Damping Power System Oscillations by VSC-Based HVDC Networks: A North Sea Grid Case Study

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***Abstract*— This paper introduces a control strategy for damping of onshore power system oscillations through a voltage source converter based HVDC offshore grid. Time domain simulations are performed for a North Sea grid case study where the DC grid connects two asynchronous power systems as well as offshore wind power plants. Dynamic equivalents of the Nordic and the UK power systems are used. Simulation results demonstrate the capability of the VSC-based multi-terminal DC grid to improve onshore power system small signal stability. However, the results reveal undesired interactions between different converters in the DC grid when some are implementing power oscillation damping. This paper proposes a coordinated control scheme between onshore voltage source converters and the offshore power plant modules (PPM), to compensate for these unwanted disturbances by making use of the available energy from offshore wind PPMs.**

***Index Terms*—VSC-HVDC transmission, multi-terminal DC grid, power oscillations damping, offshore wind integration, small-signal stability**

I. Introduction

High voltage DC transmission based on voltage source converter technology (VSC-HVDC) is becoming a mainstream alternative for the grid connection of large-scale offshore wind power plant modules (PPM) located far from shore. The controllability of VSC-HVDC allows additional control features such as power oscillation damping (POD) of AC-system inter-area oscillations as well as multi-terminal VSC-HVDC (VSC-MTDC) operation within envisaged transnational offshore grids.

This paper explores the POD functionality provided by VSC-based HVDC systems interconnecting transnational grids and demonstrates it on a future North Sea grid case study. Such a situation, in which multiple synchronous areas are involved, complicates the application of POD controllers to VSC-HVDC units for improvement of onshore power system small signal stability. The contribution of this paper is to both quantify and also compensate for the perturbed DC voltage due to adding POD controllers to the VSC-MTDC grid. As such, the results shown in this paper could be useful for future grid code designs that encompass transnational offshore grids.

This study has been performed on a realistic test system, which consists of dynamic equivalent models of the UK and Nordic power systems [1], [2] and a five-terminal VSC-MTDC network. This network interconnects a total amount of 800MW offshore wind power to the two synchronous areas. The landing points are assumed to be the North Scotland coastline and the Norwegian Southwest coastline. Both AC systems are implemented in PSS®E using standard models while the VSC-MTDC grid is added via a user-written dynamic model. For the case of offshore wind power plant modules, standard improved full converter wind turbine models from PSS®E have been used.

The paper is organised as follows: Section II introduces the modelling approach for VSC-MTDC networks and discusses its main controllers. The simulation results as well as the main discussion and analysis are presented in section III. The conclusions are drawn in section IV.

II. Modelling Framework

A. Model of VSC-Based HVDC Systems for Bulk Power System Stability Studies

A VSC terminal consists mainly of the power electronic interface, the modulator system, the inner controller which gives the voltage reference set points, outer controllers and appropriate fault ride-through equipment. For this study the DC chopper method is used for FRT of the VSC-MTDC grid. Fig. 1 illustrates the block diagram of such a VSC terminal.

The outer controllers are responsible for setting the VSC active and reactive current set-points. These current set-points are the outputs of the DC voltage and active/reactive power controllers. The phase reactor is needed to provide an angle displacement for the vector control next to operating as a low-pass filter for the high frequency current harmonics in the AC terminal of the VSC. i_{abc}, is the instantaneous current

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flowing through the phase reactor while U_{dc} is the instantaneous DC voltage amplitude across the DC terminal capacitor.

The time-averaged modelling approach is commonly used to represent VSC-based HVDC transmission systems in power system stability studies. Note that only AC side disturbances will be simulated. A VSC is modelled as a controllable three-phase AC voltage source at the AC side, while at the DC side it is modelled as a DC current injection in parallel to the equivalent model of the HVDC cables.

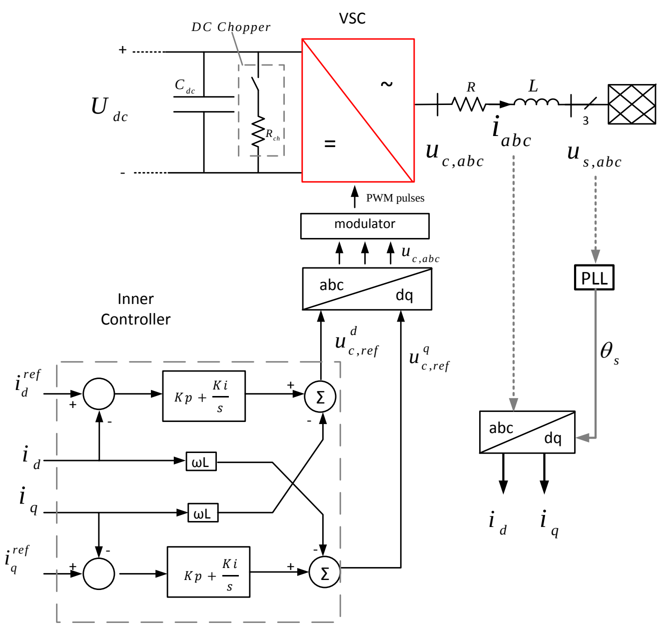


Fig. 1 Block diagram showing the relevant control modules of the VSC-based HVDC system

Due to the transient and small-signal stability scope of this research, all currents and voltages at the AC side are assumed to contain only fundamental-frequency components and are assumed balanced. This allows the neglect of detailed IGBT commutation and switching modelling, and allows voltages and currents to be represented by quasi-stationary phasors.

At the DC side, the current injection is calculated from the active power balance between the AC and DC side. The HVDC cables for the MTDC connection are modelled by lumped π-equivalent models which are combined in a state-space representation.

Finally, the control of the DC voltage is important for the stable operation of the MTDC grid. In a VSC-based MTDC network there must be at least one VSC-HVDC station responsible for the control of the DC voltage [3]. The DC voltage controller regulates the converter's active power based on given droop line characteristics, as can be seen in fig. 2a, maintaining the DC voltage within stiff operating limits. For completeness, the AC voltage controller which provides reactive power support is shown in fig2b.

B. Damping of Onshore Power System Oscillations by VSC-Based HVDC Grids

Significant damping of power system oscillations can be achieved when the active power flowing through transmission lines is modulated [4], especially in the situation where the transmission line is interconnecting two areas which oscillate against each other [5]. This technique has demonstrated significant success in radial HVDC transmission systems that operate in parallel to high voltage AC transmission lines [6].

The modulated active power by the converter stations at the end of the HVDC lines can accelerate (or decelerate) the local generators thus contributing a net damping effect to the power system [7]. In addition, generators in the remote system are only slightly affected. The technique of active power modulation at the terminal of HVDC lines could in principle be used with onshore VSCs that operate in multi-terminal VSC-MTDC offshore networks as well.

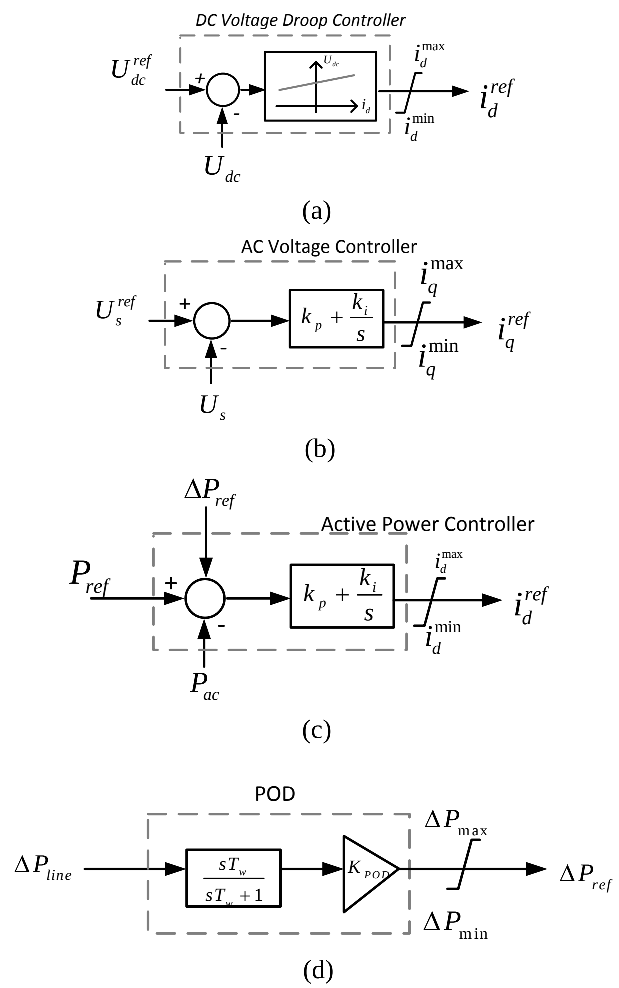


Fig. 2 Outer Controllers providing current references: (a) DC voltage droop controller, (b) AC voltage controller, (c) Active power controller, (d) POD controller operating as a supplement to the active power controller

As it has been discussed there are converters in the DC grid which perform DC voltage control and converters which operate in active power control mode, applying the controller in fig. 2c. The latter converters, next to their ability to transport constant active power, could also integrate a POD controller, as given in fig. 2d. It modulates the active power at the AC terminal of the VSC under post-fault conditions. In this way, the onshore VSC contributes a net damping effect for low frequency power system oscillations.

The classical power system stabilizer (PSS)-type POD that has been introduced in [6] [8] has been successful in terms of damping power system oscillations and has been applied in a number of radial HVDC applications. However, the application of such PSS-type POD needs careful design and parameter selection, especially when used in (multi-terminal) HVDC applications. A badly-tuned POD may amplify instead of damp power system oscillations introducing thus a negative damping effect to the onshore power system.

Another POD solution, originally adopted for the design of power system stabilizers implemented in full converter direct drives wind turbines [7] [8] is proposed in this paper, as shown in fig. 2d. The controller employs a washout filter with time constant T_w, so that the power set point is not affected in steady-state. The input could be the speed deviation of the closest generator or active power flow of a transmission line. The output is used as an input to the active power controller of the onshore VSC.

The operation of this simple POD controller is based on basic physical considerations [7] and does not require the design of special lead/lag compensators as in the PSS-type POD. A typical washout time constant of 10-20s can be applied and the only degree of freedom is the gain K_{POD}, which determines the damping effect and the power system poles displacement. Therefore, the POD can be designed for every application without sophisticated tuning, simplifying both the design and its application. The only necessary constraint is the determination of the specific mode in the system which is both observable and controllable by the given onshore VSC. This method is further extended in section III.D from individual onshore VSC terminal to coordinated operation of onshore VSC and offshore wind Power Plant Modules (PPM).

III. Simulation Results

A. North Sea Grid Case Study

In this paper we introduce the coupling of the UK equivalent benchmark power system model as given in [1] with a Nordic equivalent system [2]. The generated power from the two offshore wind PPMs (2x400 MW in this case study) is transported onshore via the VSC-MTDC network to both asynchronous power systems. The control of the direct voltage in the VSC-MTDC offshore network is performed by the two onshore VSCs of the Nordic system which both implement the droop control shown in fig. 2a.

All generators (mainly equivalent generators that represent areas in the UK system) are modelled by the 6^{th} order standard IEEE dynamic model using dedicated parameters, taken from [1]. This study uses standard IEEE excitation and governing (TGOV1 & SEXS) model.

The proposed UK equivalent model exhibits various local modes and one inter-area mode of electromechanical oscillations. The inter-area mode is 0.5 Hz for this particular case study, and occurs between the North part of UK system (which represents North and South Scotland) and the South part which represents the main and South England).

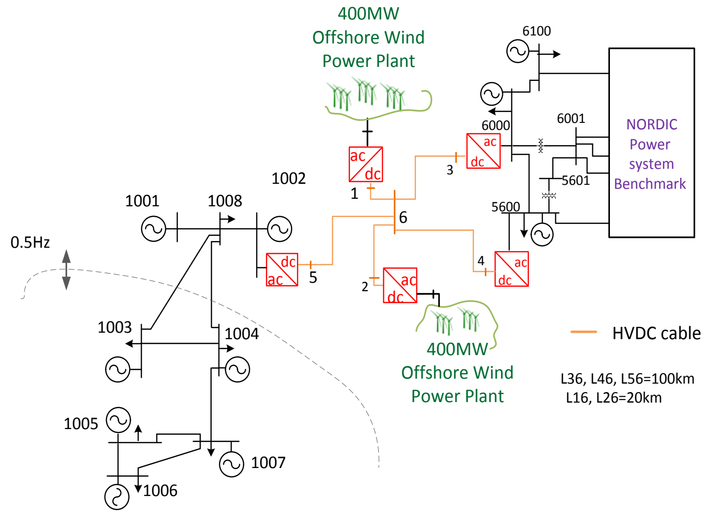


Fig. 3 A North Sea grid case study. UK and Nordic system benchmark models, coupled via a VSC-MTDC grid for offshore wind power and trade.

The detailed Nordic system consists of 3000 buses, 4000 branches and 1100 generators. It was reduced to an equivalent benchmark model of 36 buses including 20 large generators, which represent each area in the Nordic system. Standard IEEE 6^{th} order models of the synchronous generators have been used, with IEEET2 excitation system and IEEEG0 governor models. Power system stabilizers STAB2A are in operation at certain generators in the Nordic system. This model is capable of reproducing the well known inter-area modes of the Nordic system [2].

B. Analysis for a Three-Phase Fault in the UK System

Fig.4 introduces the rotor speed (SPD) response of the generators in the UK system for a self-cleared 140 ms symmetrical three-phase fault at bus 1007. It can be seen that apart from the local modes (which are clearly fast damped) there is also an inter-area mode of 0.5 Hz frequency with poor damping.

From the time domain simulations shown in fig. 5, it can be observed that the AC-side voltage drop at the AC terminal of the onshore VSC at bus 1002 creates an active power drop at the onshore VSC 1002, fig. 6b. Following the disturbance, the power balance at the DC capacitor is lost and the direct voltage at the DC side will rise, as shown in fig. 6a. However, for this disturbance the DC overvoltage is below the DC chopper threshold (1.1 p.u.), and the chopper is not activated. After the fault is cleared, both direct voltage and active power return back to their pre-fault operating point in a short time.

The active power response of the converters clearly demonstrate the well known argument that VSC-based HVDC systems are not participating in the electromechanical modes of the onshore power system if no control actions are taken.

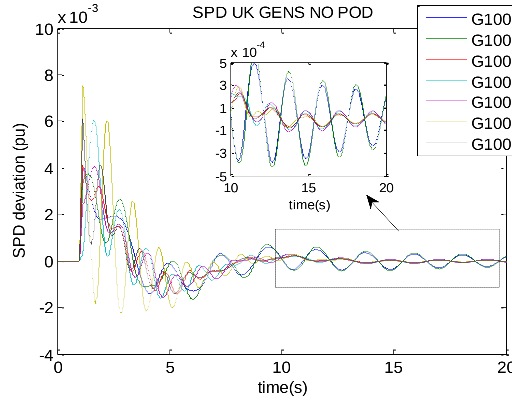


Fig. 4 UK system generators response for 140ms symmetrical fault.

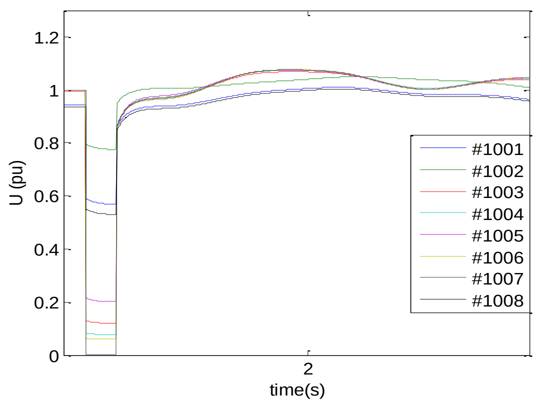


Fig. 5 Voltage response of the UK benchmark system.

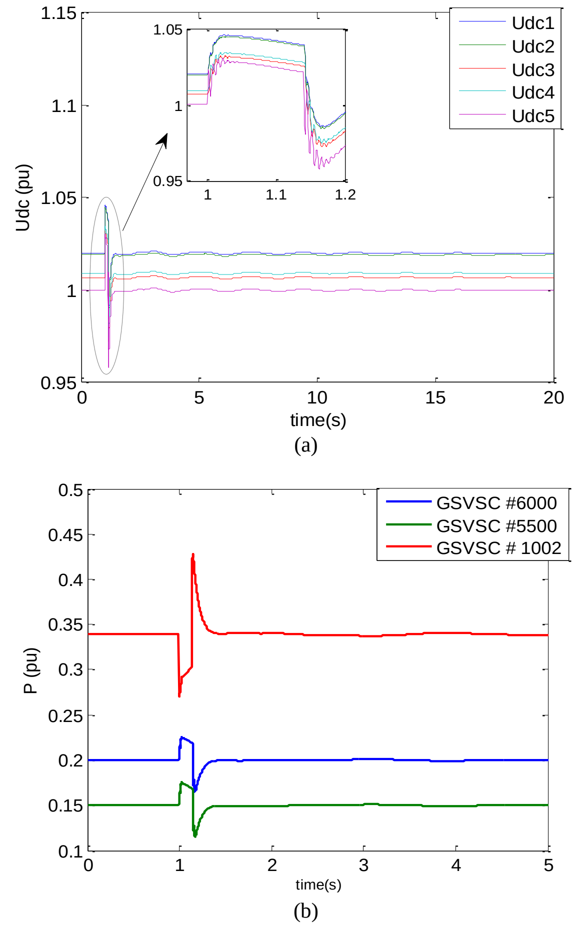


Fig. 6 (a) DC voltage response at the terminals of the VSC-MTDC. (b) Active power response of the onshore VSCs (1000MVA base).

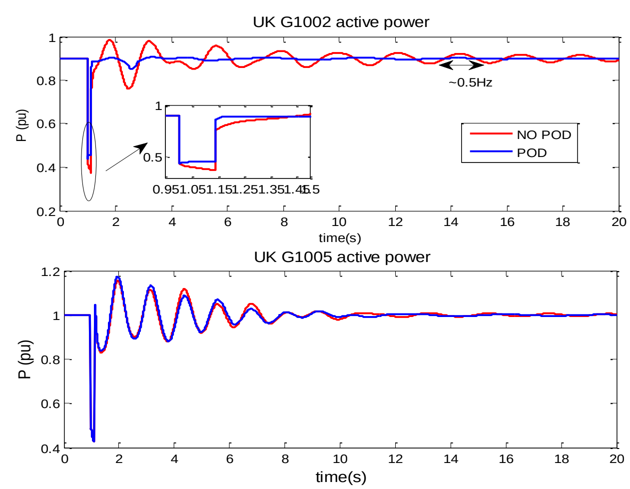


Fig. 7 UK benchmark system generator response with and without POD at the onshore VSC of bus 1002 (1000MVA base).

C. Stabilizing Onshore Power Systems via VSC-MTDC

In this section we present the time domain response of the UK test system model when the onshore VSC at bus 1002 is equipped with a POD controller. Comparing the response of the synchronous generators' active powers it is clear that there is a positive effect of the proposed POD on the small signal stability of the UK power system. Fig.7 shows the time domain simulations for selected generators with and without the POD at onshore VSC 1002. As can be seen, this simple type of POD controller is not only a simple approach for damping inter-area modes of electromechanical oscillations but it neither negatively influences the other generators in the same system (at least for the case studies presented in this paper).

Fig. 8 illustrates the active power variation of the onshore VSC at bus 1002 in the UK system, as modulated by the POD. In this graph it can be seen how the onshore VSC active power is varied in order to stabilize generator at bus 1002. It is important at this point to refer to the limiter of the POD (see fig. 2d). As it can be seen the limiter of the POD is responsible for limiting the variation of the active power within acceptable levels. The main reason for restricting the VSC active power is the triggered direct voltage variations created in the MTDC network as it can be seen in fig. 9. The selection of the limiter is a trade-off between higher damping action and DC voltage maximum allowable variation.

These direct voltage variations in fig. 9 appear instantly at all DC nodes of the VSC-MTDC grid. It can be argued that the DC grid behaves like a large capacitor and the DC voltage variation is equivalent to the way that frequency behaves in AC power systems. So, in DC grids, the introduced variation of power from one VSC to damp onshore power system oscillations will create direct voltage oscillations of same frequency at all DC terminal voltages.

What is important to note is the fact that these DC voltage variations are reflected in the active power of the Nordic system converters' as shown in fig. 10 as a result of their DC voltage droop control, introduced in fig.2a. Consequently, damping of power oscillations in one asynchronous power system, such as the UK system, can be achieved, but special care needs to be taken in order not to propagate this mode via the MTDC grid to a second asynchronous power system (Nordic in this study).

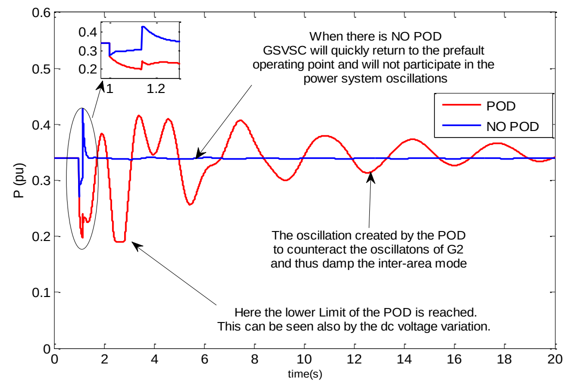


Fig. 8 Response of the onshore VSC 1002 of the UK system with and without POD in operation (1000MVA base).

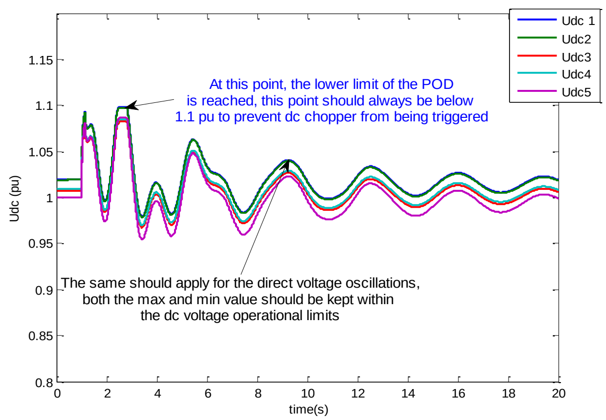


Fig. 9 DC voltage variations created by the modulated active power of the onshore VSC as a result of the POD.

D. *Coordinated Operation of the Onshore VSC and Offshore wind PPMs*

In order to cancel the disturbance added to the DC grid by the operation of stabilizing POD control, the POD output signal is also sent via a communication link to the controller of a offshore wind power plant. As a result the active power of the wind power plant is varied accordingly so that the power balance in the MTDC grid is not changed significantly. In this work, communication link delays are not considered. Fig. 11a introduces such a control scheme. Only one offshore wind PPM is considered enough for counteracting the effect of the POD at the onshore converter. Fig. 11b shows the park level control, which implements such a damping scheme.

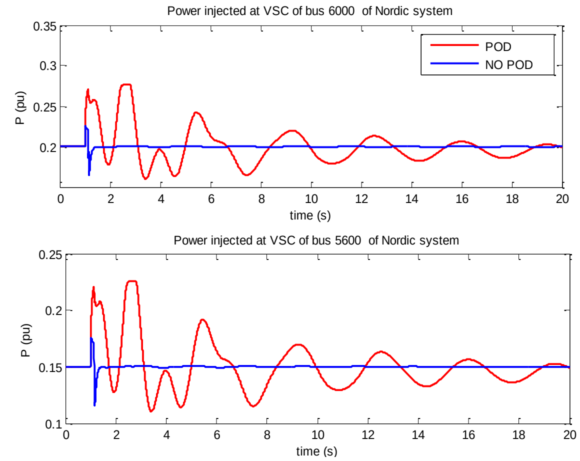
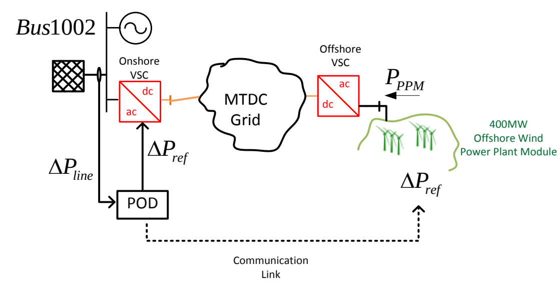
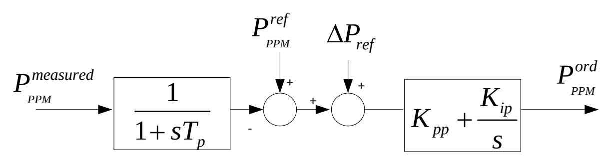


Fig. 10 Responses of the onshore VSCs connected to the Nordic system (1000MVA base).



(a) Coordinated control with communication link

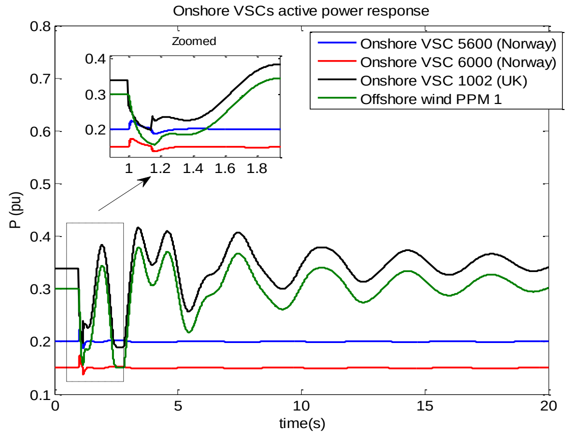


(b) Block diagram of PPM level controller

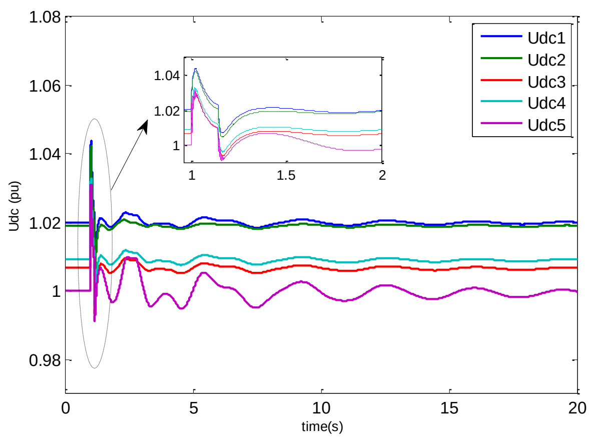
Fig. 11 Coordinated operation of the onshore VSC with the offshore wind power plant module

In the case that the active power of the wind power plant is modulated in a similar manner as the onshore HVDC converters, the power balance is kept constant in the MTDC grid and the direct voltage variations are limited at the same level as in the case where the POD signal was not fed to the VSC active power controller. Fig. 12b illustrates the direct voltage profiles in the MTDC network. From that it can be seen that the coordination of the POD with the offshore wind power plants would limit the direct voltage oscillations. Further investigations should consider the impact of time delays to validate the robustness of this concept but are out of the scope of this paper.

From the response of the Nordic system generator at bus 5500, fig. 12c, it can be concluded that the operation of the MTDC network is triggering a poorly-damped 0.5 Hz mode in the Nordic system, which needs to be tackled appropriately. In addition, when the POD is only in operation at the UK system onshore VSC, the amplitude of this mode is doubled as a result of the disturbance that the POD adds, see fig.12c. The proposed coordinated operation of the onshore VSC control and the offshore wind PPMs is cancelling this effect, as shown in fig. 12c.



(a)



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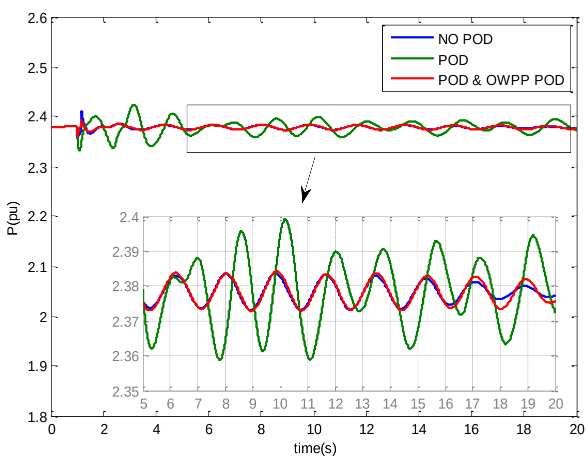

(c)

Fig. 12 (a) Active power response of VSCs and offshore wind PPMs. (b) DC voltage variations when offshore winds PPMs participate in the damping control. (c) Active power response of generator 5600 of the Nordic system.

IV. Conclusion

This paper has shown that it is possible to improve the small signal stability of a power system by use of an appropriate control scheme applied to the onshore VSC station connected to a multi-terminal DC grid.

However, the simulation results revealed that the operation of the POD controller at the onshore VSC terminal may trigger DC voltage oscillations in the MTDC network, with the same frequency as the mode the POD is trying to damp out. In addition, these oscillations can be passed on to another, asynchronously connected AC power system.

A coordinated control scheme between the onshore VSC (which applies the POD) and offshore wind PPMs could limit the direct voltage variations created by the POD. What is more, it engages offshore wind power plants to actively participate in the damping of onshore power system oscillations by making use of their rotor-blade inertia, which in the case of MTDC networks is fully de-coupled from the AC system frequency. The limitations that can be noted for this method are the necessity for fast communication link and the capability of the offshore wind PPMs to follow up the active power variations. Future work will investigate sensitivities for the drive train system of the wind turbines to respond in such a coordinated method for improvement of small signal stability of the onshore power system by MTDC grids extended between asynchronous systems.

V. References

[1] T. Knüppel, J.N Nielsen, K.H Jensen, A. Dixon, J. Ostergaard , "Small-signal stability of wind power system with full-load converter interfaced wind turbines," *Renewable Power Generation, IET* , pp. vol.6, no.2, pp.79-91, March 2012.

[2] Chaudhuri, Nilanjan Ray, Domahidi Alexander, Chaudhuri Balarko, Majumder Rajat, Korba Petr, Ray Swakshar; Uhlen Kjetil , "Power oscillation damping control using wide-area signals: A case study on Nordic equivalent system," *Transmission and Distribution Conference and Exposition, IEEE PES*, pp. vol., no., pp.1-8, 19-22 , April 2010.

[3] Jun Linag, Oriol Gomis-Bellmunk, Janaka Ekanayake and Nicholas Jenkins, "Control of mulit-terminal VSC-HVDC transmission for offshore wind power".

[4] R. Preece, A. M. Almutairi, O. Marjanovic and J. V. Milanovic, "Damping of Electromechanical Oscillations by VSC-HVDC Active power Modulation with Supplementary WAMS Based Modal LQG Controller," in *Power and Energy Society General Meeting, 2011 IEEE , vol., no., pp.1-7, 24-29 July 2011.*

[5] Lingling Fan and Zhixin Miao, "AC or DC Power Modulation for DFIG Wind Generation with HVDC Delivery to improve Interarea Oscillations," in *Power and Energy Society General Meeting, 2011 IEEE , vol., no., pp.1-6, 24-29 July 2011.*

[6] H. Latorre and M. Ghandhari, "Improvement of Power System Stability by Using VSC- HVDC," *Electrical Power & Energy Systems, vol. 33, NO.2, pp. 332-339, Feb*, 2011.

[7] Georgios Tsourakis, Sotirios Nanou and Costas Vournas, "A power system stabilizer for variable speed Wind generators," in *18th IFAC World Congress*, Milano, 2011.

[8] N.D. Calia, G.Ramtharan, J.Ekanayake and N.Jenkins, "Power Oscillation damping for fully rated converter wind turbines".*Universities Power Engineering Conference (UPEC), 2010 45th International , vol., no., pp.1-6, Aug. 31 2010-Sept. 3 2010.*