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Inertial Control in Off-shore Wind Farms Connected to AC Networks through Multi-terminal HVDC grids with VSC

The supergrid(s): HVDC and Power Electronics, HVDC Grids and hybrid AC/DC systems

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SUMMARY

The massive interconnection of offshore Wind Farms (WF) brings challenges for the operation of electric grids. The predicted amount of offshore wind power will lead to a smaller ratio of conventional units operating in the system. Thus, the power system will have less capability to provide fast dynamic regulation. Despite of offshore WF being able to inject power on the AC grid through High Voltage Direct Current (HVDC) convertors, they cannot participate on frequency support by the intrinsic decoupling that DC adoption brings. This paper proposes a control methodology, based on local controllers, to enable the participation of offshore WF in primary frequency control. Additionally, enhancements were made on the Wind Energy Converters (WEC) controller to make them capable of emulating inertial behaviour. Tests were performed in a multi-terminal DC network with two off shore wind farms to assess the feasibility and effectiveness of the concept in a communication-free framework.

KEYWORDS
Ancillary Services, Frequency Support, Inertial Emulation, Multi-terminal HVDC, Offshore WF, Primary Frequency Control.

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INTRODUCTION

Wind energy will be the most prominent renewable resource that will be used in Europe to contribute to GHG emission reduction by 2050 [1]. However, the restricted licensing rules, spot unavailability, resource scarcity or lack of on-shore promising sites in some countries is forcing the exploitation of offshore resources, namely wind energy. Formerly, one of the major constraints of offshore Wind Farms (WF) is related with the problems in the deployment of long AC submarine cables to interconnect the offshore facilities with the mainland network. Nowadays, with the consolidation of High Voltage Direct Current (HVDC) technology, this issue no longer exists and it is possible to efficiently transmit large amounts of power for very long distances. Additionally, the use of HVDC technology based on Voltage Source Converter (VSC) makes possible gathering several offshore WF facilities in a multi-terminal HVDC system, which is an important characteristic that can be used to increase the offshore WF reliability.

The integration of large amount of renewable generation units in the power systems implies, usually, a dispatch with less conventional units. This might be critical, given that the systems inertia and the capability to perform frequency control will be reduced [2].

This paper demonstrates the possibility of using HVDC multi-terminal network converters, endowed with proper control characteristics, to improve the AC grid stability, regarding frequency control, in the moments subsequent to a severe disturbance. To accomplish the proposed objective, proper control loops were developed and integrated in each Wind Energy Converter (WEC) in the offshore WF. These control loops enable the WF operation as a Virtual Power Plant (VPP), providing them the capability of emulating the inertia of a conventional power plant.

OFFSHORE WIND FARM AS A VIRTUAL POWER PLANT

The adoption of Multi-Terminal HVDC (MTDC) networks enables the interconnection of several geographically dispersed offshore WF to a single or multiple onshore AC grids. The rationale of gathering the offshore WF is based on the cost reduction for cables acquisition and deployment, reliability increase, by permitting DC network reconfiguration and, finally, facilitating the operation of the WF as a Virtual Power Plant (VPP). The concept of a VPP consists on exploring a set of Distributed Generation (DG) as a conventional unit. This concept is often related with market issues, where joint energy packs produced by different generation units are presented in the electricity market as a single bid. Additionally, VPP are also capable of performing regulation tasks by offering ancillary services that can be used to enhance the system's reliability [3, 4].

Although being fairly easy to integrate HVDC systems in the electricity markets framework, by exploiting the concept of VPP, its usage to provide ancillary services to the AC mainland grid can be a rather complex task. This fact is related with the decoupling between AC connected zones in what regards frequency and voltage. Thus, the VPP will not be able to sense the variations of these variables in the AC mainland grid, not being capable of supplying the proper ancillary services. To deal with this problem, two approaches might be followed.

The first consists on relaying on a central controller that collects all the required data from AC grids and offshore WF, processes the information and sends set-points to the WF to adjust their operation in accordance with the current AC network status. To achieve such complex control, bidirectional, fast and accurate communication links should be established between the controller and all the MTDC network nodes. This approach might be very expensive and, in case of communications failure, it might interfere with the overall MTDC reliability.

The second, which is the one studied in this paper, consists on the adoption of local controllers on the MTDC onshore converter, with the objective of masking AC system variations in the DC voltage profile. Simultaneously, offshore converters should be also endowed with proper control procedures to translate the DC voltage variations into a frequency deviation in the AC WF offshore network. This methodology is very likely to be less expensive and much more reliable, since it will be a communication-free solution, relying only on the existing infrastructure.

MODELLING VPP CONSTITUENTS

To operate a set of offshore WF as a VPP, some key infrastructures and components must be included and modelled as VPP constituents. Thus, it is considered that all components that promote the power delivery, from the generation point to the mainland AC grid collection point, are part of the VPP. In the particular case study addressed in this paper, two offshore WF with Permanent Magnet Synchronous Generators (PMSG), with maximum power of 250 MW, each, were interconnected to two AC independent networks by a multi-terminal HVDC infrastructure, operated at $\pm$300kV, as depicted in Fig. 1.

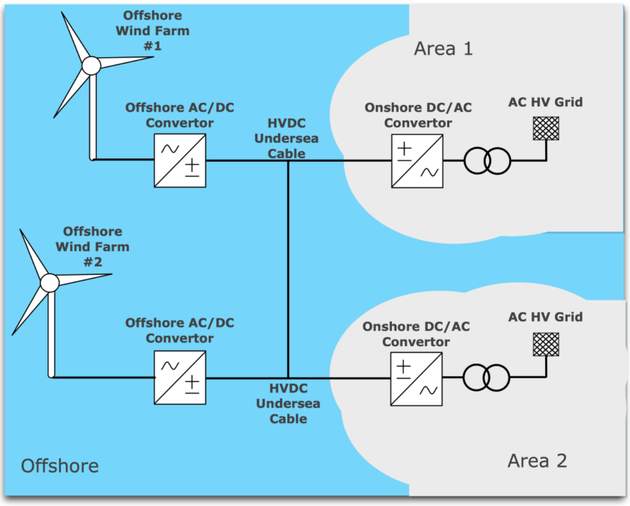

Fig. 1: Adopted MTDC topology

The simulations performed were carried out in Matlab/Simulink software, being each component modelled by its algebraic and state equations on a DQ frame. The modelling of the MTDC cable circuit was accomplished by defining the electric circuit's equations for bipolar DC cable. The topology shown in Fig. 1 was modelled following the methodology proposed in [5]. The converter stations were represented by their control loops that were developed to perform as described next:

- The offshore converters were designed to act as the slack bus for each the offshore WF AC networks. Therefore, they impose a stiff voltage and deliver all the generated power to the HVDC network. Additionally, these converters operate with variable frequency around the nominal value.
- The onshore converters were designed to maintain the DC terminal voltage at a specified value, which can be controlled by the amount of power delivered to the AC onshore network. To guarantee the power sharing between the converters, an additional Active Power/DC voltage droop was included in each converter control loop, being the converters' voltage set-point defined by:

$$V_{DC} = V_{DC_{ref}} + k_{pv} \times P_{inj} \tag{1}$$

Where V_{DC} is the desired DC voltage value at the onshore converter's terminal, $V_{DC_{ref}}$ is a constant reference value (can be changed by the grid operator to promote a dispatch through power sharing), k_{pv} is the Active Power/DC voltage droop and P_{inj} is the active power injected by the convertor into the AC grid. The inclusion of this Active Power/DC voltage droop enables the power sharing between the converters, depending on the available generated power. The definition of equal $V_{DC_{ref}}$ and k_{pv} values guarantees that the active power delivered to each AC system is equal (within this network topology). The definition of the $V_{DC_{ref}}$ value will dictate the contribution that each converter will have on the active power that will be delivered to the respective AC grid.

LOCAL CONTROLLER TO ENABLE FREQUENCY SUPPORT

Nowadays, in some European countries, WF are required to provide frequency support by providing additional active power during AC system disturbances. Several authors have investigated the possibility of endowing WEC with proper mechanisms to making them able to supply frequency ancillary services, such as primary frequency control and inertial emulation. In [2, 6, 7] it was introduced the concept of reserve on the wind power generation, being shown that primary frequency control can be easily performed by WEC, by keeping the generators operating below their maximum capacity. The inertial emulation, together with primary frequency control, has also been investigated in [2, 8]. As referred previously, the physical decoupling of the frequency between the interconnected zones, the offshore WF and AC grids, is the main obstacle that impedes offshore WF to provide frequency support to the AC grids. To overcome this obstacle, it was developed in this paper a controller that consists on transposing the mainland AC frequency deviation into a DC grid voltage deviation. To achieve this objective, an additional Frequency/DC voltage droop was included in the onshore MTDC converter control loop. Thus, the control presented in Eq. (1) was enhanced, being represented by:

$$V_{DC} = V_{DC_{ref}} + k_{pv} \times P_{inj} + k_{fv} \times (f_{ref} - f) \quad (2)$$

where k_{fv} is the Frequency/DC voltage droop, f_{ref} is the AC reference frequency value and f is the current frequency value. This new relation allows not only reproducing the AC mainland frequency deviation on a MTDC network voltage deviation, but also propagating the DC voltage profile within the MTDC network terminals. This way, offshore converters will be capable of sensing the DC voltage deviation and translate it to a frequency deviation in the AC offshore network where the wind generators are located. To achieve this last step, an additional control loop has been included on the offshore converter, as expressed in Eq. (3):

$$f_{off} = f_{off_{ref}} + k_{vf}(V_{DC_{ref}} - V_{DC}) \quad (3)$$

As mentioned previously, to comply with primary frequency support, the WEC controller must be designed to respond to frequency deviation by increasing the active power injected. To test the performance of the methodology proposed in this study, the two offshore WF presented in Fig. 1 have been modelled with the PMSG operating with a "de-loaded" power curve. To increase the output power, the WEC controller changes the pitch angle of turbine's blades, extracting more power from the wind, thus generating more active power. In addition, the WEC controller was also endowed with the capability of emulating inertial behaviour, by adding a supplementary term that varies with the frequency derivative.

The overall control rule for providing frequency support and inertial emulation can be described by the block diagram depicted in Fig. 2.

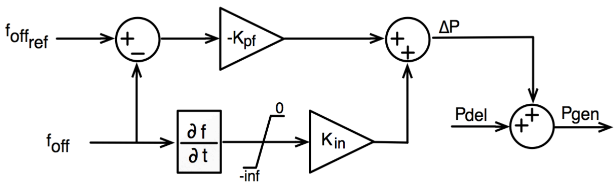

Fig. 2: WEC frequency and inertial emulation control loop

where P_{gen} is the generated active power, P_{del} the normal operation "de-loaded" power, k_{fp} the Active Power/frequency droop, $f_{off_{ref}}$ the reference frequency value, f_{off} the current frequency value (defined by Eq. (3)), $\frac{df_{off}}{dt}$ the frequency rate of change and k_{in} the inertial emulation gain.

According to the control loop presented on Fig. 2, the generated active power will increase if the AC offshore frequency decreases and, simultaneously, an additional power output will be collected from the rotor speed, proportionally to the frequency decrease rate.

SIMULATION AND RESULTS

A set of simulations were carried out for the study case depicted in Fig. 1 aiming to test the effectiveness of the proposed control methodology. Three different cases were simulated. In the first, named “Without Frequency Control”, the convertors control did not included the control rules expressed in Eq. (2) and (3). In the second, denominated by “Primary Frequency Control”, all control loops were included, except the inertial behaviour. In the third, the so called “Primary Frequency Control + Inertial Emulation”, all the control loops were included. To test the VPP behaviour, under the same circumstances, a load increase was simulated on AC grid #1 for all the cases. The obtained results are presented in Fig. 3 and Fig. 4.

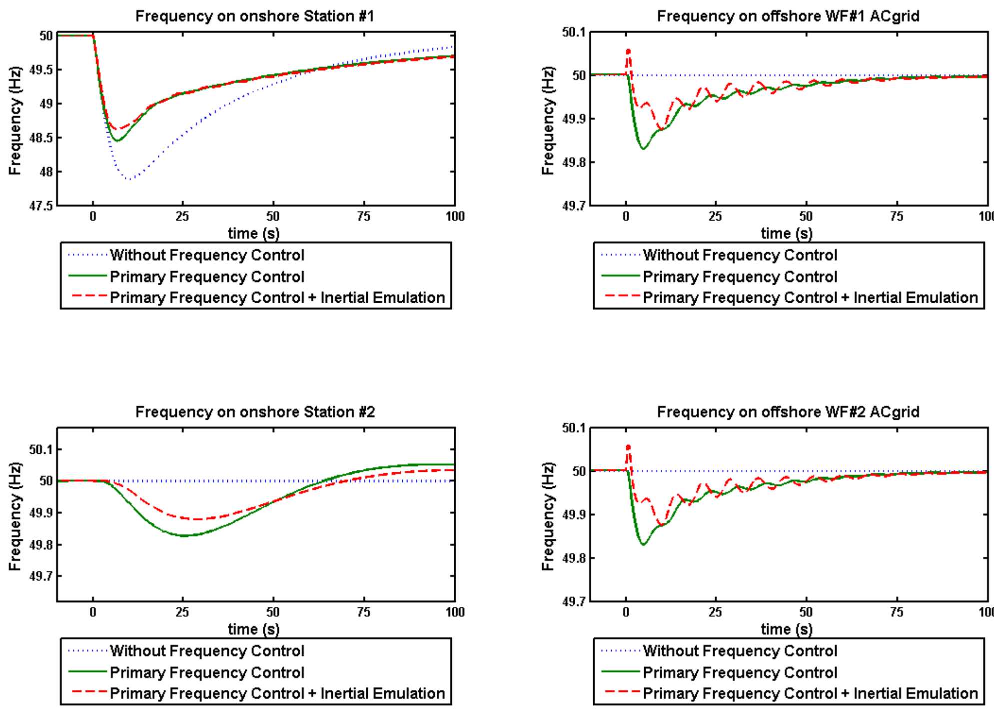

Fig. 3: Frequency behaviour on mainland and offshore AC networks

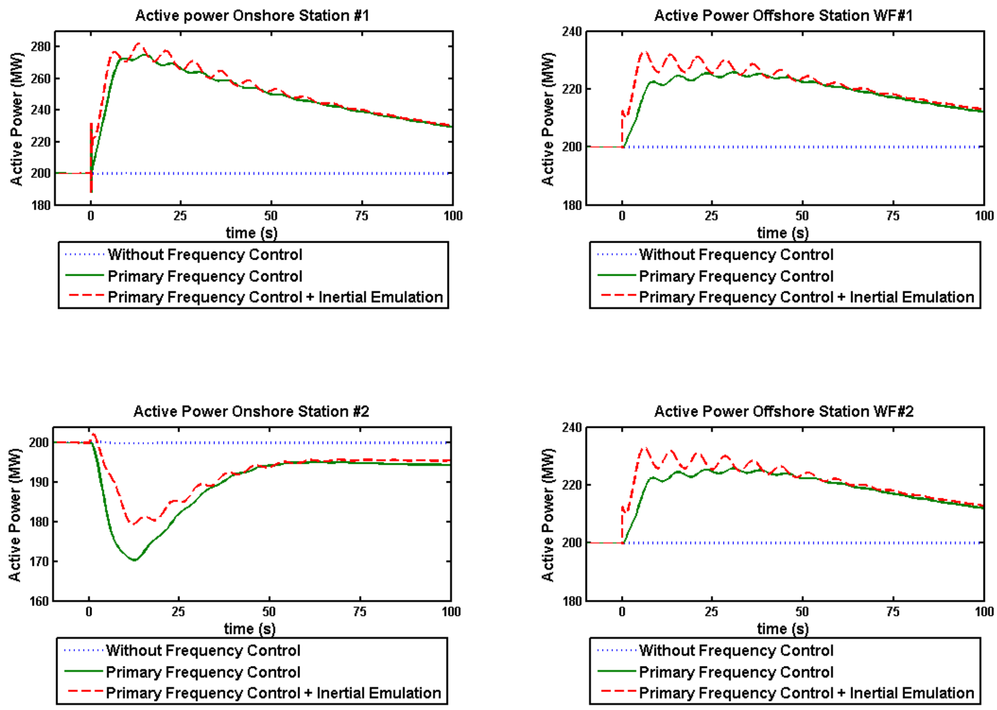

Fig. 4: Active power injected/collected by HVDC converters

For the base case (without frequency control) it is possible to verify that AC grid#1 frequency drops under 48Hz. Nevertheless, the AC offshore frequencies and the AC grid#2 remain unaltered since the converters are not parameterized to reproduce the frequency deviations on DC voltage profile variations. So, neither offshore WF nor AC grid #2 contributes with active power injection towards the AC grid #1 frequency restoration. When the new control rules are imposed, in case two – "primary frequency control", it is possible to verify that the frequency drop on AC grid #1 was not so severe, due to the power contributions from both the AC grid#2 and the offshore WF. Though, it is important to stress that the contribution provided by AC grid#2 led to a minor frequency drop in this area, as depicted in Fig. 4. For the third analysed case – "Primary Frequency Control + Inertial Emulation", it is possible to verify that the offshore WEC are able to respond to the frequency deviation rate, by rapidly supplying an active power surplus. This power surplus is then delivered to the onshore networks, contributing to the reduction of the frequency sag. This contribution, despite being small, might be extremely important to avoid under-frequency protection tripping.

CONCLUSIONS

The adoption of innovative control approaches by the convertor stations of multi-terminal DC offshore wind farms as proposed in this paper proved that offshore WF are capable of contributing to support AC grid frequency, without resorting to fast communication technologies. The control approach implemented is local, what makes the generators located at each network terminal respond differently, in accordance with the local DC voltage variation. Additionally, results have shown that the inertial emulation control implemented enables the provision of inertial behaviour to AC onshore grid, by offshore WF and HVDC VSC, leading to onshore smaller frequency deviations.

The control method developed proved to be very effective on dealing with some dynamic problems that might be a concern for large scale integration of offshore WF.

ACKNOWLEGMENTS

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