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Cluster Control of Offshore Wind Power Plants Connected to a Common HVDC Station

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Abstract

In this paper a coordinated control for cluster of offshore WPPs connected to the same HVDC connection is being implemented and analyzed. The study is targeting two cases as; coordination of reactive power flow between HVDC converter and the WPP cluster while providing offshore AC grid voltage control, and coordinated closed loop control between the HVDC and the WPPs while the cluster is providing Power Oscillation Damping (POD) via active power modulation. It is shown that the coordinated cluster control helps to improve the steady-state and dynamic response of the offshore AC grid in case of offshore AC grid voltage control and onshore ancillary services provision, i.e. POD by the active power modulation of the cluster. The two cases are simulated using DIgSILENT PowerFactory, where the IEC 61400-27-1 wind turbine and WPP control models and a generic offshore layout with cluster of three WPPs are utilized.

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1. Introduction

Rich wind resources in the North Sea and the Baltic Sea region are being explored and utilized by the offshore wind power plants (WPPs) [1]-[2], where the HVDC is being the preferred solution to transfer the wind power from far offshore WPPs. In many cases, multiple (e.g. three) offshore WPPs are being connected to a single HVDC offshore station as a cluster; for instance the Butendiek, Dan Tysk, and Sandbank WPPs (each 288 MW) connected to the SylWind1 HVDC station (864 MW) [2].

Currently such installations are not known to be operated with separate WPP controllers in a coordinated way; however this is anticipated to be favored in the near future. In this paper, a coordinated control for cluster of offshore WPPs connected to the same HVDC connection is being implemented and analyzed. The study is aimed to coordinate the reactive power flow between the HVDC converter and WPPs' cluster, while staying within the steady-state operational limits of the WPPs. Additionally, WPPs are coordinated to improve the dynamic response of the offshore AC grid in case of onshore ancillary services provision, e.g. power oscillation damping (POD) [3]-[6] by active power modulation of the HVDC link and hence the WPPs. Aggregated model of WPPs and their controls used in this study are based on the IEC type 4B wind turbines (WTs) and the WPP control models in IEC 61400-27-1 [7], using a generic offshore layout with cluster of three WPPs [8]. The IEC type 4 WT model represents the latest generation WT type, where the generator is connected to the grid through a full scale power electronics based converter (hence decoupled from the grid). The generator can be either asynchronous (squirrel cage induction) generator or (permanent magnet or separately excited) synchronous generator; with or without gearbox (i.e. direct drive). The full-scale power converter usually employs a chopper circuitry in the DC link, which helps for fault ride-through of the WT. Depending on the sizing of the chopper, post-fault power oscillations might be observed at the WT output, where the IEC type 4A represents an ideal WT with sufficient chopper neglecting aerodynamic and drivetrain parts thus without any post-fault oscillations and the IEC type 4B includes aerodynamic and drivetrain blocks replicating the post-fault oscillations.

It is shown that the objectives of coordinated flow and improved dynamic response can be reached via configuring and setting the WPP and WT controllers accordingly; and further improved by a coordinated cluster control. Analyzing the currently existing AC offshore hub concept, the paper aims to provide a benchmark case towards further meshed AC and/or DC network studies. Cluster control of WPPs connected to a common HVDC stands as a new research concept, where such a case is known to be studied only in few references, e.g. in the eighth chapter of [9] for frequency support and POD provision, in [11] for coordination of the cluster during offshore faults, in [12] for HVDC feasibility analysis for a cluster of WPPs.

In the next section the developed generic benchmark layout will be described. In the third section, a general overview of the IEC 61400-27-1 WT and WPP control model will be given. In the fourth and fifth sections, the offshore AC grid voltage regulation and POD cases will be studied, respectively, together with the simulation results. In the last section the concluding remarks will be provided.

2. Benchmark Layout – Cluster of Three WPPs

In order to study the phenomenon related to the cluster connected WPPs to a common HVDC station, a generic benchmark layout is created [8], as given in Fig. 1. However, in this study the onshore HVDC terminal and DC link is not modeled since the focus is coordination of reactive power (during offshore AC voltage control) and active power (during POD) between the WPPs and the HVDC offshore station. The offshore HVDC station is modeled as a voltage source converter with constant DC voltage; thus acts as an ideal voltage source. This simplification helps to focus on the main scope of this paper; cluster control of HVDC connected offshore WPPs and impact of communication delays within the offshore cluster, while eliminating the impact of external factors such as the non-linearity of the offshore HVDC converter, DC-link voltage control dynamics, etc. However, a complete analysis definitely requires the HVDC link to be included as in [10], where these external impacts are studied thoroughly. In the offshore cluster benchmark, the first WPP (A) is located very close (2 km) to the HVDC station, whereas the other WPPs (B and C) are located 25 km and 50 km away from the HVDC station, connected with separate submarine cables. Each WPP is represented as aggregated single WTs, since the focus of the study excludes internal dynamics between the WTs within the WPPs.
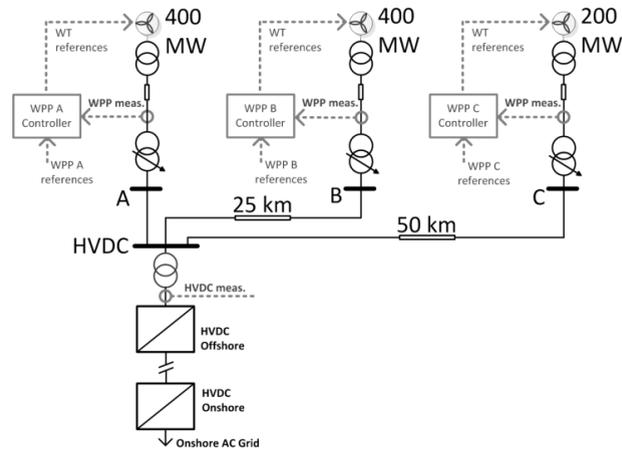
Fig. 1. The generic benchmark layout with cluster of three WPPs.

The parameters for the WPP and HVDC transformers are given in table 1 below, while the collector network and connection cable parameters are given in tables 2 and 3. The WT transformer values in Table 1 are given for the aggregated units which have ratings as the WPP ratings.

Table 1. WPPs' and HVDC's transformer specifications.

	WPP-A	WT-A	WPP-B	WT-B	WPP-C	WT-C	HVDC
Apparent power [MVA]	240	240	480	480	480	480	1160
Low voltage [kV]	33	0.69	33	0.69	33	0.69	150
High voltage [kV]	150	33	150	33	150	33	380
Transformer X [%]	13.77	5.935	13.77	5.935	13.77	5.935	15
Transformer R [%]	0.277	0.88	0.277	0.88	0.277	0.88	1

Table 2. WPPs' internal (aggregated) network cable impedance characteristics [Sbase].

	WPP-A [400 MVA]	WPP-B [400 MVA]	WPP-C [200 MVA]
X [%]	1.68	1.68	2.422
R [%]	0.51	0.51	0.812
B [%]	2.154	2.154	1.726

Table 3. WPPs' connection cable specifications [Sbase].

	WPP-A [400 MVA]	WPP-B [400 MVA]	WPP-C [200 MVA]
Length [km]	2	25	50
X [%]	0.2	2.5	5.02
R [%]	0.032	0.4	0.8
B [%]	1.62	20.3	40.6

The study is performed on the developed benchmark system having three offshore WPPs connected through a single HVDC system, shown in Fig. 1, using DIgSILENT PowerFactory rms simulations. The reactive power flow

and the active power losses in the offshore AC grid are calculated by performing load flow at various generation levels from the WPPs.

AC cables generate high amount of reactive as seen by the stray capacitance values in Table 2 and 3, while the transformers are still large consumers of reactive power especially under high load. As will be seen in the fifth section, the cables totally produce 200 MVAr of reactive power when the WPPs' active power generation is close to minimum or zero. As a common practice, in order to absorb this excess reactive power, especially during low generation levels, shunt reactors are employed, whereas HVDC converter and the WPP (WT) converters have the capability to absorb or inject reactive power. In this study, in order to observe and compare pure converter responses, the WPP shunt reactors and OLTC (On Load Tap Changer) are not operated.

3. IEC 61400-27 WT and WPP Control Models

The international standard IEC 61400 from the International Electrotechnical Commission is a series of standards regarding WTs. This paper will use IEC 61400-27-1, which considers electrical simulation model of WTs [7]. As the penetration of wind energy in power systems is increasing system operators need to use dynamic models of wind power generation for studies regarding power system stability. As the models developed by the WT manufacturers are too detailed to assess power system stability and usually confidential, the IEC has developed the standard series 61400-27 to provide a frame for generic models. This specific standard consists of two parts, the first part provides WT models and validation procedures which can be applied in power system stability studies and the second part contains WPP models and their model validation procedure. These fundamental frequency positive sequence models are specified to represent the wind turbines' behavior in the large-disturbance short-term voltage stability, the rotor angle stability, frequency stability, and the small-disturbance voltage stability studies. The type 4B WTs, which are used in this study, employ power-electronics converters, which are modelled by ideal current injection sources (e.g. static generators in PowerFactory) in the IEC models. The IEC WPP and WT active and reactive power control paths are shown as cascaded in Fig. 2, which is a simplified representation from [7].

3.1. Reactive Power Control Loop – Voltage Control with Droop Compensation

The WPP reactive power controller has four operating modes; it can perform reactive power control, power factor control, static voltage control, and voltage control. In case of reactive power control and the power factor control modes, the resultant reactive power reference is closed-loop regulated by a PI controller and also a feedforward path. In case of static voltage control mode, a reactive power reference is generated from a lookup table based on the voltage error and the reactive power reference is regulated by the same means as reactive power control mode. In case of voltage control mode, the voltage is closed-loop regulated by a PI controller, and additionally a droop gain (named as k_{qdroop} in Fig. 2), modifies the WPP voltage reference based on the measured reactive power value.
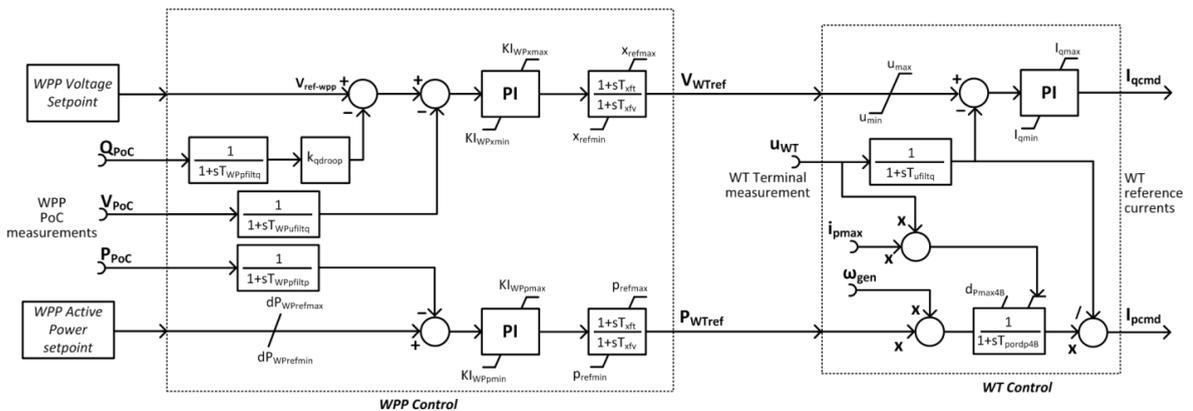

Fig. 2. Simplified block diagram for WT and WPP voltage and active power controller of IEC 61400-27-1.

As mentioned above and shown in Fig. 2 the IEC WPP voltage controller has the "Plant voltage control droop" gain which modifies the WPP voltage reference based on the WPP reactive power flow and the droop gain, as shown in (1). This function (1) will be utilized in the offshore AC grid voltage control section below, in order to share the reactive power between the WPPs and the HVDC station. The droop helps to decrease the reference voltage if there is a high reactive power injection from the WPP, and increase in a contrary case.

$$V_{WPP-compensated} = V_{WPP-ref} - Q_{WPP-actual} \times kq_{droop} \tag{1}$$

3.2. Active Power Control – Closed Loop Regulation and De-loaded Operation

As seen in Fig. 2, the active power control of the type 4B WT is assumed as an open loop implementation that the active power reference is divided to the voltage magnitude to generate active current reference. The outer WPP active power control performs closed loop control based on the feedback from the WPP PoC measurement, which provides possibility to operate the WPP as de-loaded (e.g. 80% of the initially available power). This active power control loop will be utilized to keep reserve (de-load) and to realize active power modulation signals referenced from the POD function at the HVDC link.

4. Offshore AC Grid Voltage Control

As mentioned in the second section, the large stray capacitance of the offshore cables generates a large amount of reactive power especially during low generation levels. However, it should also be remembered that the WPP-A is located very close to the HVDC station with almost no cable in between. Hence the WPP-A is observed to generate reactive power during high generation levels in order to compensate for the reactive losses at the WPP and WT transformers. Another important point due to the close location of the HVDC station and the WPP-A, the voltage controllers at these two terminals start to impact each other and at the HVDC station starts injecting reactive power, in contrast to a general offshore case (where the shunt reactors and WT converters absorb the reactive power). This creates an unnecessary flow of reactive power such that the HVDC station is injecting reactive power while the WPP-B and WPP-C are absorbing (the excess reactive power of their cables) and WPP-A changing reactive power flow direction after 0.75 pu generation level, as seen in Fig. 3 (a).

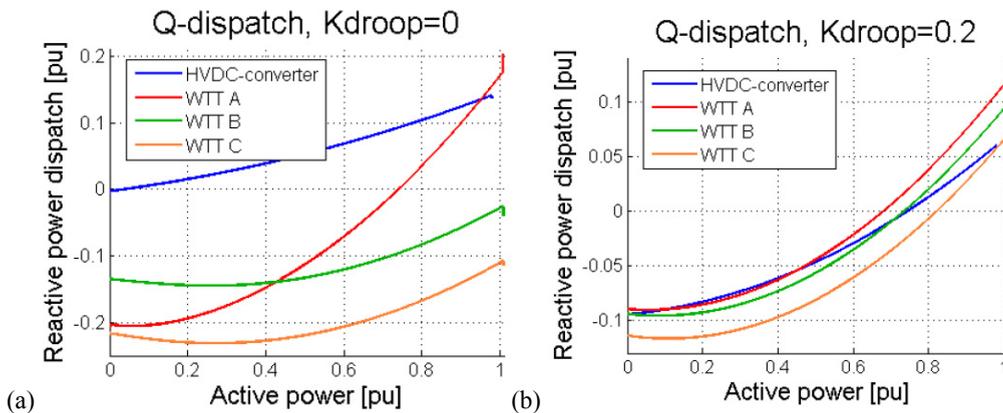(a)   (b)

Fig. 3. (a) Reactive power flow without droop; (b) Reactive power flow with droop.

The voltage profiles are shown in Fig. 4 below, where a stiff 1 pu voltage is achieved for all control terminals when the droop gain is set as zero, however resulting in a reactive power flow as in Fig. 3 (a) above. In order to provide a coordinated response between the WPPs and the HVDC station, the droop function is utilized and the reactive power provision (absorbing and injecting) is shared fairly as seen in Fig. 3 (b). Here the reactive power

values from the WT and HVDC converters are shown, which absorb the excess reactive power from the cables during low generation and inject reactive power to compensate the losses at the transformers during high generation in a harmonized way. As seen in Fig. 4, using the droop results in compromise of voltage as approximately 0.03 pu deviation from rated, which is considered to be acceptable.

5. Active Power Modulation by the WPPs for POD

The POD function requirement is being introduced for the converter based generation units in order to substitute the PSS function of the conventional synchronous generators, e.g. by the recent ENTSO-E "Network Code on High Voltage Direct Current Connections and DC-connected Power Park Modules" [4]. Though it is considered for the HVDC stations (of interconnectors) for the time being, the contribution of the DC-connected WPPs to the POD is anticipated in the literature [9]. An up-to-date survey of POD and implementation details can be found in [10]. The
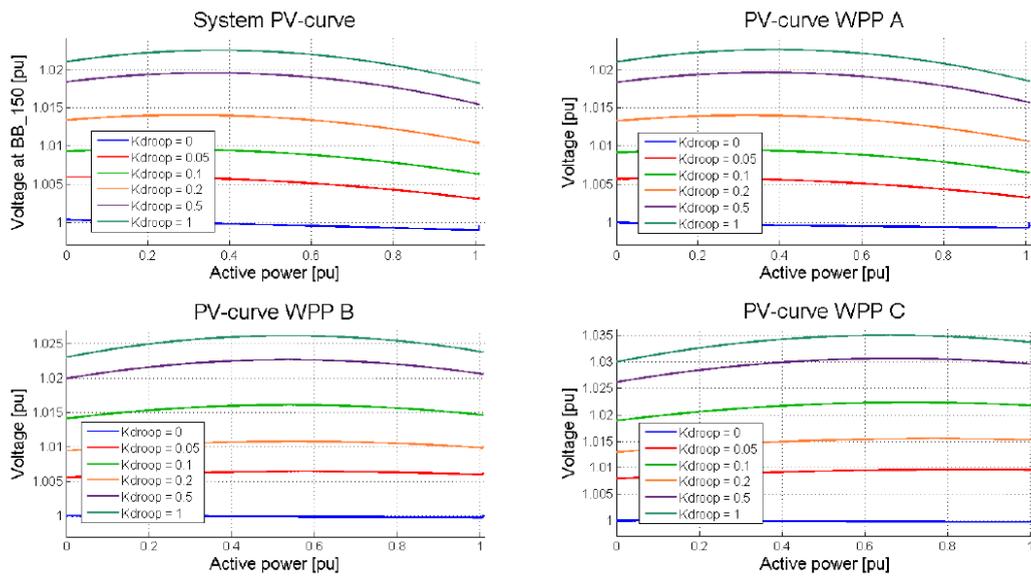

Fig. 4. Voltage profiles versus active power generation levels for various droop constants.

POD by the converter based renewables can be provided by active and/or reactive power modulation. In case the POD is realized by reactive power, it can easily be provided by the onshore HVDC converter without considerable impact on the offshore side [9]. However, provision of the POD by active power requires modulation of active power from the offshore WPPs.

In this study, the scenario is assumed as; the onshore HVDC station has the necessary feedback from the onshore AC grid (which experiences and senses the power system oscillation problem) and sends the necessary POD modulation signal to the HVDC offshore station, which tries to realize this POD modulation signal via sending references to the WPPs. The dynamic delay due to the DC voltage control at the HVDC link is not considered here, since this delay is known to be small and the main focus is on the offshore coordination. An artificial POD modulation signal is referenced as if it is coming from the HVDC onshore station, which is 0.1 Hz with 0.1 pu magnitude. Additionally, the same settings have been simulated for a case with 0.5 Hz modulation as well.

The realization of the POD active power modulation is implemented in two different ways in this paper; the first one as uncoordinated open loop reference dispatch to the WPPs and the second as the closed loop coordinated

control at the offshore HVDC station, which are shown in Fig. 5 and results compared in Fig. 6. In both cases the resultant references to each WPP are phase-gain compensated in order to account for the dynamics of the WPP and communication delays between the cluster controller at the HVDC station and the WPPs. The same compensation is applied in both cases. The communication delays between the cluster controller and the WPP controllers are modeled with time delay function of the DIgSILENT PowerFactory.

The results with the open loop dispatch method are shown in Fig. 6 (as dashed), where the WPP responses are unsynchronized (despite the phase-gain compensation) mainly due to non-deterministic dynamics of the WPPs and non-deterministic delay between the HVDC station and the WPPs. This results in ineffective overall active power response from the HVDC link to the onshore grid. However, the coordinated closed loop method results in synchronized response from the WPPs, since the mismatch between the reference and measured active power is regulated. It should be noted that the HVDC measured active power in Fig. 1 is used as the feedback, which is filtered to remove the steady-state generation from the WPPs. The power regulator here is implemented simply as a proportional-integral (PI-controller) structure, whereas more complicated methods (e.g. adaptive gain-scheduling) can be considered for improved response. In the coordinated closed loop method the WPPs' generation level is also taken into account. This is important considering the stability of the WT rotor speeds since a long and excess loading to a WPP with low generation level (e.g. due to low wind speed for that WPP) would cause problems [9]. As seen in Fig. 6 (b), the performance deteriorates for the increased modulation frequency (0.5 Hz), which implies a need for improvement for the regulator at the cluster controller and the WPP dynamic responses.
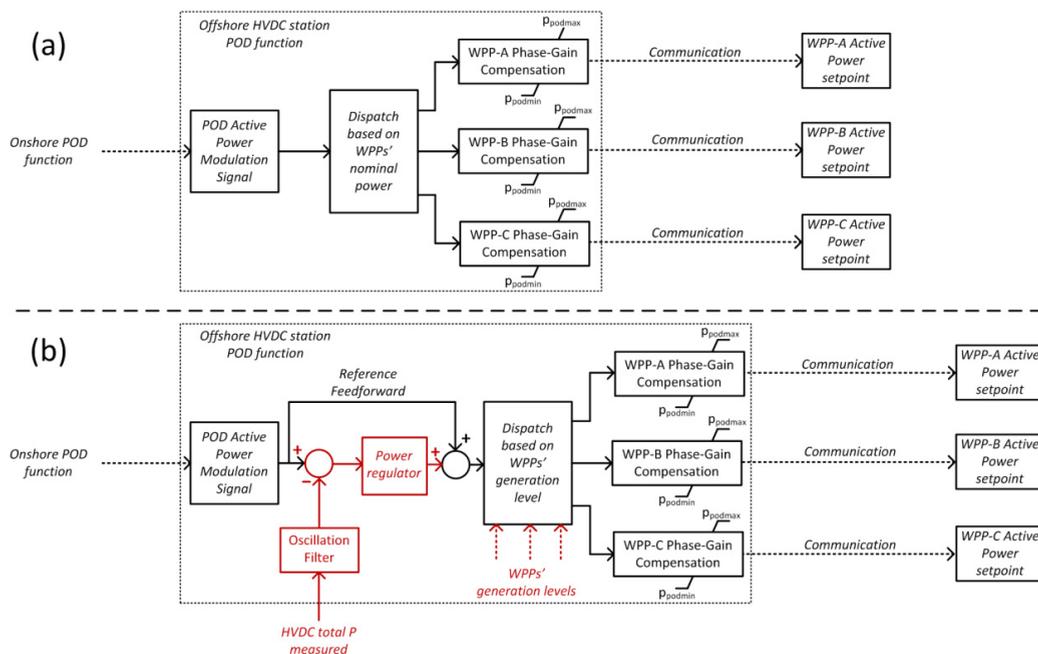

Fig. 5. (a) POD as open loop dispatch; (b) POD as closed loop coordinated regulation.
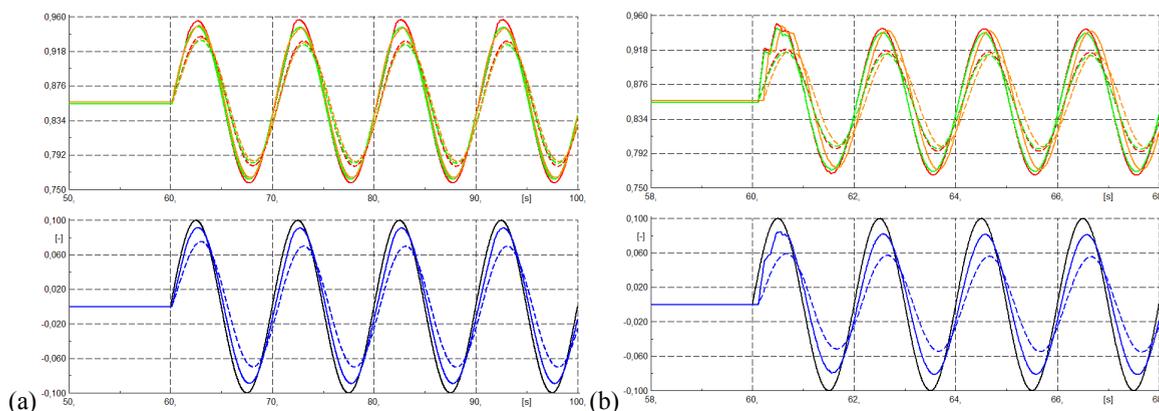
Fig. 6. POD results (a) 0.1 Hz (b) 0.5 Hz case. Black is the POD reference signal. Dashed red, green, orange, and blue are WPP A, B, C, and HVDC active power [pu] values, respectively with open loop dispatch. Solid red, green, orange, and blue are WPP A, B, C, and HVDC active power [pu] values, respectively with closed loop coordinated regulation.

6. Conclusion

In this paper the cluster control of HVDC connected offshore WPPs is studied on a generic benchmark layout of three WPPs with individual WPP controllers connected to a common offshore HVDC station, which is modeled with an ideal voltage source converter. The IEC 61400-27-1 models are shown to be utilized in DC-connected offshore WPP studies, where the offshore AC grid voltage is generated by the HVDC converter and the WPPs contribute to offshore grid voltage control. It is shown that when the WPPs are referenced with unity voltage, an uncontrolled reactive power flow occurs. The plant voltage droop compensation is shown to avoid this via providing fair share between the WPPs and the HVDC converter. This is considered to improve efficiency of the offshore grid via decreasing losses. Optimization of the voltage setpoints based on the active power losses stands as a future work. The POD function is performed by the active power modulation of the offshore WPPs with and without coordination. It is shown that the closed loop control at the offshore HVDC station provides effective active power response, hence better potential support to the onshore AC grid, in case it is implemented. A potential application of the offshore cluster controller is shown, which may improve implementation of system services by DC-connected offshore WPPs, which is considered to be a demand in the near future. Implementation and analysis of other ancillary services, e.g. frequency support, with the DC-connected cluster of offshore WPPs worth to be a future work.

Acknowledgement and Disclaimer

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of Statoil ASA or Halvorsen Power System AS.

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