The multiDC project: Research Towards a Holistic Integration of HVDC Links into Large-Scale AC Power Systems

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Abstract

In this paper, strategies for a holistic integration of multiple HVDC links into existing power systems are presented. High Voltage Direct Current (HVDC) links can support the operation of AC grids on different timescales. Contrary to AC transmission lines, the power flow on HVDC links can be freely controlled. Due to their ability of rapidly controlling the power transmitted, they can help to stabilize the dynamic system response of interconnected power systems, e.g. providing fast frequency response. Moreover, they can be an important tool in controlling and in optimizing the operation of interconnected power system. In this paper, different strategies are presented, then their benefits and potential challenges are discussed.

Keywords— High Voltage Direct Current (HVDC), Emergency Power Control, Frequency Containment Reserves, Low- and Zero-inertia, Electricity market, Loss Factors, Frequency Reserve Sharing

1 Introduction

The ambitious plans of countries around the world to reduce greenhouse gas emissions [1] and the resulting change from power generation based on fossil fuels to Renewable Energy Sources (RES) poses large challenges for the existing power systems. At the same time, the number of interconnections between countries is growing around the world. The Transmission System Operators (TSOs) of Denmark, Finland, Norway and Sweden, published plans for a significant number of new interconnections in their joint grid development plan [2]. Several of these interconnections stretch over long distances and interconnect asynchronously operated power systems, e.g. Norway with the UK. Consequently, the only technology option for these interconnections is High Voltage DC (HVDC) links. The transmission of power using HVDC technology can provide a number of benefits from a technical as well as an economical point of view [3]. Three benefits are subsequently discussed in more detail.
1) *HVDC links offer high controllability.* The transmitted power is fully controllable and by increasing the flexibility of the grid higher shares of RES could be integrated into the system. Research has shown that, in power systems with high penetration of RES, increasing the transfer capacity of interconnectors reduces the required balancing energy. In [4], the authors calculate that, in a fully renewable European power system, increasing the interconnectors capacity by 5.7 times results in a reduction of the needed balancing by approx. 37 %. Furthermore, due to the ability of HVDC links to very fast adjust active and reactive power independently, they could be used to support the interconnected AC grids.
2) *HVDC links are the best option for power transmission over long distances*, e.g. through submarine cables. Consequently, they can make offshore sites with very good wind conditions, but far from shore, accessible. In order to reach the ambitious climate goals in Europe set in [1], utilizing wind resources located far from shore will be essential. The authors of [5] estimate that in order to realize a fully sustainable power supply in Europe by 2045 a total of 230 GW wind power need to be installed and of this 180 GW in the North Sea. This huge challenge resulted in the foundation of a Danish, Dutch and German consortium to explore the possibility of developing wind power hubs in the North Sea [6]. These will be located far offshore and are connected to shore via HVDC links. Preliminary studies deal with the feasibility of building hubs to collect the power from thousands of offshore wind turbines with a total capacity of up to 36 GW [7]. In order to realize such hubs, new concepts for its operation need to be developed.
3) *HVDC links can be used to interconnect asynchronous power systems.* By creating a more interconnected power system, security can be increased, e.g. by means of sharing system service. From a market view point an extension of the interconnections enables to exchange power between more countries and this can help to decrease price differences. For example, the interconnection between West and East Denmark, Storebælt, has decreased electricity prices in East Denmark by 2 €/MWh in average

since 2010, resulting in $20-25$ million euro savings per year for Danish consumers [8]. Another example is NordBalt, the link between Sweden and Lithuania: electricity prices in Lithuania dropped by 30 % when the link was operated for the first time in 2016, followed by an average decrease of 5 €/MWh compared to before 2016 [9]. In order to optimally utilize the benefits of existing and future HVDC links, additional research efforts are needed. The development of advanced control and optimization methods for AC and HVDC grids is the topic of the multiDC research project (www.multi-dc.eu). In this paper, recent results of the project are presented and references to the published works are provided.

2 HVDC links for the interconnection of AC systems

Due to the increased integration of RES, power systems are gradually shifting from synchronous-based to converter-interfaced power generation. As RES units usually produce electricity at lower marginal costs (sometimes zero), synchronous generators are often replaced by RES in the market dispatch. Consequently, system parameters, such as inertia and system damping can no longer be considered constant, but instead they may vary significantly over time. This influences greatly the system's frequency dynamic behaviour, e.g. the Rate Of Change Of Frequency (ROCOF) and the damping ratio of electromechanical modes, which are affected by the absence of rotational inertia, Power System Stabilizers (PSS) and damper windings, respectively [10]. Conventional power plants are also responsible for providing various system services, such as Short Circuit Capacity (SCC) and frequency control. Frequency control is partly provided inherently, due to the generators' inertia, and through dedicated controllers, e.g. frequency droop controllers, which contribute to the system's Frequency Containment Reserves (FCR). After a large disturbance causing an active power imbalance, FCR ensures that the active power balance is restored, and frequency is stabilized. If conventional power plants can no longer provide these services other solutions need to be developed. Due to their controllability, HVDC links are good candidates to provide such services and help stabilizing the system. However, system conditions like a low SCC can also cause issues in the operation of HVDC links, which may require advanced controls.

2.1 Dynamic limit of the power transfer capability of HVDC links

To ensure stable grid operation and safe integration of HVDC interconnectors in weak power grids with low SCC, transmission system operators need to perform a series of analyses. In [11] the controller parameters of an HVDC Voltage Source Converter (VSC) were tuned. Then the performance of a grid-following and a grid-supporting VSC under sudden changes of SCC were investigated. To select the control parameters of the PLL-based vector-control of the two VSCs, either operating in a purely grid-following or a grid-supporting mode, modal analysis were performed in [11] and [12]. The findings and conclusions are summarized in the following five points.

1) *Fast active power control*: Accelerating the response of the controller deteriorates small-signal stability.

2) *Voltage control vs active power control*: The range of stable operating points is increased, when the VSC's voltage control is faster than its active power control.

3) *PLL response time*: The time constant of the PLL should be carefully tuned. It was found that time constants in a certain range resulted in an unstable system response, while PLL time constants below and above that range resulted in a stable system response.

4) *Frequency droop control*: This control increases the damping of modes associated with the state variables of the VSC.

5) *Voltage control vs const. reactive power control*: In weak grids, an AC voltage controller is preferable to a constant reactive power control.

To investigate the dynamic active power transfer limit of VSCs, a large disturbance analysis was carried out in [11] and [12]. In [12], it was shown that the transfer limit determined by small-signal stability analysis may be too optimistic, depending on the sequence of events leading to the SCC depression. In [11], the analysis was extended to investigate grid-supporting converters. The results showed that the dynamic active power transfer limit of a grid-supporting converter is higher than of a grid-following converter. The reason is that grid-supporting converters are equipped with a P/f droop characteristic. During sudden changes of SCC, a sudden change in angle occurs. The active power loop detects this as a sudden change in frequency and the transferred power is temporarily decreased. This gives the voltage controller time to restore the voltage. Figure 1 shows simulation results were the performance of a grid-supporting and a grid-following converter are compared. For further details, the reader is referred to [11].

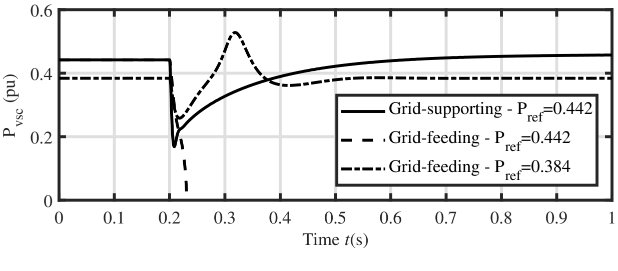

Figure 1 Comparison of the active power response of a grid-following and a grid-supporting converter to a sudden decrease of SCC [11].

2.2 Robust frequency control in varying inertia systems

To compensate for the varying time profile of system inertia and damping, a robust frequency control design for grid-supporting VSCs is needed. The control design has three objectives: (i) reduce the ROCOF, (ii) increase the damping of electromechanical modes and (iii) rely only on local measurements. Several methods can be applied for solving this problem. In [10], the H-∞ loop shaping methodology was chosen as the preferred one, because it allows to assign desirable properties to the controller, such as tracking performance, disturbance rejection, frequency filtering effect and cut-off frequency. For the control design, in this study only structured controllers were considered. These controllers, such as PID, lead-lag controllers, etc. are preferred, since they are easy to implement and retune whenever performance or system properties change. In Figure 2, the singular values of the resulting controller are shown. The controller has zero gain at low frequencies, which means that the system is not affected within that range. At mid-range and higher frequencies, the controller achieves a negative gain. Consequently, it will increase the damping ratio and decrease ROCOF as well as maximum frequency deviation. For further details, the reader is referred to [10].

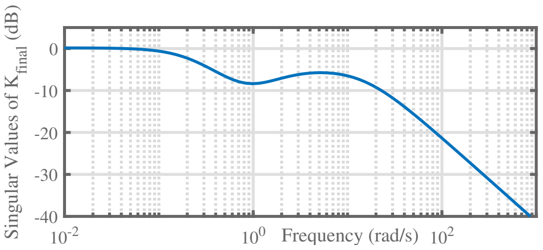

Figure 2 Resulting singular values of a robust frequency controller of a VSC obtained with the H-infinity loop shaping methodology [10].

2.3 HVDC emergency power control

Due to the controllability of HVDC links, they can be used to support the grid in emergency conditions, e.g. for exchanging emergency reserves between asynchronous zones. This could be achieved by adding a supplementary power control to HVDC converters in the form of Emergency Power Control (EPC). The effectiveness of this approach is demonstrated on a test case representing the Nordic Power System (NPS) in [13].

The power balance in a power system is defined as:

$$\Delta P_{sys} = \sum P_{mech} - \sum P_{elec},$$

where $\sum P_{mech}$ and $\sum P_{elec}$ are the sums of the mechanical and electrical power of all synchronous generators connected to the system. Therefore, for the scope of this analysis, a single machine equivalent model of the NPS can be used as stated in [13] and [14].

FCR are deployed to limit the maximum Instantaneous Frequency Deviation (IFD) after a disturbance. To ensure a certain quality of power supply, limits on the maximum IFD are imposed by TSOs: in the NPS, frequency must not drop below 49 Hz. The requirements for units participating in the provision of FCR are described in [14] and are used in that work to assess how system stability is improved using the EPC functionality. The first finding is that, with the current FCR requirement, additional fast power support is needed in case of low inertia conditions, since the frequency may drop below 49 Hz following a large loss of generation.

In the NPS, the EPC functionality is already implemented on most of the HVDC interconnectors. The current parameters of the EPC ramp/step functions are provided in [15], and the basic principles are illustrated in Figure 3. This functionality is used only in case of large frequency deviations. When the frequency drops below the activation level, and remains there for a certain time, the power injected through the link is increased with a constant power ramp (MW/s) until the EPC capacity (MW) is reached. One HVDC link may have several steps of activation with different ramp rates or capacity (see the blue dotted curve in Figure 3). In [13], the drawbacks of these EPC settings were investigated. The main weaknesses are the slow response and the lack of a feedback loop, which becomes apparent in large values of the sensitivity function peak M_S of the closed loop system [16]. These weaknesses may result in a prolonged increase of HVDC injections even after the maximum IFD was reached [13], [15].

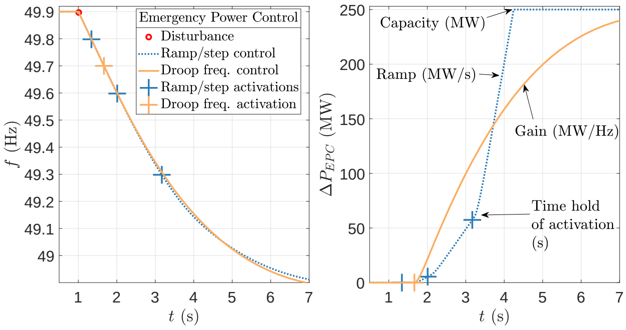

Figure 3 The working principles of the EPC methods.

2.3.1 Improved settings for the step-wise trigger

In order to avoid these issues, modifications of the ramp/step EPC settings are proposed, which avoid unnecessary large HVDC power injections. In this case, all HVDC links have only one step with unique control parameters of activation, time hold, and ramp rate. A comparison of the system response between the current EPC setting (EPC Nordic), and the modified EPC settings (Eq. Ramp) with two different levels of activations are shown in Figure 4. Results are provided for the dimensioning incident (loss of 1450 MW generation) with system inertia equal to 100 GWs. Both methods could provide a satisfactory IFD value of $\Delta f = 0.9$ Hz, with the modified EPC settings reducing the additional power provided by the HVDC links. However, there are still over frequency issues, and a poor closed-loop stability margin.

2.3.2 Novel control: Frequency droop-based EPC

In order to improve the overall system frequency response, the implementation of a frequency droop-based EPC was proposed in [13]. The control method is based on a frequency deviation input and a proportional power output,

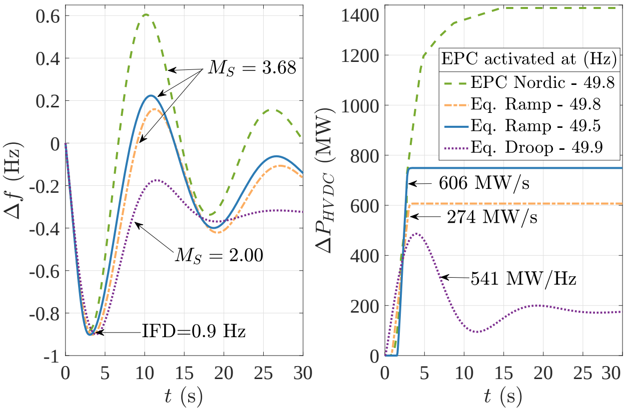

Figure 4 System response comparison for ramp/step and droop frequency-based EPC methods.

as illustrated in Figure 3 (yellow solid curve). By setting an appropriate HVDC gain (MW/Hz), the maximum allowed IFD is not exceeded, and the closed-loop margin is significantly improved, as it can be observed in Figure 4. Moreover, it was shown that the frequency droop-based EPC can achieve the desired system frequency response for various inertia levels, even for a value equal to 60 GWs, which is considered extremely low in the NPS. Figure 5 shows the frequency nadir (Hz - left figure) and the power injections (MW - right figure) for different values of total HVDC gains (MW/Hz). As shown, the frequency droop-based EPC can provide efficient support during low inertia situations, given that HVDC gains are adjusted to the system inertia. Moreover, they can significantly reduce the amount of needed power reserves. For further details the reader is referred to [13].

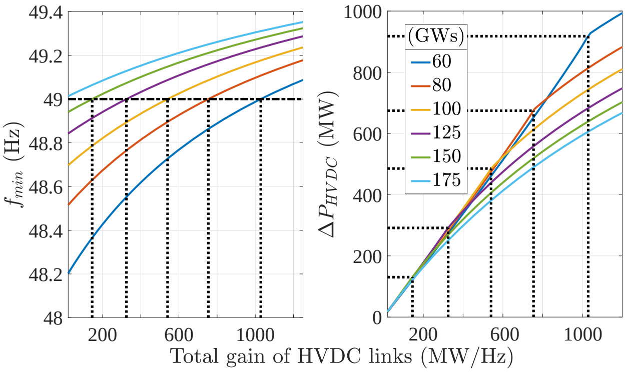

Figure 5 The required values of HVDC gain and power in the case of frequency droop-based EPC and various inertia.

2.4 Optimal operation of HVDC links

HVDC technology is the most cost-efficient option for long-distance transmission lines, submarine power cables and asynchronous interconnections. On the one hand, HVDC interconnectors are of great value for society as they facilitate the exchange of energy and ancillary services between countries. On the other hand, HVDC operation comes with a cost for TSOs as HVDC interconnectors produce a non-negligible amount of losses that is currently not considered in the market clearing.

2.4.1 Cost savings from reserve sharing through HVDC links

During summer 2018, the kinetic energy in the Nordic System dropped below 150 GWs three times, jeopardizing the N-1 security of the system. In those situations, the occurrence of the dimensioning incident (the disturbance used to set the requirement for frequency reserves) would have caused an IFD greater than the allowed maximum of 1 Hz. To deal with this problem, Svenska kraftnät ordered the reduction of the power output of Oskarshamn 3, whose loss is the dimensioning incident. The costs associated with these power limitations in 2018 amount to approximately 0.8 million euros. Given that more and more low-inertia periods are expected in the coming years, this calls for a reassessment of whether there exist cost-efficient options which guarantee safe operation while avoiding redispatching actions. Such options were investigated in [17] and the findings are summarized here. As discussed in Section 2.3, the controller of HVDC converter can operate in a frequency sensitive mode, i.e. the power flow is adjusted in response to a frequency deviation. For this reason, an HVDC link connecting asynchronous areas can be used to provide frequency reserves: to limit the IFD in case of a disturbance, the necessary active power can be imported from the neighbouring system in the form of EPC. With this mitigation strategy, the possible costs for Nordic TSOs would only be the reservation of HVDC capacity and the procurement of primary reserves in the neighbouring countries. In addition, the costs associated with HVDC EPC would be incurred only for those hours when the frequency can fall below 49.05 Hz whereas the reduction of the dimensioning incident would be prolonged for more hours due to technical limitations. The results in [17] show that, if the EPC functionality was used, the costs in 2018 could be reduced to 0.27 million euro. The extension of the analysis to year 2020 and 2025 suggest that HVDC EPC would reduce the costs by 70 %, resulting in cost savings in the range of 1.7 – 16.16 million euros per year by 2025.

2.4.2 Internalizing HVDC losses in market clearing

Contrary to AC lines, HVDC interconnectors are often hundreds of kilometres long and produce a non-negligible amount of power losses, which are not considered in the current day-ahead market clearing process. In case of equal zonal prices between neighbouring bidding zones, the cost of HVDC losses cannot be covered because of the zero-price-difference, and the cost is transferred to local TSOs. For this reason, Nordic TSOs have proposed to introduce linear loss factors for HVDC lines to avoid HVDC flows between zones with zero price difference [18]. In [19], a rigorous framework was developed to assess this proposal; however, the results showed that the benefits of such a measure depend on the topology of the investigated system. Therefore, different loss factor formulations were tested on the Nordic power market. It was concluded that, in general, linear HVDC loss factor are not a good solution for this problem in transmission networks with parallel HVDC paths or parallel AC and HVDC paths (Figure 6).

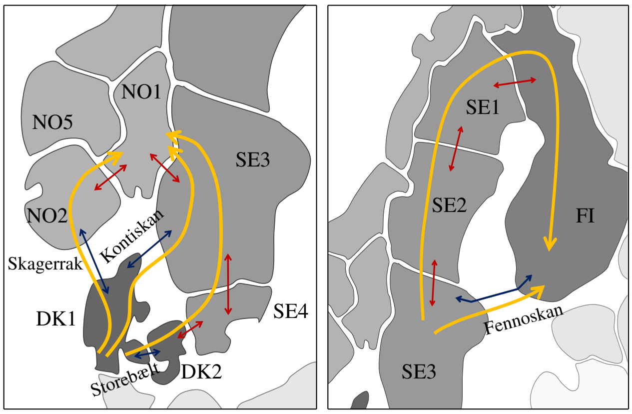

Figure 6 The required values of HVDC gain and power in the case of frequency droop-based EPC and various inertia.

The results in [20] show that there is room for improvement in two directions. First, by using piecewise-linear loss factors. This leads to a better representation of the loss functions, resulting in further decrease of losses and higher cost savings. Moreover, piecewise-linear loss factors allow for a better distribution of power flows among interconnectors, avoiding line discrimination (important in case of merchant lines). Second, by introducing also AC loss factors. HVDC loss factors may disproportionately increase AC losses; the inclusion of AC loss factors helps identifying the optimal paths that produce the least amount of losses, maximizing cost savings (losses could be reduced by 12 %, resulting in 4.8 million euros cost savings per year). Implementing such measures in real systems is possible: for instance, piecewise-linear loss functions are already used in real power exchanges, e.g. NZX, and several power markets in the US already use sensitivity factors to determine AC losses.

3 HVDC links for massive renewable energy integration

The best wind power reserves are often far offshore, where the winds are more steady and the average wind speed is higher. In a Danish-Dutch-German effort to tap into this huge potential, the three TSOs are investigating the concept of wind power hubs to harness the wind resources in the North Sea [6]. These hubs are artificial islands where the wind power generated far offshore is collected and transmitted to onshore power systems. Due to the long distances to shore, HVDC transmission is the only feasible solution. The HVDC links serve two purposes. First, they are used to transmit the harnessed wind power to shore. Second, they can be utilized to allow power exchange between the countries interconnected through the hub. For realizing the interconnection of a hub with the onshore AC power system either a multi-terminal HVDC grid could be used or multiple point-to-point HVDC links. The first option was not investigated in the multiDC project, due to the lack of experience with DC circuit breakers. In the second option, multiple point-to-point HVDC links interconnect the hub with the onshore AC systems, while an offshore AC system is used to connect the wind farms to the hub. Two approaches are further investigated for the offshore AC system, which are referred to as zero-inertia and low-inertia approach.

3.1 Zero-inertia approach

The zero-inertia approach includes multiple grid-forming converters operating in parallel, controlling the voltage at their individual terminal. A sketch is shown in Figure 7. Each offshore VSCs is equipped with a frequency droop control scheme, which is used to correct any active power imbalance in the offshore AC grid (in the absence of local energy storage). An example response to a loss of one wind power plant is shown in Figure 9. The objective is to distribute the change in power among the converters in the zero-inertia systems based on predefined participations. Moreover, the output voltage of each offshore converter is controlled. The reactive powers injected/absorbed by the offshore converters react to voltage deviations on the point of common coupling caused by reactive power imbalances in the system. In order to assess the stability of such a system, there are several aspects that need to be addressed. In the following, two of them are discussed. The first aspect concerns the controller tuning of the grid-forming converters, while taking into account the effect of the network line dynamics on the stability of the converter. In [21], an algorithm is presented to determine the controller parameters of a grid-forming converter. The parameters are tuned to optimize the damping using small-signal stability analysis. The second aspect is related to the modelling of inverter-based offshore systems. While a detailed modelling of the system dynamics, using ElectroMagentic Transients (EMT) models, increases the accuracy of stability analyses, it also increases significantly the required computation time of simulations. Particularly,

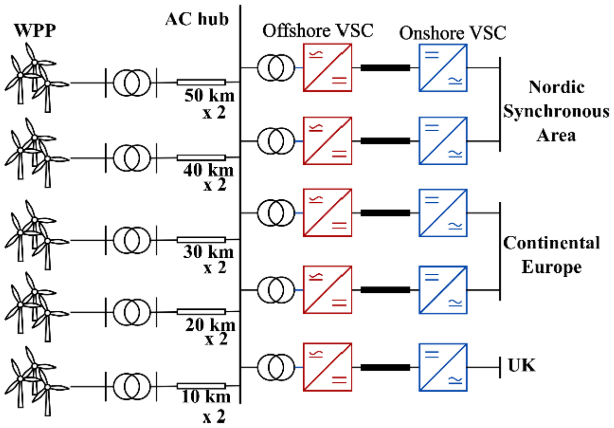

Figure 7 North Sea Wind Power Hub zero-inertia configuration.

when a part of the interconnected large-scale AC system needs to be simulated. This may become an issue, when online dynamic security assessment analyses should be carried out in close to real-time. To decrease computation times, TSOs could resort to phasor-mode (also called RMS) simulations. In these, reduced models are used, which neglect for example network line dynamics, the inner controllers of converters and signal processing dynamics. This comes at the cost that RMS models are unable to capture fast dynamics, such as harmonic instability. However, they are well-suited for investigating slower phenomena, such as frequency dynamics. RMS models can also be used in analyses, where the dynamics of the outer controllers of converters need to be considered, if the following two conditions are fulfilled. First, there is a distinct time-scale separation between the converters' outer controllers and voltage dynamics. Second, the system is stable with respect to fast dynamics. Consequently, there is a need to identify the conditions under which online dynamic security assessment can be performed with phasor-mode simulation tools and when EMT models need to be used. In [22] an analytical control design approach is proposed, where sufficient conditions are derived for the control parameters, which ensure stable performance and allows the use of RMS models due to time-scale separation.

3.2 Low-inertia approach

In the low-inertia approach, Synchronous Condensers (SCs) are installed on the wind power hub as indicated in Figure 8 and the offshore converters are operated in grid-following mode. The SCs serve two purpose on the hub. First, they act as a local energy buffer due to the kinetic energy stored in rotating masses. Second, the SCs provide a voltage and frequency reference, to which the grid-following offshore VSCs synchronize. In the absence of other synchronous generators on the hub, it is the SCs, which are defining the frequency of the offshore AC system. A mismatch in the power balance will become visible in a deceleration or acceleration of the SCs. In order to ensure stability, the offshore VSCs need to be equipped with frequency-droop controllers, which adjusts their power transfer. For example, in case of a loss of a wind power plant, in the first time instance the power transfer through the VSCs will remain unchanged. Since the generated power is now less than the power transmitted to shore, there is a lack of power on the hub. This results in a deceleration of the SCs, which provide the missing power from their kinetic energy. In order to stabilize the offshore AC system, the VSCs use the measured frequency deviation to adjust their transmitted power. In the above example, the drop in frequency will result in a reduction of the power transmitted to shore from the hub. This will restore power balance on the hub and the frequency will settle at a new steady-state value deviating from nominal frequency. Subsequently, a secondary controller on the hub will restore nominal frequency through an adjustment of the power transmission setpoints of the VSCs. The feasibility of this concept was investigated in [23]. Figure 9 shows the VSC power response obtained from an RMS simulation where the loss of a wind power plant was assumed. It can be seen that the SCs succeed in smoothening the response to the disturbance. While RMS are sufficient when studying "slow" dynamics such as system frequency, in the future detailed EMT simulations are needed to assess faster dynamics of cables and power electronic devices.

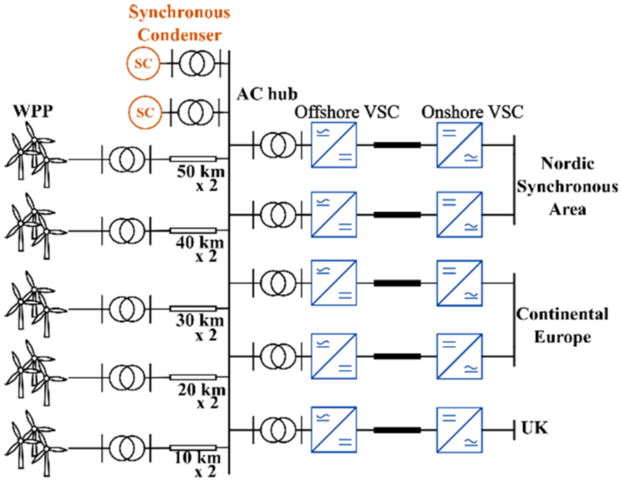

Figure 8 North Sea Wind Power Hub low-inertia configuration.

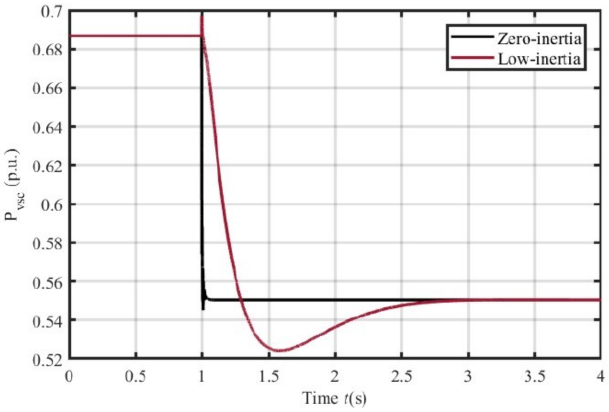

Figure 9 Comparison of the VSC power transmission to a loss of generation on the hub in the zero-inertia (black curve) and the lower-inertia approach (red curve), respectively.

4 Conclusion

In this paper, advanced control and optimization methods to holisticly integrate HVDC links into the operation of AC power systems and electricity markets were presented, which were developed in the multiDC project (www.multi-dc.eu). With respect to advanced controls, the findings are the following: 1) the dynamic power transfer limit of grid-supporting VSCs is higher than of grid-following VSCs in case of sudden changes of SCC. 2) a robust frequency controller for VSCs 3) an improved EPC method suitable for low-inertia systems. From a market point of view, the results 4) highlight the economic benefit of using the EPC functionality of HVDC lines for the provision of frequency support and 5) show the importance of internalizing losses in market operation to guarantee cost recovery for those TSOs which operate HVDC links. When investigating the ability of HVDCs to enable massive RES integration, 6) two approaches for the realization of wind power hubs were discussed. The results showed that HVDC links have a great potential for supporting the grid and can help to operate 100 % RES based power systems.

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