Manuscript version: Author’s Accepted Manuscript
The version presented in WRAP is the author’s accepted manuscript and may differ from the published version or Version of Record.

Persistent WRAP URL:
http://wrap.warwick.ac.uk/171515

How to cite:
Please refer to published version for the most recent bibliographic citation information. If a published version is known of, the repository item page linked to above, will contain details on accessing it.

Copyright and reuse:
The Warwick Research Archive Portal (WRAP) makes this work by researchers of the University of Warwick available open access under the following conditions.

Copyright © and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable the material made available in WRAP has been checked for eligibility before being made available.

Copies of full items can be used for personal research or study, educational, or not-for-profit purposes without prior permission or charge. Provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

Publisher’s statement:
Please refer to the repository item page, publisher’s statement section, for further information.

For more information, please contact the WRAP Team at: wrap@warwick.ac.uk.
Coordinated Power Oscillation Damping From a VSC-HVDC Grid Integrated with Offshore Wind Farms: Using Capacitors Energy

Zuan Zhang, and Xiaowei Zhao

Abstract—This paper proposes a novel coordinated control strategy for a voltage source converter (VSC) based high-voltage direct current (HVDC) grid integrated offshore wind farms (OWFs) to damp the power system oscillations. A feature of this strategy is aiming to use the DC-link capacitor energy of offshore wind turbines (WTs) to reduce interactions between power oscillations and HVDC grid voltage when onshore grid-side VSCs (GSVs) modulate the active and reactive power injections. Unlike the previous communication-based method, the coordination from offshore WTs in this strategy depends on the local measurements of the HVDC grid voltage instead of the remote communication data from the onshore AC grid. A modified IEEE 39-bus power system with a 5-terminal VSC-HVDC grid connected to two OWFs has been developed to validate the effectiveness of this proposed strategy. Both the eigenvalue analysis and time-domain simulation results indicate that this strategy can significantly improve the power oscillation damping (POD). Comparative simulation studies also conclude that the proposed strategy has similar POD improvements to the previous communication-based method without the negative impact of communication delay from onshore to offshore.

Index Terms— Voltage source converter (VSC), HVDC grid, power oscillation damping (POD), offshore wind farm, capacitors energy.

I. INTRODUCTION

VSC-HVDC system has now become one of the preferred technologies for long-distance power transmission due to its advantages of fast independent active and reactive power control, black start capability, and small station footprint. Those features enable VSC-HVDC especially suitable for connecting distant OWFs to the onshore power system [1]. Integrating several OWFs by building separate point-to-point HVDC systems will be costly and inflexible. Instead, interconnecting the HVDC terminals to form a HVDC grid can reduce the number of converters and improve the possibility of transmitting power in case of DC faults. Thus, the HVDC grid has been recognized as an attractive solution to large-scale offshore wind energy connections, which has already been applied in a few real-world projects [2].

However, the increasing wind energy penetration with the adoption of a HVDC grid will lead to a displacement of conventional synchronous generators (SGs), which can reduce the total inertia of the power system and weaken its damping of low-frequency (0.1–2 Hz) oscillations [3]. Therefore, more and more transmission operators (TSOs) require the HVDC grid and wind farm systems to provide ancillary POD services to enhance the stability of power systems.

POD from HVDC has been studied for several decades [4]. Early efforts focus on utilizing the line-commutated-converter (LCC) based HVDC to damp the inter-area power oscillations [5]-[8]. In those papers, POD improvements were achieved by active power modulation (P-modulation), or in combination with reactive power modulation (Q-modulation) of the HVDC terminals. Thanks to the large-scale installation of phasor measurement units (PMUs) in modern power grids, the implementations of POD control in LCC-HVDC links have become reality and have been successfully tested in China Southern Power grid [9] and the Pacific dc Intertie [10]. Recent developments in power electronic converters have shifted the focus from utilizing the classical LCC-HVDC to VSC-HVDC for POD. Compared to LCC, the VSC not only allows more flexible independent P-modulation and Q-modulation of HVDC but also avoid commutation failures. Authors in [11]-[16] investigate P-modulation of VSC-based multiterminal HVDC (MTDC) system to damp the power oscillations and develop supplementary POD controllers based on Lyapunov theory [12], sliding mode method [13], and communication-free DC voltage feedback loop shaping approach [14]. The conclusions suggest that P-modulation from VSC-MTDC can damp the power oscillation effectively, and a more noticeable improvement of damping is obtained when using global rather than local measurement as the feedback of POD control [15]. The improvements of AC system transient stability by Q-modulation of VSC-MTDC are validated in [17]-[18]. The paper [18] proposes a communication-free method to control the reactive power injections based on estimated weighted-average frequency, which is only applicable when P-modulation is disregarded. Coordinated P and Q modulations in VSC-MTDC for POD have been reported in [19]-[20], where results demonstrate that coordinated POD is more effective than individual P or Q-modulation. However, the interaction between the POD and DC grid voltage, and the coordination of the wind farms for
POD in VSC-MTDC are rarely discussed in those studies.

In addition, considerable publications [21]-[26] have shown that WTs can provide POD by directly modulating the active and reactive power of the wind energy conversion system (WECS). Hence, for HVDC-connected OWFs, it is necessary to fully utilize the potential of WTs to contribute to POD. So far, few publications have studied coordinated POD control from HVDC and wind farm [27]-[30]. Among them, the system of an OWF connected through a point-to-point VSC-HVDC has been utilized in [27]-[28], which conclude that the coordinated P-modulation of the wind farm and Q-modulation of onshore VSC can damp the power oscillations more effectively than the case without coordination. Only the work in [29]-[30] consider coordinated control from the VSC-MTDC and wind farms, in which reference [29] unifies P-modulation of onshore VSCs and OWFs while reference [30] adds Q-modulation of onshore VSCs. Results in both papers show that the coordinated control strategies significantly improve the inter-area oscillation damping in the AC grid, and the variations of the DC grid voltage could be mitigated as the OWFs participate in POD. However, the coordinated strategies in both papers rely on the communication links to send real-time POD signals to offshore WTs, both the cost and reliability issues caused by such communication systems may discourage the implementation of these strategies. In addition, the potential time delay or communication failure may deteriorate the overall effects of the POD as well as the operation of MTDC.

Therefore, we propose a novel coordinated POD control strategy for a VSC-HVDC grid integrated with OWFs. The major contributions of this paper are listed below,

1) Based on the analysis of the interaction between power oscillations and HVDC grid voltage when GSVSCs modulate the active and reactive power injections, the interaction factor concept is put forward, which can be used to evaluate the negative impacts of this interaction on the POD effectiveness.

2) For this proposed strategy, one of the main features is aiming to utilize the DC-link capacitor energy of offshore WTs to reduce the interaction factor. Unlike the previous communication-based method [30], the coordination of OWFs in this strategy depends on the local measurements of the HVDC grid voltage instead of the remote communication data from the onshore AC grid, which benefits the communication-less POD applications in the HVDC grid connected OWFs system.

3) A model of the modified IEEE 39-bus power system with a 5-terminal HVDC grid connected to two OWFs has been developed. Based on this model, both the eigenvalue analysis and time-domain simulation results indicate that this proposed strategy can significantly improve the POD effectiveness.

The rest of this paper is organized as follows. Section II analyzes the interactions between power oscillations and HVDC grid voltage and proposes the novel coordinated POD strategy. Section III describes the studied system of a 5-terminal VSC-HVDC grid integrated with two OWFs and introduces the control design. Section IV verifies the effectiveness of the coordinated POD by small-signal analysis. Time-domain simulation results are presented in Section V. Conclusions are given in Section VI.

II. THE PROPOSED COORDINATED POD CONTROL STRATEGY

A. POD from a HVDC Grid

Fig.1 shows the diagram of a VSC-HVDC grid connecting the OWFs to the onshore AC grid system with POD control. In Fig.1, the HVDC grid consists of $n_1$ wind farm side VSCs (WFVSCs) and $n_2$ GSVSCs; The number of OWFs assumes to be the same as the WFVSCs; The onshore AC grid includes $m$ SGs, and the frequency ($f_{g}$) and phase angle ($\delta_{g}$) of $i$th SG are measured by a corresponding PMU.

Considering the inter-area power oscillations involve the global behavior of the AC grid, the real-time POD control center prefers to use the feedback of wide-area PMUs as the input signals of the POD controllers. When power oscillation occurs, the POD control center first selects the frequencies and phase angles of the targeted SGs and enables the outputs of POD controllers. Then the outputs of POD controllers are sent to the local controller (LC) of the corresponding GSVSC, and the GSVSC modulates the active and reactive power injections into the AC grid to damp the power oscillations. A fast communication system that links the PMUs, POD control center, and GSVSCs is required, which can use a dedicated optical fiber network to reduce delays and inconsistencies [10].

Fig. 2 depicts the typical diagrams of the POD controllers for P-modulation and Q-modulation in $k$th GSVSC. In Fig. 2, $f_{g1}$ and $f_{g2}$ are the selected frequencies of a single SG or weighted frequencies of multiple SGs located in one area, which depends on the major participation states of the oscillatory mode to be damped, and the same rule applies to the selection of $\delta_{g1}$ or $\delta_{g2}$; $\tau$ and $T_w$ are the time constants of...
low pass filter (LPF) and wash-out filter, respectively; \( T_{i,k} \) and \( T_{i,k} \) are the time constants of the lead/lag compensators; \( K_{p,k} \) and \( K_{q,k} \) represent the gains; \( P_{pod,k} \) and \( q_{pod,k} \) are P-modulation and Q-modulation signals, and they pass through a limiter to prevent VSCs exceeding the safe operating range.

B. Analysis of the Interaction Factor

The Q-modulation in GSVSCs has no interactions with the HVDC grid voltage. However, the operation of a GSVSC for P-modulation can induce HVDC grid voltage variation. Such interaction is analyzed as follows. Generally, the GSVSCs employ power-voltage (P-V) droop control [31] instead of traditional master-slave control. Because P-V droop control can autonomously achieve a better DC voltage balance in the cases of a VSC outage, as well as variability and intermittency of the wind power. With P-V droop control, the output active power (in watts) of a GSVSC is

\[
P_{GVS C,k} = (P_{ref,k} + P_{pod,k}) - K_{dpc,k}(v_{dc,ref} - v_{dc,k})P_{N,k}
\]

where \( P_{ref,k} \), \( v_{dc,ref} \), and \( v_{dc,k} \) are the reference active power, reference and actual DC voltages in per unit (p.u.), respectively; \( K_{dpc,k} \) is the droop gain; \( P_{N,k} \) is the rated active power (in watts). The variables with subscript ‘k’ represent they belong to the kth GSVSC.

Neglecting the power losses of the cables, transformers, and VSCs, the relation between the output power of OWFs and the HVDC grid can be expressed as,

\[
P_{WFS} = \frac{1}{2} C_{hvdc} \frac{dV_{dc}^2}{dt} + \sum_{k=1}^{n_2} P_{GVS C,k}
\]

where \( V_{dc} \) and \( \bar{v}_{dc} \) are the rated HVDC grid voltage (in volts) and the actual value (in p.u.), respectively; \( C_{hvdc} \) represents the equivalent capacitance value (in farad) of the HVDC grid. The linearization of (1) and (2) at the steady operation point is derived as,

\[
\Delta P_{WFS} = \sum_{k=1}^{n_2} \Delta P_{pod,k} + K_{dpc,k} \Delta \bar{v}_{dc} P_{N,k}
\]

\[
+ 2H_{hvdc}\frac{S_B}{V_{dc}} \frac{d\bar{v}_{dc}}{dt} - \frac{d\Delta v_{dc}}{dt}
\]

where the prefix ‘\( \Delta \)’ denotes the deviation of a variable; \( \bar{v}_{dc} \approx 1 \) during normal operation; \( H_{hvdc} \) is the inertial constant (in second) of the HVDC grid and \( H_{hvdc} = 0.5C_{hvdc} V_{dc}^2/S_B \); \( S_B \) is the base power of the system (in VA); Based on (3), the DC grid voltage deviation is derived in the Laplace domain as,

\[
\Delta \bar{v}_{dc}(s) = \frac{\Delta P_{WFS}(s) - \sum_{k=1}^{n_2} \Delta P_{pod,k}(s)}{2H_{hvdc}\frac{S_B}{V_{dc}} \cdot s + \sum_{k=1}^{n_2} K_{dpc,k} P_{N,k}}
\]

where \( P_{pod,k} \) is the reference modulated active power (in watts) used for POD in kth GSVSC, and \( P_{pod,k} = P_{pod,k,\lambda} P_{N,k} \). Based on (1) and (4), the linearized active power of kth GSVSC can be described in the Laplace domain as,

\[
\Delta P_{GVS C,k}(s) = \left(1 - R_{IF,k}(s)\right) \Delta P_{pod,k}(s) + R_{IF,k}(s) \sum_{1 \leq \lambda \leq n_2} \Delta P_{pod,\lambda}(s)
\]

Here we define \( R_{IF,k} \) as the interaction factor on kth GSVSC, which is

\[
R_{IF,k}(s) = \frac{K_{dpc,k} P_{N,k}/S_B}{2H_{hvdc}\cdot s + \sum_{k=1}^{n_2} K_{dpc,k} P_{N,k}/S_B}
\]

The amplitude of \( R_{IF,k} \) in the frequency domain is,

\[
| R_{IF,k}(j\omega) | = \frac{K_{dpc,k} P_{N,k}/S_B}{\sqrt{(2H_{hvdc})^2 \omega^2 + (\sum_{k=1}^{n_2} K_{dpc,k} P_{N,k}/S_B)^2}}
\]

Since the values of the inertia constant, droop gains, and rated power in (7) are generally fixed for a HVDC grid, the amplitude of the interaction factor increases as the frequency of the power oscillation decreases. Without coordinated POD control from OWFs, it sees in (5) that the existence of the interaction factor can cause two main problems. The first one is that it weakens the effect of POD from P-modulation in kth GSVSC because the actual amount of modulated active power used for POD is reduced from \( \Delta P_{pod,k} \) to \( (1-R_{IF,k}) \Delta P_{pod,k} \). Another one is that it can transfer power oscillations from some areas to other areas of the AC grid through GSVSCs, which may deteriorate the stability of those areas. Specifically, for the area that is connected to the kth GSVSC, the amount of the injected active power (which is unfavorable) corresponds to the power oscillations in other areas equal to \( R_{IF,k} \sum_{1 \leq \lambda \leq n_2; \lambda \neq k} \Delta P_{pod,\lambda} \). Therefore, the interaction factor can be used as an indicator of the negative impacts on the POD when the power oscillations interact with the DC grid voltage. To mitigate these negative effects, a simple method is to let the OWFs modulate the same amount of active power as the GSVSCs during POD events. To achieve this, POD signals for P-modulation are dispatched to each offshore WT through communication links, as proposed in [30]. Ideally, if there are no communication delays or operational delays, the variation of \( \bar{v}_{dc} \) is zero, which means the interaction can be avoided within this strategy. However, in practice, it is very difficult to realize that due to those time delays are inevitable. Besides, communication data loss is another concern.

C. Proposed Coordinated POD Control Strategy

To coordinate the potential contribution of OWFs to POD while avoiding the adverse effects of the communication system, this paper proposes a measurement-based POD control strategy for offshore WTs with full power converters. This proposed strategy is aiming to utilize the DC-link capacitor energy of offshore WTs to reduce the interaction factor when GSVSCs modulate the active power injections during POD events. In this strategy, as shown in Fig.1, the LCs of WFVSCs need to modulate the amplitude of the Point of Common Coupling (PCC) bus voltage according to the measurement of DC grid voltage variation (\( \Delta V_{dc} \)) during POD events, and then the LC of each WT modulates the DC-link voltage based on the measurement of offshore grid-side AC voltage variation. The LCs of WFVSCs and WT converters depend only on local measurements, which avoids the communication-based control scheme and the resulting delays and data losses. The proof of this proposed strategy can reduce the interaction factor is as follows.

Assuming the WTs in an OWF are the same type, the dynamic of the back-to-back converter in the aggregate model of an OWF is described as,
where \( P_{m,i} \) and \( P_{wli} \) are the active power (in watts) of the WT machine-side converter (MSC) and grid-side converter (GSC), respectively; \( V_{DCL,i} \) and \( V_{DCLi} \) are the DC-link voltage (in volts) and the actual value (in p.u.) of WT converter in \( i \)th OWF; \( C_{wli} \) is the equivalent DC-link capacitance value (in farad) of \( i \)th OWF and \( C_{wt} = \frac{N_{w} \times C_{wii}}{N_{w}} \), where \( N_{w} \) is the number of WT and \( C_{wii} \) is the DC-link capacitance value (in farad) of one WT. Given \( P_{m,i} \) remains steady, the linearization of (8) is

\[
\Delta P_{WPS} = \sum_{i=1}^{n_2} \Delta P_{wli} = -\sum_{i=1}^{n_2} C_{wli} V_{DCL,i} \Delta V_{DCLi} \frac{dt}{dt} \tag{9}
\]

where \( \Delta V_{DCLi} \) is controlled to be 1 during normal operation. The DC-link voltage of the WT converter is regulated according to

\[
\Delta V_{DCLi} = K_c \Delta V_{dc} \tag{10}
\]

where \( K_c \) is the amplification factor. Substituting (9) and (10) into (3) will get,

\[
\Delta V_{dc}(s) = -\sum_{k=1}^{n_2} \Delta P_{pod,k}(s) / S_B \tag{11}
\]

\[
2(K_c \sum_{i=1}^{n_2} \Delta P_{wli} + H_{hvdc}) s + \sum_{k=1}^{n_2} K_{dp,k} P_{N,k} / S_B \tag{12}
\]

where \( H_{wli} \) is the inertia constant (in second) of the \( i \)th OWF and \( H_{hvdc} = 0.5 C_{wli} V_{DCL,li}^2 / S_B \). Hence, \( R_{IF,k} \) in (6) now becomes,

\[
R_{IF,k}(s) = \frac{K_{dp,k} P_{N,k} / S_B}{2H_{sys} \cdot s + \sum_{i=1}^{n_2} K_{dp,i} P_{N,i} / S_B}
\]

where \( H_{sys} \) is the total virtual inertia constant (in second) of the OWFs and HVDC grid, and \( H_{sys} = K_s \sum_{i=1}^{n_2} H_{wli} + H_{hvdc} \). As the \( H_{sys} \) in (12) is larger than the \( H_{hvdc} \) in (6), it proves the proposed strategy can reduce the interaction factor at any power oscillation frequency.

---

**Fig. 3.** The overall diagram of the 5-terminal VSC-HVDC grid and offshore wind farms with the proposed coordinated POD control strategy.

### III. SYSTEM MODELING AND CONTROL DESIGN

#### A. System Description

The studied system is depicted in Fig. 3. The AC grid employs the benchmark IEEE 39-bus power system model, in which each SG is rated at 1000MVA and modeled by a 6th order IEEE model with a standard excitation system and governor. All loads are static and represented as constant impedances. The main parameters of the SGs, active and reactive power set-points of the loads are listed in Table A1 ~ A2 in the Appendix.

The embedded VSC-HVDC grid is in pseudo bipolar configuration and with 5 terminals and a rated DC voltage of ±350kV. Each VSC employs the modular multilevel converter (MMC) topology, and subsequently, we use the GSMMC and WFMCC to represent the GVSC and WFVSC, respectively. WFMCC1 and 2 are connected to OWF1 and 2 respectively, with the same rated capacity of 900 MVA. GSMMC1, 2, and 3 are connected to B20, B16, and B6 of the onshore AC grid, respectively, with the same rated capacity of 700 MVA. The location of the MMCS suggests that their main roles are taking power from OWF1 and 2 (WFMCC1 and 2) and feeding loads L28, L16, and L6 (GSMMCC3, 4, and 5). All the MMCS use the half-bridge sub-modules (SMs). The parameters of the MMCS and DC transmission cables are shown in Table A3 in
the Appendix.
Each OWF is composed of 90×10 MW permanent-magnet synchronous generator (PMSG) based WTs with full power converters. Each WT has a medium-speed drivetrain, and the parameters of the WT are listed in the Appendix and some data are referred to [32].

B. Control of the HVDC Grid

The overall control diagrams of MMCs with the proposed coordinated POD strategy are shown in Fig. 3. In this figure, the GSMMCs are assigned with P-V droop control and reactive power control, in which the outer-loop proportional-integral (PI) and inner-loop PI controllers regulate the active (or reactive) power and current, respectively. In Fig. 3, \( u_{abc} \) and \( i_{abc} \) are the grid-side three-phase voltage and current; The phase angle \( \theta \) of \( u_{abc} \) is measured by the Phase-locked loop (PLL); \( i_{cut} \) represents the three-phase circulating arm current in MMC; \( v_{dc} \) is the DC grid voltage, which is passed through a LPF to avoid the noise during measurements; \( v_{ac,ref}, p_{ref} \) and \( q_{ref} \) are the reference voltage, active power and reactive power set for MMC, respectively. \( X_{eq} \) is the total equivalent reactance and \( X_{eq}=0.5X_{arm}+X_T \), in which \( X_{arm} \) and \( X_T \) are one-phase MMC arm reactance and transformer reactance, respectively; \( p_{num} \) and \( q_{num} \) are the output active and reactive power of MMC, which are calculated as \( p_{num}=u_{dq}i_{dq}\) and \( q_{num}=u_{dq}^*i_{dq}^* \); \( p_{pol} \) and \( q_{pol} \) are the P-modulation and Q-modulation signals. All the variables are described in p.u. except for \( \theta \). The variables in Fig. 3 with subscript ‘k’ mean they belong to kth GSMMC, with subscripts ‘d’ and ‘q’ representing the d-axis and q-axis components of a corresponding variable.

The WFMMCs are commonly controlled to maintain the PCC bus voltage at its nominal amplitude \( v_{ac,ref} \), and frequency \( f_0 \). In addition, current limit control is also indispensable in each WFMMC [33], but it is not the focus of our study. To transduce the deviation of DC grid voltage into PCC bus voltage change, WFMMCs are controlled to vary \( v_{ac,ref} \) along with \( v_{ac} \). To realize that a supplementary voltage \( \Delta v_{ac} \) is added to the control loop, which is

\[
\Delta v_{ac,k} = K_{v1} \cdot \frac{s^2}{s^2 + 2\xi_n\omega_n s + \omega_n^2} \cdot \frac{1}{sT_f + 1} \cdot v_{dc,k} \tag{13}
\]

where the variables with subscript ‘i’ mean they are for ith WFMMC; \( \omega_n=2\pi f_n \), \( f_n \) and \( \xi_n \) are the natural frequency and damping ratio of the second-order high-pass filter (HPF); \( T_f \) is the time constants of the LPF. Considering the range of power oscillation frequencies and avoiding large phase shift of \( \Delta v_{ac} \), the reasonable values of \( f_n \) is 0.1 Hz and \( T_f \) is \([0.01, 0.05] \) s; \( K_{v1} \) is the gain which should be high enough to ensure the amplitude variation compliances with the resolution of AC voltage measurement devices. Nevertheless, the excessively large gain might affect the safe operation of HVDC and OWFs. Thus to avoid an undesired operation, \( \Delta v_{ac} \) is restricted to \([-0.05, +0.05] \) p.u..

Different from conventional two-level VSCs, MMCs should also include the circulating current suppression controller (CCSC) to suppress the second-order harmonic components in the arm currents, as well as the capacitor balancing controller (CBC) to maintain SM voltages within the nominal value. We refer to [34] for the details of CCSC, CBC, and pulse width modulation (PWM) techniques.

C. Modeling and Control of Offshore Wind Farms

The offshore WT utilizes a two-mass-shaft model [35] and a three-level neutral point diode clamped back-to-back converter [36]. As shown in Fig. 3, the MSC adopts the dual-loop PI controllers to control the electromagnetic power \( p_m \) of PMSG, whereas the GSC utilizes the dual-loop PI controllers to regulate the DC-link voltage \( v_{dcl} \) and the reactive power \( q_f \). In this figure, \( p_{m,ref} \) and \( q_{f,ref} \) are the reference active and reactive power dispatched by the OWF control center; \( \theta_m, \phi_m, L \) represent the angular speed, rotation angle, magnetic flux, and stator inductance of the PMSG, respectively; \( i_m \) is the three-phase current of MSC. For the GSC controller, \( i_q \) and \( v_p \) are the AC side three-phase current and voltage; \( \theta_p \) is the phase angle of \( v_p \); \( X_i \) is the tie reactor; all the variables are described in p.u except \( \theta_m \) and \( \theta_p \); the variables with subscript ‘j’ means they belong to jth WT. The pitch angle controller should be also included in each WT model, interest readers are referred to [35].

For the proposed coordinated POD strategy, an additional voltage \( \Delta v_{dcl} \) is added to the reference DC-link voltage of each WT converter, which is

\[
\Delta v_{dcl,j} = K_{v2} \cdot \frac{s^2}{s^2 + 2\xi_n\omega_n s + \omega_n^2} \cdot \frac{1}{sT_f + 1} \cdot v_{p,j} \tag{14}
\]

Here \( v_{p,j} \) is the amplitude of \( u_{p,j} \), and if \( p_{m,ref} \) does not change significantly during the POD event, \( \Delta v_{p,j} \approx \Delta v_{ac,j} \). \( K_{v2} \) is the gain, and a larger \( K_{v2} \) will make DC-link capacitors of WTs provide more energy to mitigate the variation of \( v_{dc} \). However, \( K_{v2} \) should not be too high due to the restriction of the WT converter. To avoid overmodulation and overvoltage of the converter, \( \Delta v_{dcl} \) is limited by \([-0.1, +0.1] \) p.u. The ancillary control is activated only when \( \Delta v_p \) is out of the range \([-0.03, +0.03] \) p.u., and has no short circuit faults detected in OWFs.

D. Critical Parameters and Impacts on Interaction Factor

Selecting 1000 MVA as the base power of the system. According to the parameters of HVDC and WTs in Appendix, the equivalent capacitances and inertia constants of the HVDC grid and OWFs are calculated and listed in Table I. The droop gains of all the GSMMCs are set to be 3.5, thus the interaction factors are the same on GSMMCs. Consequently, the amplitude of the interaction factor on each GSCM within the frequency range of power oscillations (0.1~2 Hz) is depicted in Fig. 4.

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{vdc} )</td>
<td>1.2 mF</td>
<td>( C_{vdc} ), ( C_{vdc} )</td>
<td>1800 mF</td>
</tr>
<tr>
<td>( S_p )</td>
<td>1000 MVA</td>
<td>( H_{ref} ), ( H_{ref} )</td>
<td>0.294 s</td>
</tr>
<tr>
<td>( K_{ip} )</td>
<td>3.5</td>
<td>( H_{ref} ), ( H_{ref} )</td>
<td>0.051 s</td>
</tr>
</tbody>
</table>

It shows in Fig.4 that without the coordinated control from OWFs, and in other words \( K_r=0 \), the interaction factor \( (R_{eff}) \) decreases from 0.33 to 0.22 as the frequency increases from 0 to 2 Hz. However, the interaction factor can be further reduced as \( K_r \) increases. For instance, \( R_{eff} \) is anticipated to be reduced from 0.29 to 0.14 in a typical frequency of 1 Hz when \( K_r \).
increases from 0 to 8. As already mentioned, $K_r$ should not be too large due to the restriction of the WT converter. Moreover, $R_{IF}$ becomes insensitive to $K_r$ when $K_r$ increases to a certain value. In this study, choosing $K_{v1}=2$ and $K_{v2}=4$, we have $K_r \approx K_{v1} \times K_{v2}=8$.

Fig. 4. The frequency-amplitude response of the interaction factor.

Fig. 5. Diagram of the simplified model of the studied system.

IV. SMALL-SIGNAL ANALYSIS

A. Small-Signal Model

As the small-signal analysis in this section emphasizes on tuning the POD controllers, thus a simplified analytical model of the studied system is utilized, as shown in Fig. 5. In this simplified model, each MMC is represented as a current source on the DC side and a controlled voltage source from the AC side, and the OWFs are simplified as active power sources. The converter losses are neglected, thus the active power from the DC side of MMC equals the one on the AC side. This simplified method has been commonly used for stability analysis in inertial response [37] and POD [11, 15, 20] from HVDC and wind farm interconnected systems.

In Fig. 5, $C_{dc1}$ to $C_{dc5}$ are the equivalent capacitances of MMCS, $L_{d1}$ to $L_{d5}$ are the smoothing reactance; The DC cables use the generic $\pi$-equivalent models, with resistances ($R_{12}$, $R_{23}$, $R_{14}$, $R_{45}$, $R_{52}$), inductances ($L_{12}$, $L_{23}$, $L_{14}$, $L_{45}$, $L_{52}$) and capacitances ($C_{d1}$ to $C_{d5}$). The linearized model of the HVDC grid can be obtained as

$$\Delta x_{dc} = A_{dc} \Delta x_{dc} + B_{df} \Delta P_{df} + B_{ac} \Delta P_{ac}$$  \hspace{1cm} (15)$$

where the state variables are the DC line currents, smoothing reactance currents, and DC voltages, and $x_{dc} = [i_{d1}, i_{d2}, i_{d3}, i_{d4}, i_{d5}, i_{s1}, i_{s2}, i_{s3}, i_{s4}, i_{s5}, U_{dc1}, U_{dc2}, U_{dc3}]^T$; $P_{df} = [P_{df1}, P_{df2}, P_{df3}]^T$; $P_{ac} = [P_{ac1}, P_{ac2}, P_{ac3}]^T$; $A_{dc}$ is the state matrix, $B_{df}$ and $B_{ac}$ are input matrices of active power for WFMMCs and GSMMCs, respectively.

To investigate the incremental improvements of POD from HVDC and OWF, the PSS in each SG is not considered. The small-signal model of SG uses a 6th order dynamic equation [38], and the linearized model of the AC grid is,

$$\Delta x_g = A_g \Delta x_g + B_a \Delta P_{ac}$$  \hspace{1cm} (16)$$

Here $x_g = [x_{g1}, x_{g2}, \ldots, x_{gM}]^T$, $x_g = [\delta_{g1}, \omega_{g1}, \psi_{g1d}, \psi_{g1q}, \psi_{g2d}, \psi_{g2q}]^T$, $M$ is the total number of SGs and the subscript ‘i’ indicates the variable corresponds to the ith SG in AC grid; $\delta_{g}$ and $\omega_{g}$ are the rotor angle and speed, respectively; $\psi_{g1d}$, $\psi_{g1q}$ and $\psi_{g2q}$ represent the fluxes of the field winding, d-axis and two q-axis damping windings, respectively; $S_{ac} = [P_{ac}, Q_{ac}]^T$. $Q_{ac} = [Q_{ac1}, Q_{ac2}, Q_{ac3}]^T$. $A_g$ and $B_a$ are the state matrix and input matrix of active and reactive power, respectively.

We assume the total time delay introduced by the communication systems between PMUs, POD control center and GSMMCs is 80 ms, which is a reasonable assumption according to the experimental results presented in [39]. The time delay has been considered as a second-order Padé approximation mathematical model [19] in the POD controllers. The linearized equations of POD controllers for GSMMCs are written as

$$\begin{align*}
\Delta x_{pod} &= A_{pod} \Delta x_{pod} + B_{pod} \Delta y_{pod} \\
\Delta y_{pod} &= C_{pod} \Delta x_{pod}
\end{align*}$$  \hspace{1cm} (17)$$

where $x_{pod} = [x_{pod1}, x_{pod2}, x_{pod3}]^T$, and $x_{pod, k}$ includes the state variables of POD controllers for P and Q modulations in kth GSMMC (k = 1, 2, and 3); $y_{pod}$ and $y_{pod}$ are the vectors of input signals and output signals, respectively; $A_{pod}$, $B_{pod}$, and $C_{pod}$ denote the state matrix, input matrix and output matrix of POD controllers, respectively. The input signals of POD controllers can be represented by the state variables of SGs, which is

$$\Delta y_{pod} = C_g \Delta x_g$$  \hspace{1cm} (18)$$

Since $\Delta P_{ac,k}$ depends on $V_{dc,k}$, $P_{ac,k}$, and $P_{pod,k}$, while $\Delta Q_{ac,k}$ is decided by $Q_{ref,k}$ and $Q_{pod,k}$. Therefore, $S_{ac}$ can be written as

$$\Delta S_{ac} = \Delta S_{ref} + K_{s1} \Delta x_{ac} + K_{s2} \Delta y_{pod}$$  \hspace{1cm} (19)$$

where $S_{ref} = [P_{ref}, Q_{ref}]^T$, and $P_{ref}$ and $Q_{ref}$ are the vectors of reference active and reactive power of GSMMCs. Combining (15)-(19) can get,

$$\Delta x_{sys} = A_{sys} \Delta x_{sys} + B_{sys} \Delta P_{df} + B_{ref} \Delta S_{ref}$$  \hspace{1cm} (20)$$

where $A_{sys} = [A_{dc}, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0]$, $B_{sys} = [B_{dc}, B_{s1}, B_{s2}, B_{dc}]^T$ and $J_i = [I, 0]; B_{ref} = [B_{ref, 0}, 0]^T, B_{ref} = [B_{ref, 1}, B_{ref, 2}]^T$.

Based on (9), (13), and (14), the deviation of the output active power of OWFs is described as,

$$\Delta P_{wfid}(s) = -K_{c,wfid} \frac{V_{DCLD}^2}{V_{dc0}} \left( \frac{s^2 + 2\zeta_i\omega_n s + \omega_n^2}{s^2 + 2\zeta_i\omega_n s + \omega_n^2} \right)^2 \cdot \left( \frac{1}{sT_f^2 + 1} \right)^2 \cdot s \Delta V_{dc,j}(s)$$  \hspace{1cm} (21)$$

where the subscript ‘j’ represents the variable corresponding to the jth OWF, and $j=1$ and 2. The prerequisites of (21) include that the OWF systems are stable, and the electromagnetic power of PMSG in each WT is controlled to
be steady during the transient process. The state-space equation of (21) is,
\[
\begin{align*}
\Delta \dot{x}_w &= A_w \Delta x_w + B_w \Delta V_{wdc} \\
\Delta P_{w} &= C_1 \Delta x_w
\end{align*}
\]
(22)
Here \(\Delta x_w\) contains the state variables in (21); \(\Delta V_{wdc} = [\Delta V_{dc1}, \Delta V_{dc3}]^T\) which can be expressed by \(\Delta V_{wdc} = C_2 \Delta x_{sys}\). Hence, combining (20) and (22) will get the linearized model of the studied system with the proposed coordinated POD control, which is,
\[
\Delta \dot{x}_{sys2} = A_{sys} \Delta x_{sys2} + B_{ref2} \Delta S_{ref}
\]
(23)
where \(x_{sys} = [x_s, x_w]^T, B_{ref} = [B_{ref}, B_u C_2 B_{ref}]^T,\) and
\[A_{sys} = \begin{bmatrix}
B_w C_2 A_{sys} & A_w + B_w C_2 B_{sys} C_1
\end{bmatrix}.\]

### TABLE II
POWER OSCILLATION MODES WITHOUT OR WITH COORDINATED POD

<table>
<thead>
<tr>
<th>Mode</th>
<th>(\tilde{\lambda}_i (\tilde{\xi}_i))</th>
<th>Major participants</th>
<th>Without POD</th>
<th>With coordinated POD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.30 ± j9.14 (3.3%)</td>
<td>SG4, 5</td>
<td>-0.30 ± j9.14 (3.3%)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>-0.25 ± j9.01 (2.8%)</td>
<td>SG8, 9</td>
<td>-1.53 ± j9.18 (16.4%)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-0.40 ± j8.97 (4.5%)</td>
<td>SG7, 6</td>
<td>-0.40 ± j8.98 (4.4%)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.09 ± j7.99 (-1.1%)</td>
<td>SG9, 8</td>
<td>-0.66 ± j8.29 (7.9%)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-0.23± j7.44 (3.1%)</td>
<td>SG5, 6, 7, 4</td>
<td>-0.22± j7.44 (3.0%)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>-0.16± j3.83 (4.2%)</td>
<td>SG10, 5, 6, 4, 7</td>
<td>-0.40± j3.91 (10.2%)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>-0.26± j8.00 (3.2%)</td>
<td>SG2, 3</td>
<td>-0.24± j7.97 (3.0%)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>-0.21± j6.83 (3.1%)</td>
<td>SG3, 2, 1, 5</td>
<td>-0.14± j7.03 (22.3%)</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>-0.59± j6.50 (9.0%)</td>
<td>SG1, 2</td>
<td>-0.59± j6.49 (9.1%)</td>
<td></td>
</tr>
</tbody>
</table>

### B. System Related Oscillatory Modes

The eigenvalues \((\lambda_i = \sigma_i \pm j \xi_i)\) of matrix \(A_{sys2}\) in (23) are obtained by \(\text{eig} \) command in MATLAB, and the frequency and damping ratio of a mode \((\tilde{\lambda}_i)\) are calculated as \(f_m = \sigma_i / 2 \pi\) and \(\xi_i = -\sigma_i / \sqrt{\sigma_i^2 + \omega_i^2} \times 100\%\), respectively. The power oscillation modes are illustrated in Table II. Without POD controllers, all 9 power oscillation modes are stable except mode 4, and most modes are lightly damped due to the negligence of PSS. Considering the locations of GSMMCs, modes 4, 6, and 8 are selected as the targeted modes to be damped from GSMMC1, 2, and 3, respectively. Among them, mode 4 is the local mode, and modes 6 and 8 are the interarea modes.

**Fig. 6. Oscillatory modes in the simplified model of the studied system with and without coordinated POD control.**

Based on eigenvalue analysis, the determined parameters of the POD controllers for GSMMC1, 2, and 3 are listed in Table III. For all the POD controllers, the time constants of LPF and wash-out filter are \(r = 0.01\) s and \(T_w = 5\) s, respectively. As shown in Table II, with coordinated POD control, the damping ratios of the targeted modes are improved significantly without jeopardizing the other modes. Moreover, the mode shapes of the targeted modes remain almost unchanged.

The oscillatory modes in the simplified model of the studied system with and without POD control are plotted in Fig. 6, where the eigenvalues of the power oscillation modes are listed in Table II. It shows that the frequencies of the modes are mainly distributed in \(0 \sim 6\) Hz and \(10 \sim 300\) Hz. Apart from the power oscillation modes, the damping ratios of system-related oscillatory modes are sufficient. Additionally, the results show that in this simplified model, the coordinated POD control will not deteriorate the stability of the HVDC grid and OWFs.

### TABLE III
PARAMETERS OF THE POD CONTROLLERS FOR GSMMCs

<table>
<thead>
<tr>
<th>N o.</th>
<th>Input PMU data (p.u.)</th>
<th>Parameters</th>
<th>Input PMU data (rad)</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(f_{ref} - f_0)</td>
<td>(K_v = 50; T_s = 0.05; T_w = 0.02)</td>
<td>(\delta_{c0} = \delta_{c1})</td>
<td>(K_v = 1; T_s = 0.05; T_w = 0.02)</td>
</tr>
<tr>
<td>2</td>
<td>(f_{ref} - 0.25(f_0 + f_{pdc}))</td>
<td>(K_v = 75; T_s = 0.03; T_w = 0.02)</td>
<td>(0.25(\delta_{c0} + \delta_{c1}) + \delta_{c2} + \delta_{c3})</td>
<td>(K_v = 1; T_s = 0.03; T_w = 0.02)</td>
</tr>
<tr>
<td>3</td>
<td>(f_{ref} - f_{pdc})</td>
<td>(K_v = 50; T_s = 0.04; T_w = 0.02)</td>
<td>(\delta_{c2} + \delta_{c3} - \delta_{c1})</td>
<td>(K_v = 1; T_s = 0.04; T_w = 0.02)</td>
</tr>
</tbody>
</table>

### V. SIMULATION STUDIES

To validate the effectiveness of the proposed coordinated POD control strategy, the detailed time-domain simulation model based on Fig. 3 is built in MATLAB/Simulink. The parameters of POD controllers included in the model are listed in Table III. Each OWF uses a single aggregate WT model. In the onshore AC grid, the governor and AVR are included in each SG model, and the power loads remain steady throughout the simulations. The main parameters of the simulation model are presented in Appendix. Seven different cases are considered in the simulation studies, and the descriptions of those cases are as follows,

1) **Case A:** None of the POD controllers is activated.
2) **Case B:** POD controllers for P-modulation are activated, while those for Q-modulation are disabled.
3) **Case C:** All the POD controllers are active, but without the coordinated POD control from OWFs.
4) **Case D:** With the newly proposed coordinated POD control strategy.
5) **Case E:** With the coordinated POD control strategy studied in [30], and assuming the GSMMCs and offshore WTs receive the P-modulation signals simultaneously. The P-modulations from OWFs 1 and 2 are the same, which are described as \(\Delta P_{w1} = \Delta P_{w2} = \sum_{k=1}^{2} \Delta P_{pod,k}/2\).
6) **Case E1:** The only difference from **Case E** is that the offshore WTs receive the P-modulation signals 100 ms later than the GSMMCs due to the communication delay from onshore to offshore.
7) **Case E2:** The only difference from **Case E1** is that the time delay is extended to 200 ms.

The limits of P-modulation for POD are \(\pm 10\%\) of the rated active power and for Q-modulation are \(\pm 10\%\) of the nominal...
power in each GSMMC. The wind speed of OWF1 is fixed at 13 m/s, while the wind speed of OWF2 has a step change from 13 to 11 m/s at 5 s and the rotor speed of the WT in OWF2 will decrease afterward. During a simulation case, a temporary three-phase-to-ground short circuit fault is applied in the AC grid at 15 s, and the fault is cleared after 0.16 s. The selected buses to apply the fault in this study are B14, 25, and 7, which will then be represented by the fault I, II, and III respectively. The PSSs in the SGs are disabled at 15 s in each case. As power oscillation is a phenomenon of SGs oscillating with each other, the simulation results will use rotor angle oscillations of SGs to represent the power oscillations.

A. Cases A ~ C

Fig.7 compares the transient responses of the SGs and HVDC grid voltage in Cases A–C under the fault I. As shown in Fig 7(a) – (c), δn1 is unstable, and δn2 and δn3 are stable but lightly damped due to the POD controllers being disabled in Case A. However, with the POD controllers for P-modulation in Case B, the damping ratios of the three oscillatory signals are improved. If the POD controllers for P and Q modulations are all activated, the power oscillations are damped out more efficiently. We use the Prony toolbox in MATLAB to analyze the frequencies of those power oscillation signals, and the results show that the dominant frequencies of δn1, δn2, and δn3 are approximately 1.32 Hz, 0.65 Hz, and 1.18 Hz, respectively, which match the eigenvalue results in TABLE II. For the HVDC grid voltage \( v_{dc} \), it shows in Fig 7(d) that \( v_{dc} \) remains almost stable after the disturbance in Case A. However, variations of \( v_{dc} \) are observed in Case B and C as the POD controllers for P-modulation are in operation. The fluctuation of \( v_{dc} \) has close relations with the power oscillation signals, which proves the existence of interactions between POD and HVDC grid voltage.

B. Performance of the Proposed Coordinated POD Control Strategy

This section will verify the effectiveness of the novel proposed coordinated POD strategy and present a comparative study of the proposed and previous methods.

Fig 8 plots responses of the SGs and HVDC grid voltage in Cases C–E under the fault I. It shows in Fig 8(a) ~ (c) that with coordinated POD control from OWFs, both Cases D and E improve the damping of power oscillations. The damping improvements seen in δn2 are more pronounced than δn1 and δn3. The reason is that the frequency of δn2 is smaller than that of δn1 and δn3, and the damping of δn2 is more sensitive to the P-modulation and the reduction of interaction factor. Hence, for particularly low oscillation frequencies, coordinated POD control is more necessary. In addition, the POD performances within Cases D and E are very close. Despite the increased damping by the coordinated POD strategies that may not seem significant, any improvement in the damping ratio is valuable for the safe operation of low-damping power grids.

In Fig. 8(d), the variations of \( v_{dc} \) in Cases D and E are smaller than the ones in Case C during the POD event, which proves that coordinate control from OWFs could reduce the variation of \( v_{dc} \). Although the variation of \( v_{dc} \) in Case E is even smaller than the one in Case D, the result of Case E relies on the assumption that the communication links from onshore to offshore do not introduce extra time delays into the close-loop POD control system, which is unlikely in a real
application. Under the faults II and III, as shown in Figs. 9 and 10, respectively, the performances of the three cases are very similar to those in Fig. 8.

Fig. 11 presents the responses of OWFs and WFMMCs in Cases C–E under the fault I. Since OWFs do not participate in POD in Case C, the active power, rotor speed, and DC-link voltage of the WTs, and the PCC bus voltages remain unaffected during the POD event. In Case D, due to the transient response of $v_{dc}$ after the short circuit fault, the active power and DC-link voltage will experience sudden steep changes firstly. Afterward, the power fluctuations of the OWFs in Case D are like those in Case E, as shown in Fig. 11(a)–(b). It is worth noting that the sources for modulating $p_{wf1}$ and $p_{wf2}$ during POD events are different in the two cases. Concerning Case D, the fluctuations of $p_{wf1}$ and $p_{wf2}$ are caused by the release and storage of energy in the DC-link capacitors, which almost has no impact on WT blades and generator. However, Case E depends on the kinetic energy of WT to modulate $p_{wf1}$ and $p_{wf2}$, which results in vibrations of WT blades and generator [see Fig. 11(c)–(f)]. As the inertia of the WT generator is much smaller than that of the blades, the rotor speed of the generator fluctuates more significantly than the blades.

As shown in Fig. 11, the largest values of $p_{wf1}$ and $p_{wf2}$ can be restricted to approximately 1.13 p.u., while the ones of $v_{DCL1}$ and $v_{DCL2}$ are 1.10 p.u by the controllers in Case D, which will not cause the overload of the power electronic converters in the WTs. In addition, the range of $v_{pcc1}$ and $v_{pcc2}$ are lower than ±5 % and should be acceptable for the safe operation of offshore AC equipment.

The active and reactive power of the three GSMMCs are plotted in Fig. 12. After the disturbance caused by fault I, the GSMMCs modulate active and reactive power proactively, and the maximum adjusted powers of the three cases are similar.

![Fig. 12. The active and reactive power of three GSMMCs under the fault I.](image)

C. Effect of Time Delay

For the previous method in [30], Cases E1 and E2 consider the time delay introduced by the communication links between onshore and offshore. As shown in Fig. 13, with a 100 ms delay in Case E1, the damping of the power oscillations is weaker and the variation of the HVDC grid voltage during POD is larger than the proposed method (Case D). If the time delay is extended to 200 ms as in Case E2, the POD effectiveness becomes worse and the HVDC grid fluctuates more significantly than the case even without the coordinated POD control from OWFs (Case C). The results show the advantage of the proposed method as it does not need the communication links to send P-modulation signals to the offshore WTs, the negative effects caused by the above communication delays can be avoided.

![Fig. 13. Comparison of the proposed and previous methods when considering the effect of time delay under the fault I.](image)

D. Discussion

The simulation results prove that the coordinated POD control from the HVDC grid and OWFs performs better than
only from HVDC in damping the low-frequency power system oscillations and reducing the variations of the HVDC grid voltage. The performance of the previous communication-based method is vulnerable to the time delay of communicating the P-modulation signals from onshore to offshore. Compared to this previous method without the negative impact of such time delay (Case E), the newly proposed coordinated strategy (Case D) can achieve similar POD improvements, but without the need for communication links established between the onshore grid and offshore WTs. In addition, the proposed strategy implies negligible impacts on the WT’s drivetrain shaft. Future work needs to investigate the cooperation of this strategy with the offshore AC grid voltage controller [40].

### Table A1: Parameters of the Synchronous Generators

<table>
<thead>
<tr>
<th>No.</th>
<th>$H$</th>
<th>$x_1$</th>
<th>$x_2$</th>
<th>$x'_q$</th>
<th>$x'_d$</th>
<th>$x_t$</th>
<th>$x_q$</th>
<th>$x_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>42.0</td>
<td>0.02</td>
<td>0.18</td>
<td>0.03</td>
<td>0.025</td>
<td>0.17</td>
<td>0.055</td>
<td>0.025</td>
</tr>
<tr>
<td>2</td>
<td>30.3</td>
<td>0.02</td>
<td>0.18</td>
<td>0.03</td>
<td>0.025</td>
<td>0.17</td>
<td>0.055</td>
<td>0.025</td>
</tr>
<tr>
<td>3</td>
<td>36.4</td>
<td>0.02</td>
<td>0.18</td>
<td>0.03</td>
<td>0.025</td>
<td>0.17</td>
<td>0.055</td>
<td>0.025</td>
</tr>
<tr>
<td>4</td>
<td>28.6</td>
<td>0.02</td>
<td>0.18</td>
<td>0.03</td>
<td>0.025</td>
<td>0.17</td>
<td>0.055</td>
<td>0.025</td>
</tr>
<tr>
<td>5</td>
<td>26.0</td>
<td>0.02</td>
<td>0.18</td>
<td>0.03</td>
<td>0.025</td>
<td>0.17</td>
<td>0.055</td>
<td>0.025</td>
</tr>
<tr>
<td>6</td>
<td>34.8</td>
<td>0.02</td>
<td>0.18</td>
<td>0.03</td>
<td>0.025</td>
<td>0.17</td>
<td>0.055</td>
<td>0.025</td>
</tr>
<tr>
<td>7</td>
<td>26.3</td>
<td>0.02</td>
<td>0.18</td>
<td>0.03</td>
<td>0.025</td>
<td>0.17</td>
<td>0.055</td>
<td>0.025</td>
</tr>
<tr>
<td>8</td>
<td>24.3</td>
<td>0.02</td>
<td>0.18</td>
<td>0.03</td>
<td>0.025</td>
<td>0.17</td>
<td>0.055</td>
<td>0.025</td>
</tr>
<tr>
<td>9</td>
<td>24.5</td>
<td>0.02</td>
<td>0.18</td>
<td>0.03</td>
<td>0.025</td>
<td>0.17</td>
<td>0.055</td>
<td>0.025</td>
</tr>
<tr>
<td>10</td>
<td>500</td>
<td>0.0022</td>
<td>0.02</td>
<td>0.006</td>
<td>0.0025</td>
<td>0.019</td>
<td>0.008</td>
<td>0.0025</td>
</tr>
</tbody>
</table>

### Table A2: Parameters of the Loads

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Name</th>
<th>Value</th>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>L3</td>
<td>3.22+j0.02</td>
<td>L18</td>
<td>1.58+j0.30</td>
<td>L27</td>
<td>2.81+j0.76</td>
</tr>
<tr>
<td>L4</td>
<td>4.00+j1.84</td>
<td>L20</td>
<td>6.28+j1.03</td>
<td>L28</td>
<td>8.06+j0.28</td>
</tr>
<tr>
<td>L6</td>
<td>6.33+j0.84</td>
<td>L21</td>
<td>2.74+j1.15</td>
<td>L29</td>
<td>2.84+j0.27</td>
</tr>
<tr>
<td>L8</td>
<td>7.22+j1.76</td>
<td>L23</td>
<td>2.48+j0.85</td>
<td>L31</td>
<td>0.09+j0.05</td>
</tr>
<tr>
<td>L12</td>
<td>0.08+j0.88</td>
<td>L24</td>
<td>3.09+j0.92</td>
<td>L39</td>
<td>11.04+j2.5</td>
</tr>
<tr>
<td>L15</td>
<td>5.20+j1.53</td>
<td>L25</td>
<td>2.24+j0.47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L16</td>
<td>6.29+j0.32</td>
<td>L26</td>
<td>2.39+j0.17</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### VI. CONCLUSION

This paper proposes a novel coordinated control strategy for VSC-HVDC grid integrated OWFs to damp the power system oscillations. To improve the overall POD performance, this strategy aims to use the DC-link capacitor energy of offshore WTs to reduce interactions between power oscillations and HVDC grid voltage when GSVSCs modulate the active and reactive power injections. The coordination from offshore WTs depends on the local measurements of the HVDC grid voltage instead of the remote communication data from the onshore AC grid.

A modified IEEE 39-bus power system with a 5-terminal HVDC grid connected to two offshore wind farms has been employed to study the effectiveness of this control strategy. The simplified small-signal model and detailed time-domain simulation model of the studied system have been built. Both the eigenvalue analysis and simulation results indicate that the strategy can significantly improve the power system oscillation damping. Additionally, comparative simulation studies conclude that the proposed strategy has similar POD improvements to the previous communication-based method without the negative impact of communication delay from onshore to offshore. This new strategy can be an alternative for future coordinated POD applications in a similar system.

### VII. APPENDIX

The parameters of the SGs and loads based on the nominal power of 100 MVA are shown in Table A1 and A2, respectively. HVDC grid data are in Table A3.

The parameters of the offshore WT are: |r|: (1) rated power: 10 MW; (2) rotor radius: 89.15 m; (3) rated rotor speed: 9.6 rpm; (4) ratio of the gearbox: 1:50; (5) number of pole pairs: 2; (6) air density: 1.225 kg/m³; (7) inertia constant of the turbine: 5.8 s; (8) inertia constant of the PMSG: 0.9 s; (9) drivetrain shaft torsional spring constant: 239 p.u./s; (10) nominal voltage of PMSG: 3470 V; (11) DC-link capacitance: 20 mF; (12) rated DC-link voltage: 7500 V.

### Table A3: Parameters of the MMC-based HVDC Grid

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated DC voltage</td>
<td>±350kV</td>
</tr>
<tr>
<td>MMCs</td>
<td>Value</td>
</tr>
<tr>
<td>WFMCC</td>
<td>GSMCC</td>
</tr>
<tr>
<td>SM number per arm</td>
<td>200</td>
</tr>
<tr>
<td>SM capacitance</td>
<td>9.2 mF</td>
</tr>
<tr>
<td>Arm inductance</td>
<td>0.2 p.u.</td>
</tr>
<tr>
<td>Rated active power</td>
<td>900 MW</td>
</tr>
<tr>
<td>Rated reactive power</td>
<td>0</td>
</tr>
<tr>
<td>DC line reactor</td>
<td>150 mH</td>
</tr>
<tr>
<td>Transmission Cable</td>
<td>0.014 Ω/km</td>
</tr>
<tr>
<td>Capacitance</td>
<td>0.86 mH/km</td>
</tr>
<tr>
<td>Resistance</td>
<td>0.41 μF/km</td>
</tr>
</tbody>
</table>

### VIII. REFERENCES


IX. BIOGRAPHIES

Zuan Zhang received B.S. degree in electronic information engineering from Zhejiang University, Hangzhou, China, in 2011 and the M.S. degree in electrical engineering from Tsinghua University, Beijing, China, in 2014. He is currently working toward the Ph.D. degree with the University of Warwick, Coventry, U.K. From 2014 to 2020, he was with the Electric Power Research Institute, China Southern Power Grid, Guangzhou, China. He is currently a Marie Curie Early Stage Researcher with the School of Engineering, University of Warwick. His research interests include wind energy systems, HVDC and intelligent control.

Xiaowei Zhao received the Ph.D. degree in control theory from Imperial College London, London, U.K., in 2010. He was a Post-Doctoral Researcher with the University of Oxford, Oxford, U.K., for three years before joining the University of Warwick, Coventry, U.K., in 2013. He is currently a Professor of control engineering and an EPSRC Fellow with the School of Engineering, University of Warwick.