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Published in:
IEEE Transactions on Power Delivery

Link to article, DOI:
[10.1109/TPWRD.2020.2971559](https://doi.org/10.1109/TPWRD.2020.2971559)

Publication date:
2020

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Bidadfar, A., Saborío-Romano, O., Sakamuri, J. N., Cutululis, N. A., Akhmatov, V., & Sorensen, P. E. (2020). On Feasibility of Autonomous Frequency-Support Provision From Offshore HVDC Grids. *IEEE Transactions on Power Delivery*, 35(6), 2711-2721. <https://doi.org/10.1109/TPWRD.2020.2971559>

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On Feasibility of Autonomous Frequency-Support Provision from Offshore HVDC Grids

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Abstract—Offshore multi-terminal high-voltage dc (HVDC) grids are emerging as a technical reliable and economical solution to transfer more offshore wind energy to inland power grids. It is also envisaged that the offshore HVDC grids pave the way for both offshore wind participation and sharing inland frequency reserves for efficient power systems' frequency control. The frequency control mechanism in an HVDC grid can be either centralized or decentralized. An autonomous frequency control (AFC) is a decentralized control, which does not require communication links between dc grid terminals. In the AFC, the dc-link voltage is used as a medium to reflect the inland frequency change to other terminals. The AFC has some technical and non-technical challenges, especially when the dc grid is connected to more than one shore ac systems. Among challenges of the AFC are the deficiency in meeting grid code requirements, adverse reaction of converters, dc voltage variations, difficulties of offshore wind participation in power markets. This paper proposes a new methodology of frequency control which uses both centralized control and AFC simultaneously. The proposed methodology shall improve system security and mitigate the listed problems of the AFC. A four-terminal dc grid is described and used for analysis and demonstration of the proposed methodology.

Index Terms—HVDC grids, frequency control, offshore wind, power system

I. INTRODUCTION

WITH increasing penetration of intermittent renewables in power systems, the technical and regulatory feasibility of such generations in providing frequency support has attracted attention. To take part in the frequency control, a generator shall bid reserve capacity in electricity markets. The traded capacity can be frequency containment reserve (primary) and/or frequency restoration (secondary) reserve. Provision of frequency control and restoration support has become a requirement for all generation types, including wind power plants [1]. Therefore, many experiments and researches are conducted to investigate and demonstrate the participation of wind power in the frequency control. In a pilot conducted at a 21 MW wind farm in west Denmark [2], the production has been decreased by 5% to provide downward regulation. In [3], a Belgian pilot for using an 81 MW wind farm to provide frequency restoration reserve has been conducted, and its feasibility has been investigated from technical and regulatory points of view.

The promised reserve must be activated when needed. Otherwise, besides penalizing the generator, the system security could be on risk. Therefore, from the technical point of view,

the reliability of frequency-support mechanism must be high, especially for the primary type, which prevents frequency dropping beyond the limits. To increase the reliability of frequency support from high voltage dc (HVDC) connected offshore wind farms, an autonomous frequency control (AFC) scheme, without using communication links between onshore and offshore stations, has been proposed in [4]. In this control, offshore frequency mirrors the land frequency by modulating the dc link voltage.

Some studies have been carried out on implementing the autonomous [communication free] frequency support from offshore multi-terminal dc (HVDC) networks [5]–[13]. In offshore HVDC grids, the shore converters are equipped with frequency droop control which transforms frequency deviations to dc voltage variations. Converters on the other ends (offshore wind and/or other land ac systems) react to dc voltage-change by regulating their active power. As a result, an AFC mechanism is established in the system. The impact of AFC on small-signal dynamics of offshore HVDC grids and onshore power systems has been studied in [13] and [14]. In [14], it has been concluded that AFC does not affect the dynamics of HVDC systems. In [13] and [15], it has been shown that frequency support can improve the onshore power systems' interarea modes. Although this method of frequency support is relatively more reliable and economical, it can result in some challenges, especially in terms of satisfying grid code requirements related to frequency control [16], [17]. In [6] it has been shown that using AFC in offshore HVDC grids, the delivered power to the land system, in response to a frequency drop, is less than what is required by grid codes. A compensation method has been proposed to mitigate the problem [6]. As presented in this paper, applying the compensation method is not straightforward when the dc grid operates with autonomous power-sharing control. Proper selection of voltage and frequency droop gains as well as interacting with dc voltage protection system are other probable challenges of using AFC [4].

There are other concerns of implementing AFC on offshore HVDC networks that have not been addressed in the literature. The main contribution of this paper is to analytically investigate the concerns challenging the feasibility of autonomous frequency support from offshore HVDC grids. The identified problems are incapability in delivering the expected power, inaccurate power-sharing among converters, dc voltage deviations, high dead-band in overall frequency control, undesired power flow in ac and dc lines, and inadaptability with different dc voltage control schemes.

In this paper, a comprehensive control scheme for frequency support from offshore HVDC grids is proposed. The proposed control scheme uses AFC in parallel with centralized frequency control (CFC), which is embedded in the HVDC supervisory control. The CFC manages the power flow based on grid code requirements, electricity market schedules, lines and converters limits, availability of components as well as other conditions and requirements. When activating the CFC, the AFC is inherently nullified. Under contingencies, such as communication failure (to cause CFC not operational) and converter outage, the AFC assists the system security by a fast reaction.

The rest of the paper is organized as follow. In Section II HVDC grid model and control of converters are introduced. Challenges associated to AFC are detailed in Section III and proposed control scheme is presented in Section IV. Section V shows the simulations results, and the study is concluded in Section VI.

II. HVDC GRID MODEL AND CONTROL SYSTEMS

The offshore HVDC network model and its control, and also assumptions made in modeling and simulations are presented in this section.

A. HVDC Grid Model

The dc grid topology is shown in Fig. 1. It has two offshore wind farms and two onshore ac systems. Each of the shore systems is modeled as an aggregated synchronous machine equipped with a turbine and governor. The wind farms are modeled as IEC type-4 (fully-rated) wind turbines using the aggregation method given in [18]. The offshore C and D have 1000 and 800 MW generation capacity. Frequency in all offshore and onshore ac networks is 50 Hz. Modular multilevel converters (MMCs) are used for HVDC connections. The model used for MMCs is an average model of half-bridge type converter with 200 submodules per arm and ± 320 kV of the dc-link voltage. The dynamics of MMC and its current and voltage controllers can be neglected when analytically studying the primary frequency control [13], [15]. Since the AFC, in comparison, has slower dynamics (rise-time is within the range of few hundred milliseconds), it is not expected to have a significant impact of MMC dynamics with an inner current control rise-time of few milliseconds, and voltage control of tens of milliseconds [19], [20]. Moreover, in [14], it has been concluded that frequency control does not affect the small-signal stability of offshore HVDC grids. This fact has also been observed in the simulations of this paper, where the MMCs have been modeled with full details. Nevertheless, the frequency control parameters, which are mainly frequency droops, are determined so that to satisfy the grid codes related to the frequency control.

The control and component parameters of the MMCs are given in the Appendix.

B. HVDC Grid Control

An HVDC grid control can be implemented in different ways [21]. *Master-slave control*: One converter controls the

dc voltage and other converters active power. Without well-defined redundancy procedure, this control method suffers from low reliability under forced converter outage [21]. *Voltage margin control*: Similar to the master-slave control, one converter maintains the dc voltage while there are other converters providing backup to control the dc voltage in the case when the slack converter fails [22]. *Autonomous power sharing*: The dc voltage control is distributed among some converters using power-voltage droop action. In the case of dc voltage change, the consequent power deviation is autonomously shared among those converters equipped with droop control. This concept is similar to power-frequency droop in ac power systems. In this paper, the autonomous power sharing control is used for studies.

To implement the AFC, the onshore frequency deviation must be converted to a voltage- or power-change, depending on the type of the converter control. When using autonomous power sharing on both the shore converters, shown in Fig. 1, the frequency deviation can be included in their control as

$$P_1 = P_1^* + k_{v1}\Delta V_{D1} - k_{f1}\Delta f_1 \quad (1)$$

$$P_3 = P_3^* + k_{v3}\Delta V_{D3} - k_{f3}\Delta f_3 \quad (2)$$

where k_v and k_f are respectively the inverse of voltage and frequency droops. The Δ sign indicates the measured value minus the reference value, e.g., $\Delta f_1 = f_1 - f_1^*$. All parameters with asterisk (*) represent the reference values.

The AFC requires the offshore converters to measure the dc voltage deviation and convert it into offshore frequency-change. In Fig. 1, if both offshore farms have reserve capacity and intend to contribute in AFC, their frequencies are respectively changed as $\Delta f_2 = R_2\Delta V_{D2}$ and $\Delta f_4 = R_4\Delta V_{D4}$. The wind farms regulate their power supply in response to offshore frequency deviations as

$$P_2 = P_2^* - k_{f2}\Delta f_2, \quad P_4 = P_4^* - k_{f4}\Delta f_4. \quad (3)$$

As (3) shows, the power generated from offshore wind can be changed in the case of onshore frequency deviations. This is a foundation of AFC mechanism in an HVDC grid.

III. CHALLENGES ASSOCIATED WITH AFC

In this section some challenges of using AFC in offshore HVDC are identified and investigated.

A. Incomplete Power Delivery to the Shore

It has been shown in [6], [23], that using AFC in offshore HVDC, the expected power cannot be delivered to a disturbed onshore ac system. In [6], it is assumed that several OWFs are connected to one onshore power system via an offshore HVDC grid. For such a connection, a compensation has been proposed for incomplete power delivery. In this section, it is shown that the compensation, proposed in [6], is challenging in the case there are more than one onshore power systems. Assume that a generation unit trips in onshore A, in Fig. 1, and results in its frequency drop. A transfer function between frequency deviation, Δf_1 , and the amount of power change in terminal A, i.e., ΔP_1 , gives the required amount of power

Fig. 1. The schematic diagram of the offshore HVDC grid used for studies.

delivered to system A. The transfer function is derived under the following assumptions. Both the converters on the shore use the dc voltage and frequency droop controls as stated in (1) and (2). The onshore grids are considered as separated with no ac link in between. Only the offshore substation C contributes to the frequency control. The dead-bands of the controllers and the dc network losses are negligible. Considering these assumptions results in $\Delta P_2 = \Delta P_1 + \Delta P_3$ and $V_{D1} = V_{D2} = V_{D3} = V_{D4}$. When frequency drops on shore A, the dc link voltage is decreased based on (1). Both shore B and offshore C respond to the voltage drop by changing their active power as

$$\Delta P_2 = k_{v2} \Delta V_{D2}, \quad k_{v2} = k_{f2} R_2. \quad (4)$$

The HVDC converter on shore B also changes its power in response to the dc voltage deviation. Since this converter feeds into the ac grid B, its power-change may result in the grid frequency deviation, i.e., Δf_3 , which activates the governors of the system B generators. Considering the aggregated damping ratio, D_3 , and governor droop, R_{g3} , of shore B, its frequency- and power-change after transients can be stated as

$$\Delta f_3 = \frac{1}{D_3 + k_{g3}} \Delta P_3, \quad k_{g3} = 1/R_{g3}. \quad (5)$$

Inserting (4) and (5) in (1), considering the made assumptions, results in

$$\Delta P_1 = - \underbrace{\frac{1}{1 + k_{v1} \frac{1}{k_{v2} + k_{v3} (1 + k_{f3} (D_3 + k_{g3})^{-1})^{-1}}}}_{\text{Attenuation factor}} k_{f1} \Delta f_1 \quad (6)$$

where the attenuation factor is less than unit and it makes the delivered power, ΔP_1 , become less than what is expected, $\Delta P_{\text{exp}} = -k_{f1} \Delta f_1$, by the relevant grid code. Because of two reasons, it is not easy to compensate the attenuation factor via multiplying its reverse by k_{f1} as proposed in [6]. Firstly, both onshore frequency controls cannot be compensated at the same

time since there is a reciprocity between them. Second, even in compensating for one onshore, the parameters of another ac system, e.g., D_3 , k_{g3} cannot be easily estimated. The transfer function of (6) will become more complex and difficult for analysis if offshore D also takes part in the AFC; though the attenuation factor will become smaller than the one obtained in (6).

B. Inability to Provide Primary Reserve

If an individual offshore wind farm becomes a primary reserve provider to support the shore frequencies, it should be able to export the expected power to the promised shore grid, e.g., shore A. With the same way as derived in (6), a transfer function between offshore C frequency, Δf_2 , and shore A frequency, Δf_1 can be obtained as

$$\Delta f_2 = \frac{R_2 k_{f1}}{k_{v1} + k_{v2} + k_{v3} \frac{1}{1 + k_{f3} (D_3 + k_{g3})^{-1}}} \Delta f_1 \quad (7)$$

which shows that using AFC, it is not easy for offshore wind to accurately estimate the frequency deviation on the land system. The Danish grid code, for instance, requires the frequency measurement to have tolerance less than ± 10 mHz, which according to (7) cannot easily be met by AFC because the control parameters and other ac system parameters, k_{f3} , D_3 and k_{g3} , are not necessarily fixed and Δf_2 cannot be linearly depending on Δf_1 . The derived transfer function will become more complex in terms of parameterization of the dc network resistances, dead-bands, limits, and accepted accuracy of the offshore wind contribution to provide an adequate frequency accuracy. AFC is not suitable for accurate estimation of the shore frequency deviation. Further, AFC is not suitable for transmission of the required power flow to a specific onshore because of the autonomous power sharing control of the onshore converters. Therefore, using AFC, an individual HVDC-connected wind farm cannot provide adequate primary reserve.

C. Inaccurate Power Control of OWFs with AFC

Enabling an OWF to participate in AFC, its converter must be equipped with voltage-frequency droop, which creates negative feedback to the active power setpoint of the OWF. As shown in Fig. 2, the feedback is taken from the dc-link voltage deviation $\Delta V_D = V_D - V_D^*$, which means that V_D^* is needed. Because of dc grid impedance [24], the dc-link voltage setpoints differ from terminal to another. The offshore voltage setpoint, V_D^* , can be obtained either from solving power flow equations or, it can be set as the nominal voltage of the dc link. In the former case, the reference value must be updated based on scheduled power flow; this method seems to be an appropriate approach for the frequency control purpose, but it relies on communication links between the grid supervisory control and different terminals. In the latter, a relatively large dead-band should be considered for offshore voltage deviation to not activate the AFC under normal operations of onshore converters. For example when the distance between the land ac systems is far and they intend to change power flow between their converters, a relatively high voltage-change is needed.

Fig. 2. Wind farm power-change based on dc voltage deviations on HVDC terminals.

This can be further explained by Fig. 2 which shows that offshore wind power production will change if the voltage deviation, ΔV exceeds the dead-band limits. If the dead-band is small, under normal operation, when the dc grid changes its operation from one point to another, the voltage deviation on the offshore terminals will act as negative feedback to power production, which can cause an inaccurate power control and also an interaction between wind farms. On the other hand, if the dead-band is too large, the overall dead-band experienced by AFC will be unacceptably large, and consequently, the response to onshore frequency deviation will not be efficient.

D. Adopting Maximum Allowable Voltage Drop

There should be alignment between the maximum allowable frequency drop and the maximum allowable dc voltage drop. The maximum allowable frequency drop can be extracted from the lowest frequency that an HVDC converter should stay connected [25]. Choosing the maximum allowable dc voltage deviation is not straightforward. If it is decided to be high, via k_{v1} , and k_{v3} , the dc grid dynamic can be affected [26]. On the other hand, if the voltage drop is chosen to be small, on the offshore side the voltage-frequency droop, R , and/or WT's power-frequency bias, k_f , should be high. This makes the wind farms sensitive to any small change on the dc link voltage, which might not be necessarily caused by AFC.

E. Different Response to Different Onshore Frequencies

If the shore converters use unequal voltage and frequency droops, i.e., $k_{v1} \neq k_{v3}$ and/or $k_{f1} \neq k_{f3}$, the same frequency deviation on the shore ac systems will result in different dc voltage-change. Therefore, the AFC reacts differently to the same frequency disturbance in different shore systems.

F. Frequency Droop is not Linear

Primary frequency control is a proportional control which does not have a single fixed droop gain for the entire range of frequency deviation. As an example, the Danish grid code requires frequency control for wind farms with four different droops, as shown in Fig. 3. Not having a single frequency droop implies that k_{f1} , k_{f3} , and k_{g3} do not have a unique value. This fact makes the transfer function derived in (6) to be nonlinear (piece-wise linear) and almost impossible to compensate for the deficiency of AFC as suggested in [6]. The nonlinearity of the primary control makes the AFC even more complicated since the different terminals do not have access to instant frequency droop of the disturbed land system.

Fig. 3. Frequency control for wind generation, with various droops in different frequency ranges [27].

G. Inconsistency with Different Voltage Control

Implementing the AFC in a dc grid which, uses master-slave control or voltage margin control, causes all the required power to be exported from the voltage controlling terminal. In the case of master-slave control, the dc voltage controlling converter (master) maintain the dc voltage to the nominal value which, means that the frequency supportive power cannot be shared amongst different terminals (power resources). In the case of voltage margin control when the dc voltage shifts from one point to another, the power resource for AFC also changes and, this creates a problem for marketing the reserve capacity.

H. Difficulties in Participating in Different Markets

To implement the AFC, offshore wind farms regulate their power concerning the dc voltage-change. Every onshore system can cause the voltage-change. If each shore system has its own electricity market, the offshore wind cannot bid the primary reserve to an individual market using the AFC. The ENTSO-E (European network of transmission operators for electricity) grid code in [25] (Article 39.1.b) requires that offshore wind should implement a coordinated frequency control when it connects to a dc grid with more than one control area. This requirement can be met only by measuring the frequency from each control area, and not by measuring dc voltage deviation. Therefore, the AFC cannot meet the grid code requirement.

I. Power Circulation Among Shore Converters

In case of ac interconnection between inland systems (ac line is connected in Fig. 1) both ac systems will have the same frequency, i.e., $\Delta f_1 = \Delta f_3 = \Delta f$. The supportive power from offshore is shared between shore converters using the AFC. Assume that the frequency control loop is activated only for converter A, i.e., $k_{f3} = 0$ and only offshore C participates in the frequency support. Using AFC, the power-change in offshore C can be stated as

$$\Delta P_2 = \frac{-k_{v2}k_{f1}}{k_{v1} + k_{v2} + k_{v3}} \Delta f \quad (8)$$

Fig. 4. Centralized frequency control (CFC) is embedded in the offshore HVDC grid supervisory control.

The power-change of both onshore converters is

$$\Delta P_1 = \frac{-(k_{v2} + k_{v3}) k_{f1}}{k_{v1} + k_{v2} + k_{v3}} \Delta f \quad (9)$$

$$\Delta P_3 = \frac{k_{v3} k_{f1}}{k_{v1} + k_{v2} + k_{v3}} \Delta f \quad (10)$$

It is clear that ΔP_1 is more than ΔP_2 , which means converter B reacts in adverse. As a result, some power, ΔP_3 , circulates among the shore converters, which is not desired and can cause problems such as lines and converters overloading, affecting power-flow between areas, and so on.

J. Other Challenges of Using AFC

Interaction between AFC and dc voltage protection system is another concern, which has been addressed in [4]. Adding to the complexity of tuning the voltage and frequency droops at different terminals is also a concern when using AFC in dc grids [4]. There might be other challenges related to AFC in offshore dc grids that have not been identified in this paper.

IV. PROPOSED COMPREHENSIVE FREQUENCY CONTROL

According to the identified challenges regarding AFC in offshore dc grid, it does not seem to be a promising solution neither from technical nor from the regulatory perspective. The ENTSO-E grid code requires fast communication between offshore and onshore HVDC stations for frequency control [25], which means the current standard does not rely on AFC. However, the AFC can assist the system security by increasing the reliability of the whole system. The reliability of offshore systems is crucial as the maintenance cost of offshore installations is considerably high comparing with those of onshore. Using AFC can assist the system reliability in two different ways. First, as shown in Section V-C, the AFC has a positive impact against a converter outage. Second, in the case of communication-based frequency control failure, for any reason, the AFC can take the responsibility of providing support to onshore power system, if needed.

This paper proposes a comprehensive frequency control in which both AFC and CFC are included. The AFC is used as a backup for CFC and also as a protective control scheme for dc-link protection. The CFC, in an HVDC grid, keeps the dc voltage within normal operating limits when the frequency

control takes action. This feature makes the backup AFC not to be activated since its operation is based on dc voltage deviation.

The schematic diagram of CFC embedded in the supervisory control of an offshore HVDC grid is shown in Fig. 4. The supervisory control requires different types of information to implement the CFC. These information include grid codes and frequency deviations (Δf^{on}) of the land systems, line and converters' limits, power flow through HVDC terminals ($P_{\text{out}}^{\text{wf}}$ and $P_{\text{out}}^{\text{on}}$), available power of wind farms ($P_{\text{av}}^{\text{wf}}$), power market bids, and so on. Based on such information, the CFC distributes the frequency-supportive power among selected terminals by sending corresponding signals, i.e., $\Delta P_{\text{cfc}}^{\text{wf}}$ to wind farms and $\Delta P_{\text{cfc}}^{\text{on}}$ to the land HVDC converters. The $\Delta P_{\text{cfc}}^{\text{on}}$ is the amount of active power that one onshore converter supplies to another disturbed onshore ac system.

If an onshore ac system contributes to the frequency control of another onshore grid, its frequency control is deactivated by signal $\text{sig}_{\text{cfc}}^{\text{on}}$, which is communicated from CFC. The proposed frequency control for onshore converters is shown in Fig. 5. There is a switch in the control system, which determines whether the converter controls its own frequency or participates in another onshore network frequency control, respectively by holding 1 or 0 positions. In case of the latter, if there is a significant deviation in the local frequency, the converter is discharged from supporting other ac grid, i.e., the output of LFD (large frequency deviation) block will be 1. The offshore HVDC converters use dc voltage-frequency droop control as shown in Fig. 6. On the turbine level, also shown in Fig. 6, a signal from CFC, ΔP_{cfc} , is used in parallel with frequency droop, which is a part of AFC.

The reserve power dispatch in CFC is fulfilled as shown in Fig. 7. Using the CFC, a disturbed onshore system can receive support from all contracted offshore wind farms and other onshore ac systems. The contracted offshore wind farms or onshore systems participate in reserve market and sell reserves to a certain power system. For example, in Fig. 7, offshore wind farms promise to provide maximum reserve power of $\text{PR}_{\text{wf1}}^{\text{on1}} \dots \text{PR}_{\text{wfn}}^{\text{on1}}$ with the gain of $k_{\text{wf1}}^{\text{on1}} \dots k_{\text{wfn}}^{\text{on1}}$ to onshore 1 in case of frequency disturbance. The other onshore systems, if contracted, can also sell maximum reserve of $\text{PR}_{\text{on2}}^{\text{on1}} \dots \text{PR}_{\text{onm}}^{\text{on1}}$ with the gain of $k_{\text{on2}}^{\text{on1}} \dots k_{\text{onm}}^{\text{on1}}$ to system 1. Should for any reason—components outage or not participating in reserve market—an offshore wind farm or other ac systems cannot provide support to a disturbed system, its corresponding signal (e.g. $\text{sig}_{\text{wf1}}^{\text{on1}} \dots \text{sig}_{\text{wfn}}^{\text{on1}}$ or $\text{sig}_{\text{on2}}^{\text{on1}} \dots \text{sig}_{\text{onm}}^{\text{on1}}$) becomes zero, otherwise it is one. A disturbed onshore is not allowed to participate in supporting other disturbed systems by making its corresponding signal zero; for example, if onshore 1 is disturbed then $\text{flg}_1 = 0$.

The total amount of reserve power that each offshore wind farm can provide is calculated as

$$\Delta P_{\text{cfc}}^{\text{wf1}} = \sum_{i=1}^m \Delta P_{\text{wf1}}^{\text{oni}}, \dots, \Delta P_{\text{cfc}}^{\text{wfn}} = \sum_{i=1}^m \Delta P_{\text{wfn}}^{\text{oni}} \quad (11)$$

where $\Delta P_{\text{wf1}}^{\text{oni}} \dots \Delta P_{\text{wfn}}^{\text{oni}}$ are generated by CFC shown in Fig. 7. Similarly, the amount of reserve power than one onshore

Fig. 7. Reserve power dispatch among onshore and offshore system in CFC.

V. SIMULATION RESULTS

Different case studies are simulated on the offshore HVDC, shown in Fig. 1. Simulation results show how the proposed control overcomes the deficiencies of AFC, which were identified in Section III. It is assumed that both offshore wind farms contribute in frequency control and onshore converters use dc voltage droop. Since the onshore converters control the dc voltage, their voltage bias (inverse of droop) is chosen higher, i.e., $k_{v1} = 10$ and $k_{v3} = 8$ pu. The base values for power and dc-link voltage are respectively 1000 MW and 640 kV.

The nominal generation capacity of offshore C and D are respectively 1000 and 800 MW and their outputs for an operating point are 800 and 700 MW. The wind farms curtail their generation to participate in onshore frequency support. Under steady state operation, it is planned that 950 MW is exported to onshore A, and 550 MW to onshore B.

For each onshore system a synchronous machine equipped with turbine, governor, and AVR has been considered plus passive loads connected to the generators via transformer and ac transmission lines. The synchronous generators have their field and one damper winding on their d-axis and two damper winding on their q-axis. Hydro-turbine governing system is used as prime mover for the synchronous generators. All component and controller parameters used for simulations are provided in the Appendix.

Measuring onshore frequencies, low-pass filters with a time constant of 50 milliseconds are used. These filters together with the hard-limiters, applied on frequency droop, prevent the reflection of transient phenomenon such as onshore ac faults into frequency control loops. Moreover, these low-pass filters

Fig. 8. Power in HVDC terminals when 200 MW shifts from converter A to B. Plots in color are the result from AFC, and those in gray from the proposed controller.

Fig. 9. Voltage in HVDC terminals when 200 MW shifts from converter A to B. Plots in color are the result from AFC, and those in gray from the proposed controller.

further decrease the dynamic interactions between frequency and other control loops of an HVDC grid.

A. Change in Operating Point

The onshore grids can trade the power through HVDC network. It is decided that shore A decreases 200 MW of its import from offshore wind to be exported to shore B. Without communication between the shore grids this power trade cannot be done accurately because of the droop control on onshore converters. Although using communication, the presence of AFC causes the adverse reaction of the wind farms. As shown in Fig. 8, changing the onshore power, offshore wind farms experience error in their power respectively by ΔP_2^{err} and ΔP_4^{err} . The reason of such undesired reaction is that the distance between onshore grids is far, in comparison, and a power change between the land grids require larger change in the both onshore terminals. The offshore terminals can detect the voltage-change and react with altering their active power. Figure 9 shows the offshore frequencies and dc voltage on four terminals. Since the farm C is closer to shore A, and farm D to shore B, their voltage change are in opposite direction, and therefore their frequencies change differently. In the proposed controller the voltage dead-band of offshore converters is higher, 0.01 pu; thereby, the adverse reaction of the farms are not observed. This fact is evident from the gray-color plots in Fig. 8 and 9.

As another scenario of a change in operating, the offshore C increases instantly its output power by 150 MW. This type of instant significant change in a wind farm output is somehow unlikely in practice, but for the sake of visibility of the error caused by AFC, this type of change has been considered in this scenario. The power flow of HVDC terminals for this case is shown in Fig. 10. The error of offshore D, ΔP_4^{err} , is the result of the feedback loop that is described in Section

Fig. 10. Power in HVDC terminals when offshore C increases 150 MW of its power. Plots in color are the result from AFC, and those in gray from the proposed controller.

III-C. The error plus the adverse reaction of offshore D result in inaccurate power sharing of the land converters which experience ΔP_1^{err} and ΔP_3^{err} . Similar to the previous scenario, the proposed control uses higher dc voltage dead-band on offshore converters, and therefore does not experience such error as shown in gray in Fig. 10.

It should be noted that in both of the examples of operating point change, the frequency control from onshore converters are deactivated since the power changes are scheduled.

B. Onshore Frequency Support

An unbalance between generation and consumption has been created on onshore A, which results in a frequency drop as shown in Fig. 11. Converter A uses a frequency droop of 0.05 pu, and the supportive power has been planned to be supplied from other terminals as 50% from offshore C, 30% from offshore D, and 20% from ac system B. Although the frequency of onshore A has been improved by using the AFC, it is still lower than what is required by the corresponding TSO. This implies that expected power cannot be delivered to ac system A as observed in Fig. 12. Moreover, the distribution of the supportive power is not what has been planned, however, exactly in opposite. The proposed control has been able to export the required power to shore A with the scheduled power distribution among other converters. As shown in Fig. 13, dc voltages at HVDC terminals have smaller deviation, when using the proposed control.

For the proposed control, a communication delay of 50 ms has been considered. It is also assumed that sampling time of wind farms supervisory control is 150 ms. Since even in the proposed method AFC reacts immediately, the transient behaviour of the system, as shown in Fig. 11, 12, and 13, is the same for AFC and the proposed method, regardless of communication delay and wind farm sampling time.

C. Onshore Converter Outage

To show an advantage of AFC as part of the proposed control, its protective reaction against onshore ac fault is investigated by means of simulation results. The worst case of an onshore ac fault can result in outage of an onshore HVDC converter. It is assumed that converter B trips, under a severe ac fault, and all offshore power flows to converter A whose maximum power capacity is 1200 MW. As a result, converter A saturates and the dc voltage is left uncontrolled in the case the offshore wind farms keep operating with constant power.

Fig. 11. AC systems' frequencies when there is a generation-consumption unbalance on shore A.

Fig. 12. Power flow of HVDC converters when there is a generation-consumption unbalance on shore A.

Fig. 13. DC grid voltages when there is a generation-consumption unbalance on shore A.

Total power from wind farms is 1500 MW while the output is 1200 MW. This imbalance gives a significant rise to dc voltage as shown in Fig. 14. In case of AFC, however, the dc voltage returns back to a bounded value after a transient. The dc voltage protection system is intentionally deactivated to show the pure reaction of the AFC. For this reason, the

Fig. 14. Offshore frequencies and dc voltage when the converter B trips. Plots in gray show the case without offshore reactions.

Fig. 15. Power flow in onshore and offshore when the converter B trips. Plots in gray show the case without offshore reactions.

dc-link voltage excursion, seen in Fig. 14, is significant even in case of AFC operation. To consider more realistic reaction of the AFC to a converter outage, the limitations of OWFs power and frequency in terms of amplitude and speed of change have been taken into account. A ramp rate limiter of power, 500 MW/sec, as well as frequency limit (52.5 Hz) are considered for the wind farms. These considerations result in temporary increase of dc voltage. Offshore frequency, dc voltage variations, and active power of HVDC converters are shown in Fig. 14 and 15. It must be noted that dc-link voltage protection is not the main responsibility of the AFC, but an add-on benefit. More protective scheme against a converter outage in an HVDC grid can be found in [32].

VI. CONCLUSIONS

The autonomous (communication less) frequency control (AFC) has been designed for point-to-point connections. However, the AFC for frequency response and control of adjacent ac grids become exhausted when applied for the HVDC grids. This paper has confirmed technical and regulatory issues concerning the feasibility and required controllability arising from utilization of the AFC in offshore HVDC grids. It is concluded that the AFC type of control does not pave the way for dc-connected offshore wind farms, as individual, not-coordinated, participants, to play in the power capacity market. Further, this paper has confirmed the AFC causing interactions between frequency and dc voltage droop control, which results in operation difficulties and control conflicts within the HVDC grids. To tackle the challenges of AFC, this paper proposed a comprehensive frequency control utilizing a centralized frequency control (CFC) in parallel with AFC. The proposed comprehensive control utilizes the CFC as the main controller and the AFC locally as a backup for unforeseen misfunctions within the CFC or forced outages of the HVDC stations.

Should for any reason CFC fails, the AFC immediately takes over and temporarily supports the disturbed ac system to some extent. Moreover, the immediate reaction of AFC can be useful in maintaining the dc-link voltage in case of outage of a single onshore converter. The paper has demonstrated by simulations that the comprehensive frequency control using AFC together with CFC create shall satisfy both grid code and market requirements, and boosts the overall HVDC wind power system security.

VII. APPENDIX

Parameters of the components and controllers used for the studied system, shown in Fig. 1, are given in this section.

TABLE I

CONTROLLER AND COMPONENT PARAMETERS OF VSC A

Active power control	$k_p = 10$	$k_i = 100$
Reactive power control	$k_p = 12$	$k_i = 100$
Droops	$k_{v1} = 10$	$k_{f1} = 20$
Inner current control	$k_p = 2$	$k_i = 500$
MMC submodule	No. = 200 per arm	$C = 10$ mF
Arm reactor	$R = 0.006$ Ohm	$L = 60$ mH

TABLE II

CONTROLLER AND COMPONENT PARAMETERS OF VSC B

Active power control	$k_p = 10$	$k_i = 100$
Reactive power control	$k_p = 12$	$k_i = 100$
Droops	$k_{v3} = 8$	$k_{f3} = 15$
Inner current control	$k_p = 2$	$k_i = 500$
MMC submodule	No. = 200 per arm	$C = 10$ mF
Arm reactor	$R = 0.006$ Ohm	$L = 60$ mH

TABLE III

CONTROLLER AND COMPONENT PARAMETERS OF VSC C

AC voltage control	$k_p = 2$	$k_i = 5$
Droops	$R_2 = 0.75$	V_{dc} deadband = 0.01 pu
Inner current control	$k_p = 2$	$k_i = 50$
MMC submodule	No. = 200 per arm	$C = 10$ mF
Arm reactor	$R = 0.006$ Ohm	$L = 60$ mH

TABLE IV

CONTROLLER AND COMPONENT PARAMETERS OF VSC D

AC voltage control	$k_p = 2$	$k_i = 5$
Droops	$R_4 = 0.5$	V_{dc} deadband = 0.01 pu
Inner current control	$k_p = 2$	$k_i = 50$
MMC submodule	No. = 200 per arm	$C = 10$ mF
Arm reactor	$R = 0.006$ Ohm	$L = 60$ mH

TABLE V
ONSHORE LUMPED GENERATOR PARAMETERS

Gen. of onshore A	$S = 10000$ MVA	$H = 10$ s	$U = 15.75$ kV
	$x_d'' = x_q'' = 0.2$ pu	$x_d' = x_q' = 0.3$ pu	$x_1 = 0.17$ pu
Gen. of onshore B	$S = 5000$ MVA	$H = 5$ s	$U = 15.75$ kV
	$x_d'' = x_q'' = 0.2$ pu	$x_d' = x_q' = 0.3$ pu	$x_1 = 0.17$ pu

TABLE VI

TURBINE AND GOVERNOR PARAMETERS USED FOR ON-SHORE GENERATORS

Gen. A	Gain = 200 MW/Hz	Type in Powerfactory = gov_HYGOV2
Gen. B	Gain = 100 MW/Hz	Type in Powerfactory = gov_HYGOV2

The other parameters, except the gain, such filters time constants and gains of governor and turbines are kept as default values in the Powerfactory tool.

TABLE VII
SUBMARINE DC CABLE PARAMETERS

Reactance $X' = 0.4$ Ohm/km	Capacitance $C' = 0.01$ uF/km
Resistance $R' (20^\circ) = 0.01$ Ohm/km	Resistance $R' (80^\circ) = 0.0187$ Ohm/km
Model = Distributed parameters	

TABLE VIII
PARAMETERS OF OWF B

WTs	No. = 200 WTs	Nominal power = 5 MW
Active power control	$k_p = 0.1$	$k_i = 5$
Reactive power control	$k_p = 0.5$	$k_i = 25$
Frequency droop $k_{f2} = 0.1$	phase reactor $X_{ph} = 10\%$	

TABLE IX
PARAMETERS OF OWF D

WTs	No. = 100 WTs	Nominal power = 8 MW
Active power control	$k_p = 0.1$	$k_i = 5$
Reactive power control	$k_p = 0.5$	$k_i = 25$
Frequency droop $k_{f2} = 0.16$	phase reactor $X_{ph} = 10\%$	

TABLE X
PARAMETERS OF TRANSFORMERS

Step-up Trans. A	No. of trans. = 10	$S_{rated} = 1000$ MVA	15.75/230 kV
VSC Trans. A	No. of trans. = 1	$S_{rated} = 1200$ MVA	230/333.6 kV
Step-up Trans. B	No. of trans. = 5	$S_{rated} = 1000$ MVA	15.75/230 kV
VSC Trans. B	No. of trans. = 1	$S_{rated} = 1000$ MVA	230/333.6 kV
VSC Trans. C	No. of trans. = 1	$S_{rated} = 1100$ MVA	66/333.6 kV
VSC Trans. D	No. of trans. = 1	$S_{rated} = 870$ MVA	66/333.6 kV
WTs Trans. C	No. of trans. = 200	$S_{rated} = 5.5$ MVA	0.69/66 kV
WTs Trans. C	No. of trans. = 100	$S_{rated} = 8.7$ MVA	0.69/66 kV

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