic system by the three generators connected to the Norwegian LFC (374 MW) and the rest of the aggregated generators, that follow their droop curve, are not enough to compensate for the power that was being imported via the HVDC links. Fig 6 (b) shows the change in flow on the HVDC links regulated by the RFC-HVDC controller. Small spikes are observed on the frequency curves in Fig 6(a) as power flow on each HVDC links reaches zero. Reversing the power flow Skagerrak 3 creates even more frequency deviation, 0.07 Hz, in the Nordic system.

6. Conclusions

It is shown that by using storm controllers and HVDC controller, the imbalance at the German-Danish border caused by un-planned shut down of Horns Rev 2 (209 MW) can be completely removed. It is also shown that the frequency deviations that arise in the Nordic synchronous system, when using Skagerrak 3 to counteract the reduction in wind farm output, can be avoided by using LFC in Norway. When shut down occurs for several winds farms with large total production output (~2000 MW), it is not possible to completely remove the border imbalance with the controllers that are implemented in this study. Coordinated use of storm controllers, HVDC controllers on all HVDC links between West Denmark and Nordic system, and LFCs in Denmark and Norway allows to significantly reduce the imbalance. This coordinated action creates a frequency deviation of ~0.04Hz in the Nordic system within the allowed limits. Furthermore, reversing power flow on Skagerrak 3, so that more power can be imported into the Western Danish system, helps in reducing the border imbalance but increases the frequency deviation in the Nordic system up to ~0.07Hz. Allowing further import of power into the West-Danish system by reversal of (any of) the remaining HVDC links will remove the Danish imbalance, but at the same time cause a frequency deviation in the Nordic system larger than the 0.1Hz allowed limit [7].

This paper demonstrated, for both studied cases, that exporting the imbalance to Norway is feasible and advantageous to the West Danish power system. However, the presented balancing actions require reservation of capacity on HVDC links and generation units in Norway if they were to be implemented in the real system.

Acknowledgements

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