Provision of Inertial and Primary Frequency Control Services using Offshore Multi-terminal HVDC Networks

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Abstract— **This paper addresses the problem of providing frequency control services with offshore WF connected through a multi-terminal HVDC network. It proposes a control scheme such that offshore wind generators can provide inertia and primary frequency control to the grid. It consists of a cascading control mechanism based on dc voltage regulation at the onshore converters and frequency regulation at the offshore converters. The control scheme involves only local measurements and actions so that it avoids security and reliability issues of control schemes based on remote information. The effectiveness of the proposed strategy is illustrated in the case of two non-synchronous areas linked by a multi-terminal HVDC system connecting two offshore WF.**

Index Terms—**Frequency control, HVDC power transmission, Inertial emulation, Multi-terminal HVDC system, Offshore wind generation**

I. Introduction

MOST actual initiatives for a sustainable energy future advocate a large-scale development of offshore wind power [1,2]. Among other aspects, the transmission of bulk offshore wind power over large distances and its integration into existing onshore AC grids is a matter of concern, leading to the development of specific studies in order to assess the potential use of HVDC and HVAC solutions taking into account both technical and economic issues. However, HVDC technology is being presently considered as the most suitable solution for large-scale and long distance offshore wind power integration into existing AC onshore grids [3-5].

The most elementary HVDC offshore transmission system consists on a wind farm (WF) connected to a rectifier, a DC power transmission cable and an inverter connecting the DC system to the onshore AC system. Depending on the types of solid state switches used both for the rectifier and for the inverter, two different HVDC solutions are possible: (1) HVDC line commutated converter (HVDC-LCC) if thyristor valves are used or (2) HVDC voltage source converter (HVDC-VSC) if IGBT valves are used. [6,7]. Although HVDC-LCC is a robust solution used for many years for bulk power transmission, HVDC-VSC seems to be the most promising technology for large-scale offshore WF integration since it allows the independent control of active and reactive power, voltage support at the offshore WF site and even has black-start capability [7, 8].

The point-to-point connection of offshore generators into the existing onshore AC grids presents important drawbacks related to reliability and flexibility of operation that considerably limit the wind power hosting capacity. Alternatively, multi-terminal DC (MTDC) networks are being studied as a flexible solution for future large-scale offshore wind power integration, including the provision of additional support for asynchronous interconnection of AC grids. Different criteria such as larger flexibility of grid operation, possibility of reversible power flows, increased redundancy and reduction of maximum power losses in case of a grid disturbance are the main drivers to the development of the MTDC concept [1, 9].

Large-scale integration of wind energy leads to a displacement of conventional generation units that negatively impact the behavior of grid frequency (leading to increased rates of change of frequency and larger absolute deviation) in the aftermath of disturbances, thus affecting the load-generation balance [10]. To mitigate such bottleneck some authors have investigated the possibility of using wind generators to provide primary frequency support to onshore grids. A common approach consists in exploiting WF below its maximum power extraction capability (wind generator de-load), hence creating a spinning reserve margin [11-15]. Additionally, the authors suggest the use of a local control loop at the wind turbine level, whose input variable is the measured frequency error that is used to turbine power output for primary frequency regulation purposes.

The predicted massive integration of offshore WF contributes for increasing frequency stability related problems in AC systems. Despite being desirable to make offshore WF connected through MTDC to contribute towards frequency regulation in AC systems, the DC link connections fully decouples AC areas and offshore stations, thus not allowing the direct implementation of previously referred primary frequency control schemes. Nevertheless some studies have

This work was supported in part by the European Commission within the framework of the European Project TWENTIES – Transmission system operation with large penetration of Wind and other renewable Electricity sources in Networks by means of innovative Tools and Integrated Energy Solutions – contract nr. 249812 (FP7) and by Fundação para a Ciência e Tecnologia under grant SFRH/BD/61600/2009.

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investigated the possibility of endowing offshore WF connected to an AC grid through point-to-point HVDC-LCC with primary frequency control capability (PFCC), without neglecting inertial emulation similarly to conventional AC synchronous generators [13]. In order to achieve such control capabilities the offshore rectifier is complemented with additional control loops whose input is the AC system frequency, which is assumed to be transmitted to the offshore rectifier station.

The development of a similar strategy in MTDC systems require installing and exploiting a dedicated communication infrastructure together with a coordination center in order to manage the sharing of the regulation actions among the offshore WF. Both cost and reliability issues will preclude the development of such communication and control centers that should be able to process and communicate real-time information, regarding the core application for frequency control purposes. Additionally, the event of a delay or communication failure can jeopardize the operation of a MTDC network with primary frequency control capability under a solicitation of an AC disturbed system [16].

In order to overcome the aforementioned difficulties, this paper presents an innovative approach consisting on the identification and development of local controllers to be installed at HVDC-VSC which will autonomously allow the provision of frequency control services. The proposed control strategies consist on the use of a cascading reproduction of AC grid frequency deviations into MTDC voltage variations. Subsequently, MTDC voltage variations are used by the offshore HVDC-VSC for controlling the offshore WF AC grid frequency. Thus, offshore WF AC grid frequency variations will be the driving signal for frequency regulation loops to be adopted at the wind generator level.

The paper is organized as follows. In Section II, the operational framework of a MTDC system is presented, together with a discussion of its main components modeling approach. The development of the proposed control strategy for the offshore MTDC system is then discussed in Section III. Section IV presents numerical simulation results that demonstrate the effectiveness of the proposed control functionalities. Finally, Section V presents the main conclusions of the paper and proposes directions for further works.

II. Modeling and Operational Framework for Multi-terminal HVDC Grids

A MTDC grid provides the connection of N offshore WF to M mainland systems, as it is illustrated in Fig. 1. The main components of the MTDC system consist on the DC grid itself, the offshore and onshore HVDC-VSC stations and the wind generators. This section details the models used in this paper to represent the dynamics of the MTDC grid, HVDC-VSC, wind generators, AC mainland systems, as well as the control philosophy required to operate the overall system.

A. Multi-terminal HVDC grid

The DC grid is assumed to be bipolar (two cables with symmetrical voltage levels – nominal voltage $\pm V_n$). Each connection within the DC grid is performed through DC cables, which are modelled by concentrated parameter (cable resistance and inductance), according to the model introduced in [17]. The MTDC grid topology dictates the algebraic and state equations of the system.

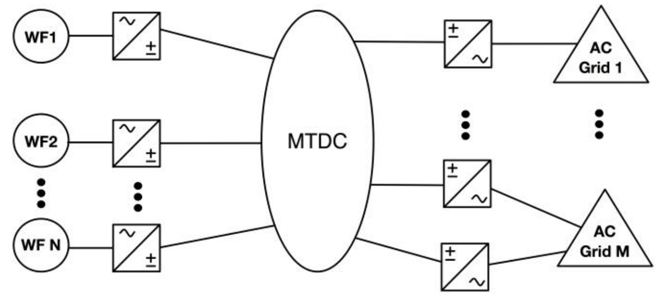

Fig. 1. Conceptual architecture of a MTDC grid.

B. HVDC converters

As previously mentioned, HVDC-VSC technology is assumed to be used both for onshore and offshore power converter stations. Independently of the topology of the HVDC grid to be studied, a key concern of the modelling approach is related to the dynamic models used for power converter stations. Considering the fast response of power electronic converters, they can be modelled from the network point of view as a controllable AC voltage source. When analysing the dynamic behaviour of the AC and DC system, it was assumed that power converters can be modelled based only on their control functions, so that fast switching transients, harmonics and inverter losses can be neglected [18,19]. Onshore and offshore converters differ mainly in the types of settings they shall apply and their control strategy. Their respective master-level control philosophies are detailed hereafter.

1) Onshore converters

The onshore DC/AC converter station is responsible for the control of the associated DC voltage measured though the DC capacitors, as depicted in Fig. 2. The internal dynamics of the converter are modelled hereafter by proportional-integral (PI) control loops, involving independent loops for active and reactive power. As HVDC-VSC converter station can independently control active and reactive power flows, two approaches can be followed regarding reactive power: reactive power injection control with a pre-defined power factor or AC terminal voltage control. Without lack of generality, a reactive power control strategy was considered at the onshore power converter station.

The converter model was implemented in the d-q synchronous reference frame [18, 19]. In this case, the error generated between the reference value of reactive power and the actual reactive power is used in order to generate the i_q current reference. Similarly, the DC voltage error measured at the DC side of the onshore converter station is used to generate the i_d current reference. Afterwards, the inner current control loop based is used in order to generate the converter output voltages v'_d and v'_q. The described modelling approach is fully depicted in Fig. 2.

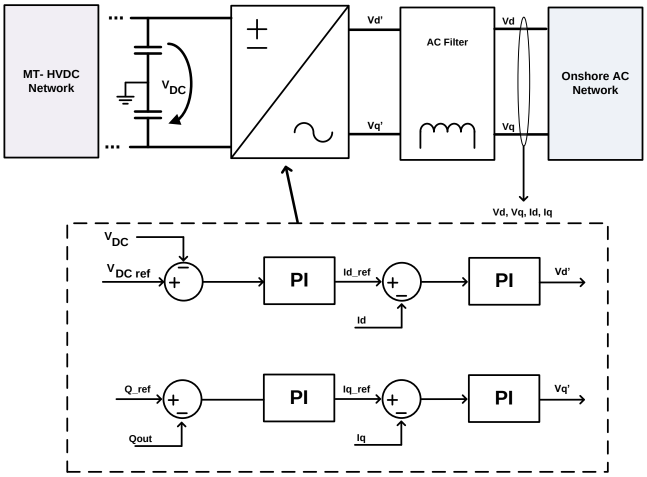

Fig. 2. Internal control loops of the onshore converters.

2) Offshore converter

The offshore converter station acts as a stiff AC voltage source/slack bus in relation to the offshore AC grid for connecting the wind generators [19]. The control philosophy of this converter station consists on setting the AC-side voltage magnitude and frequency. Hence, offshore converters will extract all the available power from the offshore WF and inject it in the MTDC network. The main control blocks used in the offshore converter station are depicted in Fig. 3. The V_d and V_q values are set through PI controllers considering the voltage and current errors in the *d* and *q* reference frame. As aforementioned, this converter will also impose the offshore AC grid frequency. Thus, this converter can impose a fixed frequency or operate with a variable range frequency. Details of this control implementation will be presented and discussed in Section III.

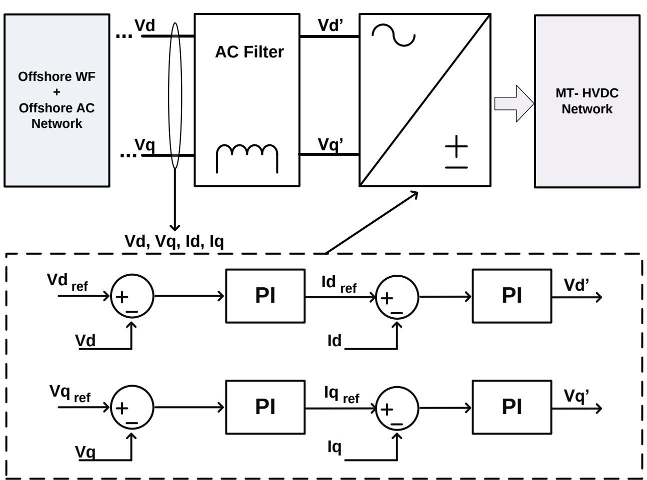

Fig. 3. Internal control loops of the offshore converters.

C. Operation and control of MTDC grids

The general philosophy associated with the control of the MTDC grid consists on controlling DC voltage level at onshore converter stations, while the offshore converter station control the current injected into the DC grid. Therefore, appropriated DC voltage magnitudes should be maintained at each onshore converter station in order to allow proper power sharing among converters in case of power variations such as the ones occurring at the offshore WF level. Regarding these control issues, two approaches can be followed [7, 18]:

1. Maintain a constant DC voltage at a single onshore converter station, which acts as a DC slack bus, while the other offshore converter stations are controlled in order to inject a pre-defined active power into the AC grid. The main drawback of such control is related with the impossibility of the system to continue operation in case of losing the DC slack bus converter station. In case of using such modelling option, the slack bus converter is controlled according to Fig. 2. In the other converter stations, the i_d current reference is calculated based on the corresponding reference and actual injected power into the AC system.
2. Use a droop control approach in order to determine the DC voltage reference at each onshore converter station as a function of the injected power in the AC system (or DC current flowing to the converter station). In this case, DC power variations are shared among the overall onshore converter stations. In such a case losing any converter station potentially allows the DC grid to continue its operation. Therefore, it was considered that each onshore converter sets the terminal dc voltage V_{DC} as a function of the converter active power injection P_{out} into the AC grid, and of a target $V_{DC\ set}$, according to the flowing control rule which is defined based on the active power/ Dc voltage droop coefficient k_{pv} [18]:

$$V_{DC} = V_{DC\ set} + k_{pv} \times P_{out} \tag{1}$$

$V_{DC\ set}$ and k_{pv} are configurable values that can be parameterized in the onshore converter station by an upstream supervision and control system, according to a specific operational strategy envisioned for the onshore AC grid.

D. Wind Generator model

Offshore wind generators are connected through an AC grid connected to the offshore HVDC-VSDC converter. The WF are considered to be equipped with Permanent Magnet Synchronous Generators (PMSG) that are connected to the offshore AC grid by an AC/DC/AC converter. To model the offshore WF, a single equivalent generator model is used, as suggested in [12].

III. Primary Frequency Control Services using Offshore WF Connected by MTDC Grids

In order to endow offshore WF with the capability of participating in primary frequency control services, it is necessary to introduce additional control loops in the HVDC-VSC stations. It is important to mention that the main objective of the additional controls that are integrated at the HVDC-VSC control level is to make possible that the MTDC system contributes to primary frequency regulation (including inertial emulation) exploiting offshore WF, similarly to the inertial and primary response of conventional synchronous generators.

The proposed approach relies on the development of controllers that requires information available only at their terminals. Therefore, the proposed solution can be implemented in a communication-free platform (for the time frame corresponding to the typical duration of the referred frequency regulation services). The rationale of the approach conduct in this work consists on endowing converters with local controllers which make use of the existing DC network infrastructure as a communication pathway. As it was previously mentioned, the use of power electronic interfaces in the MTDC grid fully decouples offshore WF from onshore AC grid. Therefore, in order to make offshore WF to contribute to AC frequency regulation services, it is necessary to explicitly translate onshore AC grid frequency variations in a cascading control structure that firstly affects MTDC grid voltage and thereafter the offshore AC frequency variations to which wind generators are connected. Then, supplementary control loops can be applied at each turbine level, similarly to the solutions used for onshore wind turbine applications regarding their participation on frequency regulation services. The additional controls that are proposed to be implemented at each offshore and onshore converter stations, as well as at wind turbine level are presented next.

A. Advanced HVDC-VSC onshore converter control

The onshore converter is the device responsible for interconnecting the DC network to the onshore AC system. Regarding the operation of the onshore HVDC-VSC converter station, two situations can be identified:

1. Normal operation mode: the load and generation in the onshore AC grid to which the converter station is connected are balanced, thus resulting in very small frequency deviations. In this situation, the offshore MTDC grid operates the HVDC-VSC converters in the active power/DC voltage droop control mode defined by (1) in order to assure the share offshore wind power production variations.
2. Disturbed operation mode: the AC grid frequency to which the HVDC-VSC converter station is connected drops below a certain margin due to any load/generation imbalance. In such situations, primary frequency regulation services are requested to be autonomously deployed in order to stabilize grid frequency.

Regarding the mode of deploying the offshore WF reserves, it firstly requires an additional control mechanism that translates onshore AC grid frequency grid variations to MTDC voltage profile variations. In this case, the onshore HVDSC-VSC converter station measures the terminal frequency and whenever it drops below the referred margin, the active power/dc voltage droop control mechanism is on hold and a new droop control relating onshore AC grid frequency and MTDC voltage enters in operation, according to the following equation:

$$V_{DC} = V_{DC}^{0} - k_{fv} \times P_{out} \quad (2)$$

where V_{DC} is the reference value for the DC voltage at the onshore HVDC-VSC, V_{DC}^{0} is the pre-disturbance DC voltage resulting from the operation of the converter in the normal mode governed by the k_{PV} droop, k_{fv} is the frequency/DC voltage droop and P_{out} is the active power flowing from the converter to the respective AC grid.

The droop control mechanisms that are proposed to be included in HVDC-VSC converter stations are depicted in Fig. 4. Regarding the European Network of Transmission System Operators for Electricity (ENTSO-E) operation rules, conventional generators providing primary frequency control should operate for frequency deviations greater than ± 20 mHz [20]. Therefore it is suggested that onshore HVDC-VSC should switch its operation mode according to this frequency dead-band. For onshore AC grid frequency deviations smaller than the assumed dead-band, the converter should operate inside the dashed zone (see Fig. 4), over the k_{pv} droop line. The solid grey zone shown in Fig. 4 defines a sliding window corresponding to the onshore converters operational zone when the k_{pv} droop mechanism is on hold and the k_{fv} droop mechanism is initiated. This moving window is continuously adapted to the converter DC voltage operation point in order to avoid sudden voltage variations when changing between the previously referred operational modes. For frequency deviations greater than $\pm 20\, mHz$ the k_{fV} droop will be responsible by defining the MTDC voltage operational point at the DC side of the onshore HVDC-VSC. When recovering from the onshore AC grid disturbance, the convertor will smoothly commutate from the disturbed operational mode to the normal operational mode. Thus, the k_{pv} droop will assume the converter control.

The frequency droops can be adjusted centrally in a coordinated way by the system operators according to the specificities of the AC onshore system operating conditions.

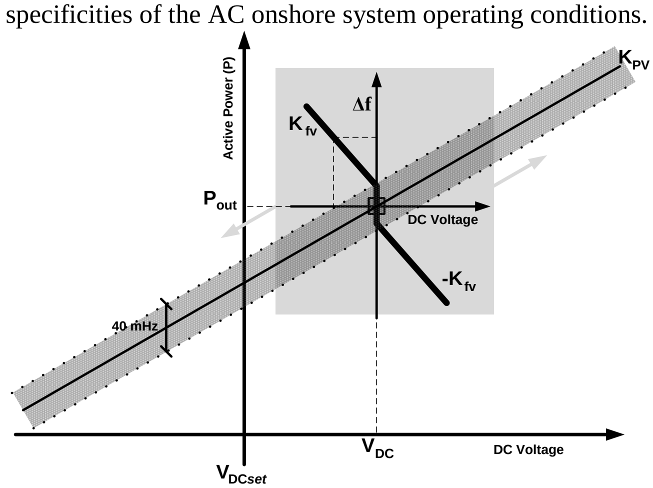

Fig. 4. Droop control mechanisms for HVDC-VSC onshore converter stations.

B. Advanced HVDC-VSC offshore converter control

From the offshore WF side, HVDC-VSC converters promote the interface between the AC offshore WF grid and the MTDC grid. In order to allow offshore WF providing frequency support, additional control rules must be included at the converter level. The cascading control that was previously mentioned must modify offshore WF AC grid frequency based on the DC voltage variation at the associated MTDC grid terminal. Therefore, the offshore HVDC-VSC control should include an additional control mechanism responsible for varying the offshore AC grid frequency proportionally to the MTDC grid voltage variation. This additional control is based on a DC voltage-frequency droop that defines the new AC offshore converter frequency, as depicted in

Fig. 5. The controller will evaluate the local DC voltage variation in relation to the pre-disturbance DC voltage value

$(V_{DC}^0 - V_{DC})$. The DC voltage deviation passes through a dead-band which allows distinguishing the DC voltage profile variations originated by wind power variation from the onshore converter imposed DC voltage variations. The DC voltage deviation will be affected by the K_f gain which will define the magnitude of the offshore frequency drift.

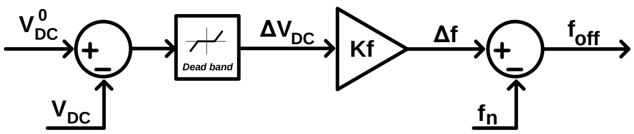

Fig. 5. Droop control mechanisms for HVDC-VSC offshore AC grid frequency.

C. *Wind generators local controllers*

The aforementioned droop control mechanism allows the translation of onshore AC grid disturbances to offshore WF AC grid frequency disturbances. To provide power reserve for primary frequency regulation in wind turbines, it is considered that they are equipped with controllers using a de-loading approach as proposed in [11, 12]. Regarding the provision of primary frequency regulation and inertial emulation capabilities, the power control system of the wind generator includes additional loops responding to the offshore AC grid frequency deviation and to the time derivative of the off-shore AC grid frequency deviations, respectively [12-15].

IV. SIMULATION AND RESULTS

In order to evaluate the effectiveness of the proposed control strategies to be applied at onshore and offshore converter stations, the test system shown in Fig. 6 was used. It consists of two non-synchronous onshore AC areas represented by a single machine equivalent machines that collects offshore power from a 4 terminal H-topology MTDC grid including two offshore WF. Regarding onshore AC grid, only primary frequency regulation capabilities by means of droop control are considered. The offshore WF are composed by PMSG connected to the AC offshore network by an AC/DC/AC converter. Each offshore WF was modelled by a single equivalent machine of 250 MW. In order to promote a reserve margin at the offshore WF the simulations were carried out with a power output of 200 MW in each WF. The MTDC network was represented by its algebraic and state equations. It was also assumed that all DC branches have equal length. Additional data on the test system is provided in Appendix A.

The test system was fully modelled in a Matlab/Simulink simulation platform, according to the dynamic models of the components that were previously described. The simulations carried out on this study are intended to demonstrate the effectiveness of the proposed control strategies and to illustrate the benefits that the possibility of endowing offshore MTDC systems with primary frequency mechanisms may have in terms of the onshore AC network stability. Thus, in order to contrast the AC network frequency behaviour in different situations, four major tests were performed following an onshore AC grid disturbance:

1. MTDC system and offshore WF without Primary Frequency Control Capability (PFCC);
2. MTDC system and offshore WF with PFCC;
3. MTDC system and offshore WF with PFCC and inertial emulation capabilities;
4. Sudden disconnection of an offshore HVDC-VSC, being the remaining MTDC system and offshore WF operating with PFCC.

These simulations allow establishing a qualitative analysis of the adopted control mechanisms.

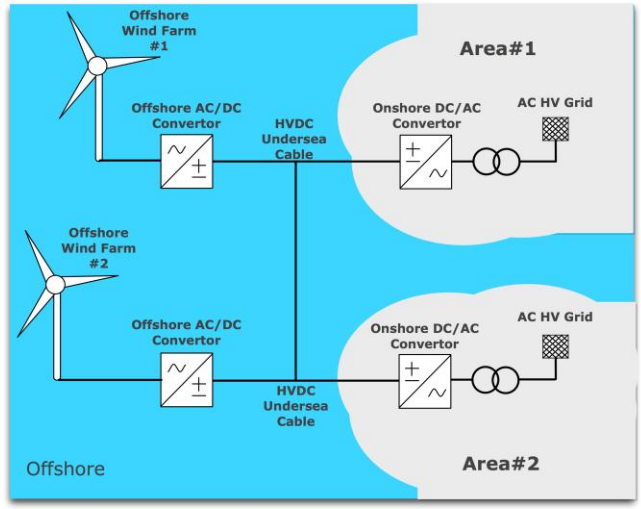

Fig. 6. Test system.

A. *MTDC system and offshore WF without and with PFCC*

As previously stated, this section aims on testing the effectiveness of the proposed control strategy regarding the participation of MTDC system and offshore WF on primary frequency regulation mechanisms following a disturbance in a onshore AC grid. As common basis for the simulations, a disturbance in Area#1 was defined. This disturbance consisted in a step load increase of 200 MW in the onshore Area#1. As it can be observed in Fig. 7, the disturbance leads to a frequency deviation of about 48 Hz in the AC Area#1 if the offshore system has no frequency regulation capabilities. As it is also observed in Fig. 7, offshore WF AC grid frequency as well as onshore Area#2 AC grid frequency are kept constant due to the decoupling introduced by the MTDC system. Resulting also from these decoupling, it can be observed in Fig. 8 and Fig. 9 that MTDC voltage profiles and power flows in the offshore system are not affected by the onshore grid disturbance.

The adoption of PFCC on the MTDC infrastructure improves frequency regulation over onshore AC Area#1, resulting in a smaller frequency deviation, as it can be observed in Fig. 7. In the same figure, it is also depicted the frequency behaviour in the other onshore AC area (Area#2) as well as in the offshore WF AC network. According to the cascading control philosophy that is proposed in this paper, it is possible to observe a frequency variation on the offshore WF AC following the AC onshore network disturbance. This offshore WF grid frequency variation is achieved by means of MTDC voltage variations, as it is shown in Fig. 7. It is important to note that the offshore AC disturbance does not completely follow the AC onshore Area#1 disturbance. This fact is related to the existence of another frequency drift in Area#2. As demonstrated in [21], the appearance of a frequency drift on the AC Area#2 is justified by the power reduction that HVDC-VSC delivered to this network, which is partially transferred for supporting Area#1. The power flow on each MTDC infrastructure terminal is depicted in Fig. 9. It can be observed in this figure that both offshore WF are able to deploy a part of their own reserve margin, coping with the frequency regulation requests from Area#1.

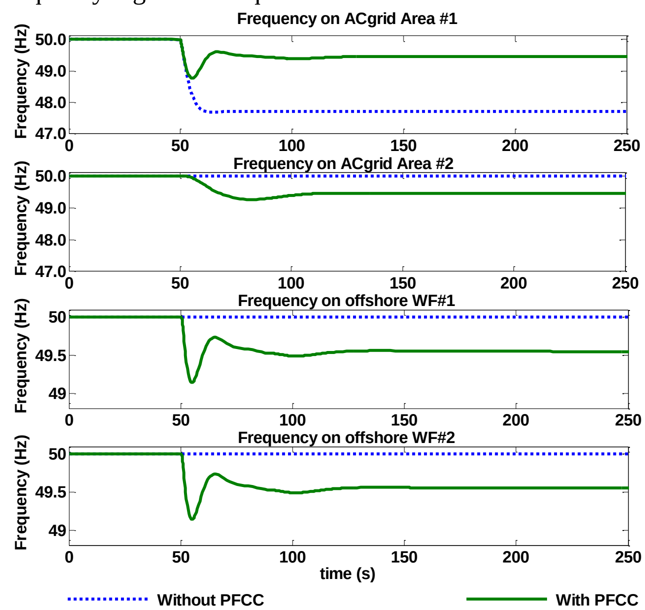

Fig. 7. Frequency behavior in AC-sides.

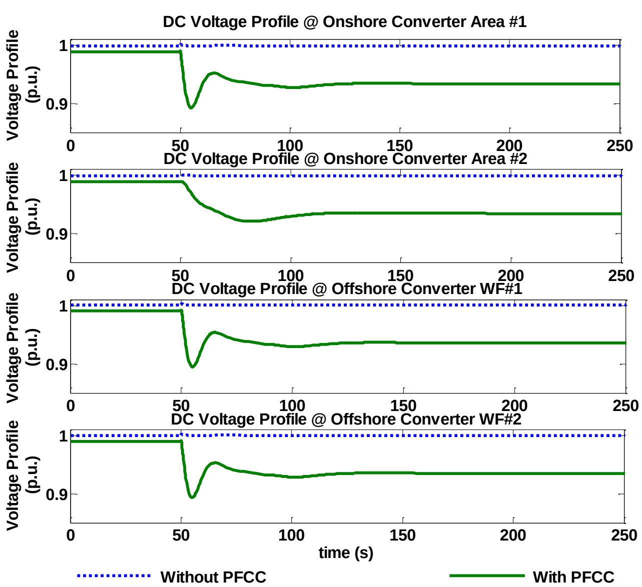

Fig. 8. Voltage Profile at each MTDC network's terminal.

According to the results presented in Fig. 9, it is possible to observe that the AC system Area#2 converter is able to reduce the power injection in this grid, complementing the power support given to Area#1 through the MTDC system. Because of the reduction of power injection from the MTDC system into the AC system Area#2, a frequency drop is observed in this grid. In this case, both onshore converters are operating in the previously referred disturbed operating mode (DC voltage-AC grid frequency droop control), which is responsible for sharing power injection into AC areas according to the magnitude of the frequency deviations.

The offshore HVDC-VSC converter stations control the offshore AC grid frequency based on a droop control function in which the input is the DC voltage variation prior to the disturbance. Therefore, the frequency in the AC grids of the offshore WF is reduced, as depicted in Fig. 7. Based on the control functionalities at the wind turbines, both WF are able to increase their power output within their reserve margin limits.

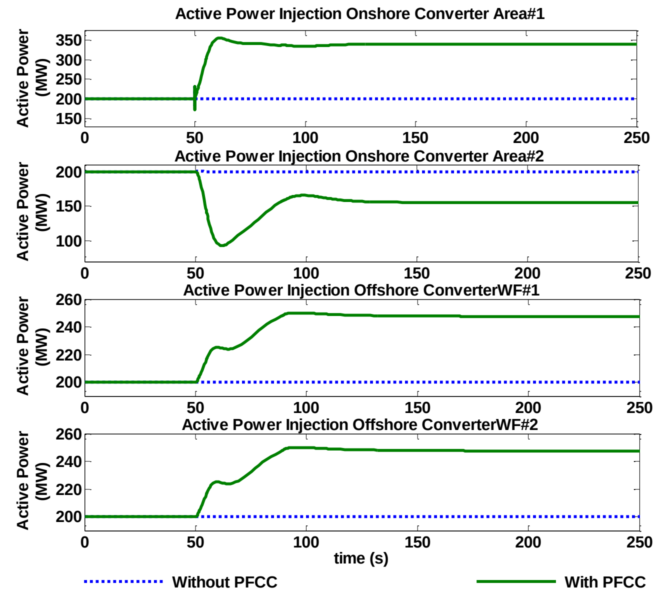

Fig. 9. Active power injection at each MTDC network terminal.

B. Inertial emulation provided by offshore WF

Following the results presented in the previous section, it is now assumed that the wind generators are enhanced with an additional control loop with the purpose of providing inertial emulation, similarly to what happens to conventional synchronous generators connected to onshore AC grids. In order to establish a comparative analysis the same disturbance was applied in AC Area#1. Inertial contribution is based on a fast extraction of kinetic energy from the rotating mass of the wind generator, which is injected in the grid. Therefore, inertial emulation is able to make wind generators injecting an additional amount of power following the disturbance as a function of the time derivative of the offshore AC grid frequency. In Fig. 10 it is possible to observe that the proposed control strategy for the MTDC system is able to make WF contributing with inertial response following the onshore AC grid frequency disturbance. Since inertial contribution has a small duration once it is based on the release of kinetic energy from the wind turbine rotor [13-15], the response of the overall system will tend to approximate to the results presented in the previous section. However, in the moments subsequent to the disturbance it is clear that the MTDC system is able to inject more power than in the case where no inertial emulation functionalities are used (as can be observed in Fig. 10). Regarding the behaviour of the onshore AC Area#1 (Fig. 12), it is possible to observe that inertial emulation capabilities lead to a lower rate of change of frequency following the disturbance. The influence of this contribution is quite dependent on the inertial characteristics of the onshore AC grid.

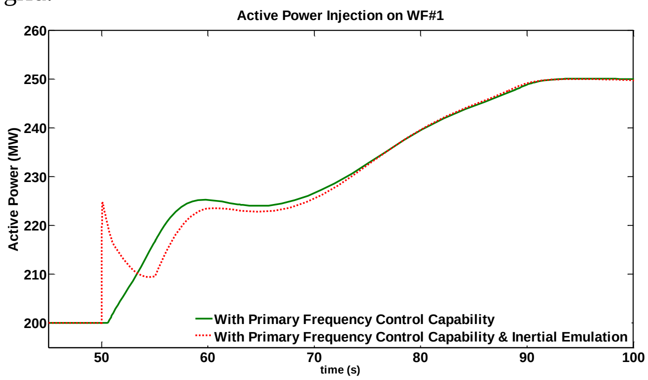

Fig. 10. Active power injected by WF#1with and without inertial emulation capability.

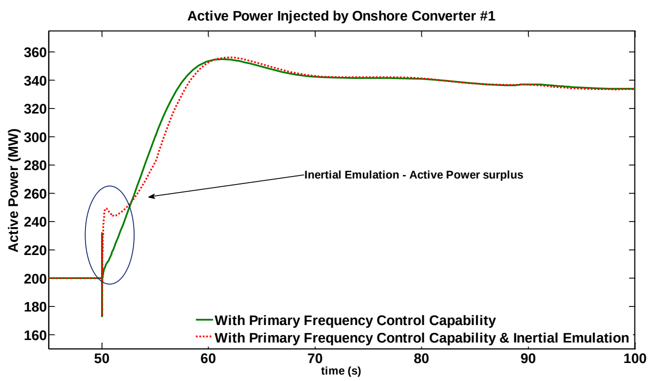

Fig. 11. Active power injected on AC network Area#1 with and without inertial emulation capability.

From the results on Fig. 11, it is possible to verify that the onshore converter placed on the AC Area#1 is able to transmit the quick power surplus to the affected AC network. The effect of power reduction on the inertial emulation can be seen on the total active power delivery to the AC Area#1. Regarding the frequency behaviour, the results depicted in Fig. 12 show that the inertial emulation is effective in the reduction of the frequency rate of descent. This is an interesting result that can be advantageous when having rate of change of frequency (ROCOF) relays in the nearby zones. Having this capability in the offshore WF can distinguish a ROCOF relay tripping / non-tripping situation in the AC network.

C. Sudden disconnection of an offshore HVDC-VSC

The results presented in the previous subsections illustrate the effectiveness of the control strategies for the MTDC system regarding its response to a disturbance in the onshore grids. However, a severe disturbance that consists on the losing an HVDC-VSC offshore converter station will also significantly affect frequency behaviour of the onshore grids. Therefore, this section aims to demonstrate that in the frequency disturbance affecting the onshore AC areas is resulting from a disturbance in the DC side, the proposed control system is also able to cope with the system behaviour by allowing the remaining offshore WF to contribute to frequency regulation (for simplicity purposes, the inertial control in WF is not considered).

The simulation results presented in the next figures illustrate the dynamic behaviour of the system following the sudden disconnection of the offshore converter station 1. As it can be observed in Fig. 13 and Fig. 14, when the operation control mode of the MTDC system is based only on the DC voltage/active power droop control mode, active power is shared between the onshore converters, but the remaining offshore WF is not able to deploy its reserve margin. However, if the PFCC is used in the MTDC converter stations, the remaining offshore WF deploys its reserve margin, thus contributing to a significant reduction in the frequency deviations observed in the onshore AC grids.

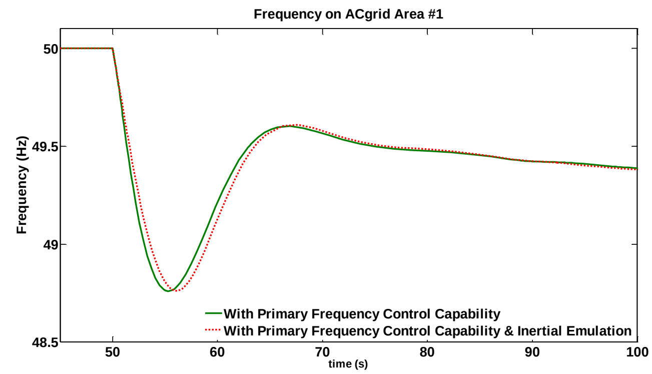

Fig. 12. Area#1 frequency behavior.

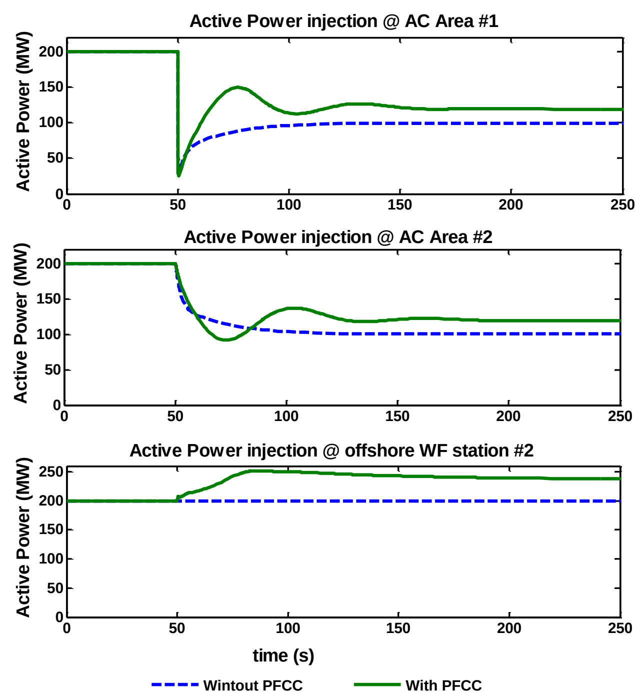

Fig. 13. Active Power at AC Area#1, AC Area#2 and offshore WF#2 HVDC-VSC converter.

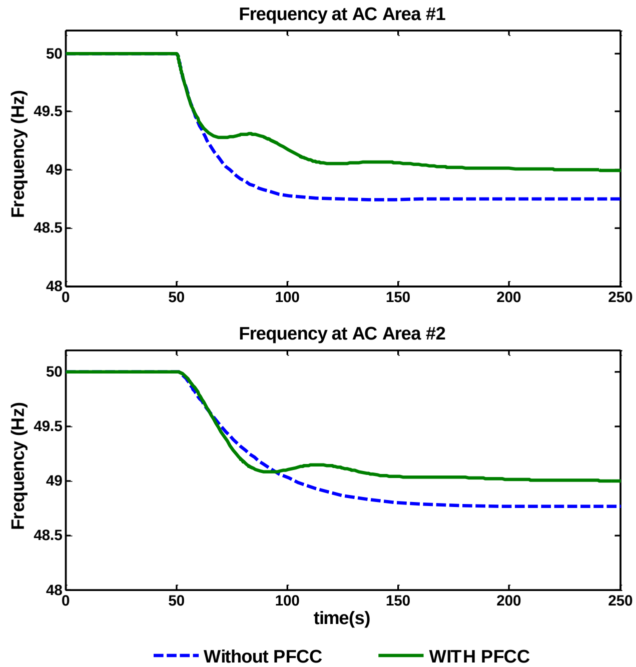

Fig. 14. Frequency behavior at AC Area#1 and AC Area 2.

V. Conclusions

This paper presents an innovative approach to design operation settings of HVDC-VSC converter stations in a multi-terminal DC network connecting offshore WF. Based on detailed simulations of the dynamic model of offshore WF, MTDC systems, and mainland power systems, it shows that offshore WF can effectively contribute to support AC grid frequency, without resorting to remote communication, which could affect the reliability and efficiency of the scheme. Furthermore, results show that the control scheme achieves a significant reduction of frequency deviations in mainland systems.

In the context of a massive development of offshore power generation, the innovative controllers in this paper is expected to help maintaining a high-level of reliability and cost efficiency for mainland systems, in particular for islands connected through MTDC infrastructures. Before applying the control scheme, further work is however needed. In particular, the definition of the controller set points should be in-depth investigated. Also, the reliability of inertia and frequency control reserves with respect to disturbance in the MTDC grid should be studied. Finally, it is necessary to investigate whether the fast-response dynamics induced by the inertia and primary frequency control scheme interfere with the adopted MTDC protection schemes.

Appendix

Table I presents the test system simulation parameters. Regarding the simulation of the onshore AC grids, it was considered a single machine equivalent model, being the turbine represented by a first order transfer function. All the DC cables have a total length of 50 km (R=0.00139 Ω/km, l= 0.159 mH/km).

TABLE I
Simulation Model Parameters

AC network units	
Turbine Governor	
Droop	0.05
T	1.5s
Synchronous Generator	
Apparent Power (S)	5000 MVA
Inertia (H)	10s
X_d	2.040 (p.u. machine base)
X'_d	0.266 (p.u. machine base)
X''_d	0.193 (p.u. machine base)
X_q	1.960 (p.u. machine base)
X'_q	0.262 (p.u. machine base)
X''_q	0.193 (p.u. machine base)
X_s	0.192
Wind Turbine (with PMSG)	
Rated Power (P_{rat})	2.5 MW
Nominal Voltage (V)	690
Rotor radius	42 m
Inertia (J)	$3x10^6$(kg.m^2)
Rotation speed (ω_n)	16 rpm
L_d	0.0016 (H)
L_q	0.0011 (H)
HVDC- VSC	
Onshore Converter (±200 kV, 400 MW)	
Droop K_{pv}	0.05 (*P(p.u.)/V(p.u.)*)
Droop K_{fv}	0.1 (*f(p.u.)/V(p.u)*)
Offshore Converter (±200 kV, 400 MW)	
Droop K_f	0.2 *(V(p.u.)/f(p.u.))*

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