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Stability and Dynamic Analysis of the PMSG-based WECS with Torsional Oscillation and Power Oscillation Damping Capabilities

Zuan Zhang, Xiaowei Zhao, Le Fu, and Mohamed Edrah

Abstract-- The direct-drive permanent-magnet synchronous generator (PMSG) based wind energy conversion system (WECS) with a soft drivetrain shaft is vulnerable to torsional oscillation when it participates in power oscillation damping (POD) services for the AC grid. This paper investigates three possible scenarios of incorporating both torsional oscillation damping (TOD) and POD controllers into PMSG-based WECS. A model of a PMSG-based offshore wind farm (OWF) connected to the IEEE 39-bus AC grid is developed and utilized to analyze the stability and dynamic performances of the WECS within these three scenarios. Comprehensive modal analysis is carried out to analyze the interaction between the torsional and power oscillations, and to tune the TOD and POD controllers to damp these oscillations simultaneously in each scenario. Furthermore, the dynamic performances of the PMSG-based WECS within these scenarios are evaluated through time-domain simulations. Then an optimal scenario for PMSG-based WECS to damp both oscillation types with close frequencies is identified, which is modulating the DC-link voltage for the TOD and the grid-side active power for the POD. This result can provide useful guidance for the future industrial application of the TOD and POD control in the PMSG-based WECS.

Index Terms-- Permanent-magnet synchronous generator (PMSG), wind energy conversion system (WECS), drivetrain, torsional oscillation damping (TOD), power oscillation damping (POD), stability, modal analysis.

ACRONYMM

DPO Drup operation
GSC Grid-side converter
LPF Low pass filter
MSC Machine-side converter
MPPT Maximum power point tracking
MXP Maximum power operation

NPF Normalized participation factor
OWF Offshore wind farm
PCC Point of common coupling
PLL Phase-locked loop
PMSG Permanent-magnet synchronous generator
POD Power oscillation damping
PSS Power system stabilizer
SG Synchronous generator
TOD Torsional oscillation damping
TSO Transmission system operator
WECS Wind energy conversion system
WT Wind turbine

I. INTRODUCTION

OFFSHORE wind power is becoming a mainstream source of renewable energy and more offshore wind farms (OWFs) have been connected to the onshore AC (alternating current) grids. With the increasing penetration of OWFs, more and more conventional synchronous generators (SGs) with well-established power system stabilizer (PSS) damping capability have been turned off, which will significantly influence power system damping capability. Due to unpredictable and random component failure and/or external disturbances, such as lightning strikes, and flashovers, the onshore AC grid may switch into operation conditions that can cause low frequency (0.1–2 Hz) power oscillations. Undamped oscillations could lead to a regional or largescale blackout. Therefore, given the amount of OWFs in the future, more and more transmission system operators (TSOs) require wind farms to provide ancillary services, particularly to damp oscillations to enhance system stability and reliability by managing future oscillations risks [1].

POD from OWF needs to control the WECS of each wind turbine (WT) to modulate its output active and reactive power injections into the power grid. At present, commercial WTs in OWF can be mainly divided into two categories according to WECS, which are doubly-fed induction generator (DFIG) type with a partial-scale power converter, and PMSG type with a full-scale power converter. Compared to DFIG, the gearless PMSG-based WTs need less maintenance and allow higher efficiency, which have gained interest from OWF applications [2]. However, PMSG-based WT has a soft drivetrain shaft and no inherent damping, which is prone to drivetrain torsional
oscillations when the system is excited by mechanical or electrical disturbances. In particular, the typical frequency of the torsional oscillation ranges from 0.1 to 10 Hz [3], which tends to coincide with the frequencies of power system oscillations. The closer the frequencies of these two types of oscillations, the more likely the torsional oscillation can be excited during POD events. Hence, the control system of the PMSG-based WECS should take account of damping both the torsional and power oscillations. Otherwise, those oscillations will not only bring high mechanical stress to the drivetrain and adversely impact its lifespan, but also influence the stability of the entire system.

Previous studies mainly focused on POD from DFIG-based WTs [4]-[13], whose results verified the feasibility of damping power oscillations by directly modulating the active or reactive power of WECS. Only a small number of published papers investigated the use of PMSG-based WTs to damp power oscillation [14]-[18]. Among these publications, a one-mass shaft model was employed in [14], [16] and [18], which cannot reflect the torsional mode. To avoid the potential torsional oscillation, regulating the electrostatic energy of DC-link capacitors rather than the output power of WECS to damp power oscillations was investigated in [15]. Reference [17] stated that the torsional oscillation might be excited by POD, but detailed studies on the interaction between them were not conducted. Supplementary TOD by controlling the active power or the DC-link voltage of WECS was investigated in [2] and [19]-[24], but the capability of POD was not covered.

Methods to depress both the torsional and power oscillations caused by frequency response from DFIG-based WTs were studied in [25], while only one active power control scheme was investigated and the interaction between these two types of oscillations was not thoroughly considered because their frequencies were not sufficiently close.

To our best knowledge, there are no publications yet that consider both TOD and POD control in PMSG-based WECS. How torsional oscillation interacts with power oscillation due to their similar frequencies when WECS is incorporated with both TOD and POD controllers remains an open question, and how to achieve better TOD and POD performances from the aspect of system stability and dynamics is unclear. Therefore, this paper comprehensively addresses these issues. It is worth noting that since supplying POD by modulating reactive power has an insignificant influence on torsional oscillation [5], this paper focuses on modulating the active power of WECS. The major contributions of this paper are summarized below:

1) Three possible scenarios of incorporating both TOD and POD controllers into the PMSG-based WECS are investigated for the first time.
2) A unified linearized model of the AC grid connected to a PMSG-based OWF system with TOD and POD control is developed. The model presents a generalized tool for analyzing the dynamic interaction of the torsional and power oscillations.
3) In cases where the torsional oscillation frequency is close to one of the targeted power oscillations, modal analysis is carried out to analyze the interaction of these two types of oscillations, and to tune the TOD and POD controllers to damp these oscillations simultaneously.
4) Using detailed time-domain simulations, the dynamic performances of the WECS within the three scenarios are compared and discussed. The optimal scenario is then recommended for PMSG-based WECS to damp both torsional and power oscillations with close frequencies. Results can provide some reference and experience for the future design and real-world application of both TOD and POD control in the PMSG-based WECS.

The rest of this paper is structured as follows. Section II is about modeling PMSG-based WECS and proposing three possible scenarios of integrating TOD and POD control into the model. Section III develops the linearized model of an OWF and IEEE 39-bus AC grid integrated system with TOD and POD control. Section IV provides the modal analysis results of the developed model in Section III. Time-domain simulation results are illustrated in Section V. Finally, conclusions are given in Section VI.

II. MODELLING AND CONTROL SCENARIOS OF THE WECS

The schematic diagram of a direct-drive PMSG-based WECS is illustrated in Fig.1, which mainly consists of the WT rotor, drivetrain, PMSG, back-to-back converter, harmonic filter, and control systems. The converter generally utilizes the three-level neutral point diode clamped topology [26] and includes a machine-side converter (MSC) and a grid-side converter (GSC). The output power of the WECS is injected into the point of common coupling (PCC) through a step-up transformer T1.

A. Drivetrain model

A two-mass shaft model [27] is applied to simulate the dynamic performance of WT, which can be expressed as

\[
\begin{align*}
2H_w \frac{d\omega_{wt}}{dt} &= T_w - T_s \\
2H_m \frac{d\omega_m}{dt} &= T_s - T_e \\
T_e &= K_e \int \omega_d (\omega_{wt} - \omega_m) dt + D_m (\omega_{wt} - \omega_m)
\end{align*}
\]

where \(\omega_{wt}\) and \(\omega_m\) represent the angular speed of the WT rotor and PMSG in per unit (p.u.), respectively; \(T_w\), \(T_s\) and \(T_e\) denote the mechanical torque of the WT rotor, the torque of the shaft, and electromagnetic torque of PMSG in p.u., respectively; \(H_w\) and \(H_m\) represent the inertia constant (in second) of the WT rotor and PMSG rotor, respectively; \(K_e\) and \(D_m\) are the equivalent torsional spring constant (in p.u./rad) and damping
constant (in p.u.) of the drivetrain shaft; \( \omega_0 \) is the base angular frequency (in rad/s).

According to (1), the natural frequency of the free-free rigid shaft torsion mode can be obtained as

\[
f_0 = \frac{1}{2\pi} \sqrt{\frac{(H_w + H_m)K_s\omega_0}{2H_wH_m} - \frac{D_m}{2H_m} + \frac{\xi^2(H_w + H_m)^2}{16H_w^2H_m^2}}
\]  

(2)

B. Control Scenarios of WECS with TOD and POD

Assuming \( T_w \) remains constant throughout the transient analysis. The small-signal form of (1) can be written as

\[
\frac{d^2\Delta \omega_d}{dt^2} + D_{d0}\frac{d\Delta \omega_d}{dt} + C_{d0}\Delta \omega_d + \frac{1}{2H_m}\frac{d\Delta \omega}{dt} = 0
\]  

(3)

where \( \omega_{d0} = \omega_{d}\mathit{m} - \omega_{d}\mathit{e}, \ D_{d0} = D_{d0}(H_{w} + H_{m})/(2H_{w}H_{m}), \) and \( C_{d0} = K_{s}\omega_{0} \) \((H_{w} + H_{m})/(2H_{w}H_{m})\). The prefix ‘\( \mathit{d} \)’ denotes the deviation of a variable. If \( \Delta \omega \) is regulated according to \( 2\alpha H_{w}\omega_{d} \) (where \( \alpha \) is a positive constant), the damping of the torsional oscillation increases from \( D_{0} \) to \( D_{0} + \alpha \). When the WECS controls the active power, \( T_c \) can be further expressed as

\[ T_c = P_e/\omega_m \]  

(4)

where \( P_e \) is the electromagnetic power of PMSG (in p.u.). Neglecting the power losses of the WECS, the instantaneous power balance of the back-to-back converter is

\[ P_e = P_g + (C_{dc}V_{dca}V_{dc}/P_0) (dV_{dc}/dt) \]  

(5)

where \( P_g \) is the grid-side active power (in p.u.); \( C_{dc} \) is the capacitance value of the DC-link capacitor (in farad); \( V_{dc} \) is the voltage of the DC-link capacitor (in p.u.), and \( V_{dca} \) is the rated value (in volts); \( P_0 \) is the rated power of the WECS (in watts). Linearizing (4) and (5) under steady-state operation point gets

\[ \Delta T_c = \Delta P_e/\omega_m - \frac{\Delta P_g}{\omega_m}\frac{\Delta \omega}{\omega_m} \]  

(6)

\[ \Delta P_e = \Delta P_g + (C_{dc}V_{dca}V_{dc}/P_0)(dV_{dc}/dt) \]  

(7)

Generally, \( \Delta P_e \) is much larger than \( \Delta \omega_m \) during TOD. Thus, \( \Delta T_c \) mainly depends on \( \Delta P_e \), according to (6). It can be seen from (7) that regulating \( P_e, P_g, \) or \( V_{dc} \) based on the relevant processed signal \( \omega_d \) can damp the torsional oscillation.

The principle of regulating the output active power of the WECS to damp the power oscillations in the AC grid was studied in [16], where the WECS modulates the grid-side active power according to the POD control signal. It is observed from (7) that two approaches can achieve this. One is to control \( P_e \) directly while another is to maintain the \( P_e \) to be stable and regulate the \( V_{dc} \) properly.

Based on the above analysis, there are three possible scenarios to incorporate the TOD and POD control in WECS, as shown in Fig. 2(a), (b), and (c), which will be subsequently referred to as Scenario A, Scenario B, and Scenario C, respectively. The differences between these scenarios are the outer-loop proportional-integral (PI) control of the active power and DC-link voltage, while the reactive power control and inner-loop current control are the same, as shown in Fig. 2(d). In Fig. 2, the \( \bar{V}_{dca}, \bar{V}_{dcb}, \bar{V}_{dcd} \) are the control signals for TOD, and \( y_{pod,a}, y_{pod,b} \) are the control signals for POD; \( i_{m} \) and \( u_{m} \) are the MSC’s three-phase current and voltage, respectively; \( \theta_m, \Phi_m, \) and \( L_s \) represent the rotation angle, magnetic flux, and stator inductance of the PMSG, respectively; \( i_p \) and \( u_p \) are the grid-side three-phase current and voltage, respectively; \( \theta_p \) is the phase angle of \( u_p \), which is measured by the Phase-locked loop (PLL); \( X_p \) is the phase reactance of GSC; \( Q_5 \) is the output reactive power of WECS; The variables with subscripts ‘\( d \)’ and ‘\( q \)’ represent the corresponding \( d \)-axis and \( q \)-axis components of the variables, with subscript ‘\( ref \)’ represent the corresponding reference value, with a lower asterisk denote the output value of the second-order low pass filter (LPF). Apart from \( \theta_{m}, \theta_{p}, \) all the variables are described in p.u.

Fig. 2. Control scenarios of the WECS with TOD and POD capabilities: (a) MSC regulates the output active power for TOD and POD. (b) MSC modulates the electromagnetic power of PMSG for TOD, and GSC controls the DC-link voltage for POD. (c) MSC regulates the DC-link voltage for TOD, and GSC modulates the grid-side active power for POD, and (d) reactive power and current control of MSC and GSC.

The reference active power \( P_{ref} \) is determined by [16]

\[
P_{ref} = \begin{cases} 
\frac{k_{opt} \omega_{wt}^3}{\omega_{wt0}^3} & \omega_{wt} < \omega_{wt0} < \omega_{wt1} \\
\frac{P_{max} - k_{opt} \omega_{wt1}^3}{\omega_{wt0}^3} & \omega_{wt0} < \omega_{wt} < \omega_{wt1} \\
\frac{P_{max} - \omega_{wt1}^3}{\omega_{max}^3} & \omega_{wt} < \omega_{max} \\
P_{max} & \omega_{max} \geq \omega_{max}
\end{cases}
\]  

(8)

where \( P_{ref} \) adjusts according to \( \omega_{wt} \) instead of \( \omega_{m} \) because the inertia constant of the WT rotor is much larger than the PMSG rotor (this means that the fluctuation of \( P_{ref} \) can be reduced during POD events); \( k_{opt} \) is the maximum power point tracking (MPPT) curve coefficient, and it can be assumed to be a constant over a relatively wide range of wind speeds; \( \omega_{wt0} \) is the cut-in angular speed (in p.u.); \( P_{max} \) is the maximum active power of the WECS (in p.u.). To ensure a smooth transition from MPPT to maximum power operation (MPX), a droop characteristic of \( P_{ref} \) is adopted during this process where \( \omega_{wt0} \) is the initial angular speed (in p.u.). This transition stage is named ‘Droop operation (DPO)’ in this paper. \( \omega_{max} \) represents the maximum angular speed (in p.u.). It is worth
noting that the pitch control [2] can prevent the WT to be overspeed as the output power reaches $P_{\text{max}}$.

C. Structures of the TOD and POD Controllers

Fig. 3 shows the structures of the TOD and POD controllers, where the POD controller structure has been widely implemented in industrial applications [12]. In this figure, $v_{\text{tod}}$ is the input signal of the TOD controller, which adopts the angular speed difference (in p.u.) between the PMSG rotor and the WT rotor. Thus $v_{\text{tod}}=\omega_{m}-\omega_{wt}$, $v_{\text{pod}}$ is the input signal of the POD controller, that uses the rotor angle difference (in rad) between the SGs which contribute to the target power oscillation in the AC grid. $K_{\text{pod,k}}$ and $K_{\text{pod,k}}$ are the controller gains. $T_{f}$ is the time constant of the LPF. $T_{w}$ is the washout time constant. $T_{1,k}-T_{4,k}$ are the time constants of the lead/lag compensators. A limiter is employed in each controller to prevent the output signal from causing the WECS to exceed the safe operating range.

Considering the frequency characteristics of the torsional and power oscillations, the time constants of the LPF and wash-out filter are set to $T_{f}=0.01$ s and $T_{w}=5$ s, respectively. The output limits for both controllers are set to ±0.1 p.u. Study the incremental improvements of POD controller gains lead/lag compensators, respectively.

The small-signal model of the aggregated OWF without TOD and POD control in WECS can be described as

$$\Delta \dot{x}_{\text{tf}} = A_{\text{tf},k} \Delta x_{\text{tf}} + B_{\text{tf},k} \Delta v_{\text{tf}}$$

where $x_{\text{tf}}$ is the vector of state variables of the aggregated model of an OWF, which includes PLL, LPFs, and proportional-integral (PI) controllers. The details of the state variables are presented in TABLE I; $v_{\text{ref}}=[P_{\text{ref}}, Q_{\text{ref}}, V_{dc,ref}]^{T}$; $u_{\text{in}}=[u_{\text{in},28}, u_{\text{in},28}]^{T}$ where $u_{\text{in},28}$ and $u_{\text{in},28}$ indicate the x-axis and y-axis components of B28 bus voltage, respectively; $A_{\text{tf},k}$, $B_{\text{ref},k}$ and $B_{\text{ref},k}$ represent the state matrix, input matrix of reference control values and bus voltage, respectively; $k=a$, $b$, and $c$ indicate the matrices belonging to the Scenarios A, B, and C, respectively.

III. LINEARIZATION OF A WIND FARM AND AC GRID INTEGRATED SYSTEM

A model of a PMSG-based OWF connected to the benchmark IEEE 39-bus AC grid is utilized to study the stability and dynamic performances of the WECS with TOD and POD control, as shown in Fig.4. The OWF contains 40 PMSG-based WTs, and the rated capacity of each WT is 10MW. The parameters of this WECS are listed in Appendix A with some data available in [28]. The OWF model is equivalent to an aggregated single WT model, its feasibility was proved in [29]. The parameter values of the grid and SGs can be found in [30] with some data modified here, which are listed in Appendix B.

The linearized model has made the following assumptions, 1) Automatic voltage regulators (AVRs) are considered for all the SGs; 2) To study the incremental improvements of POD provided by OWF, the PSS in each SG has been disregarded; 3) The power loads in the AC grid employ constant impedance model; 4) The mechanical torque of the WT rotor and mechanical power of SGs remain constant throughout the transient analysis.

A. Linearization of the PMSG-based Wind Farm

Previous studies have described the linearization of the PMSG-based wind farm in detail [31]-[33]. However, those papers did not consider both the TOD and POD control in the WECS. The small-signal model of the aggregated OWF without TOD and POD control in WECS can be described as

$$\Delta \dot{x}_{\text{tf}} = A_{\text{tf},k} \Delta x_{\text{tf}} + B_{\text{tf},k} \Delta v_{\text{tf}}$$

where $x_{\text{tf}}$ is the vector of state variables of the aggregated model of an OWF, which includes PLL, LPFs, and proportional-integral (PI) controllers. The details of the state variables are presented in TABLE I; $v_{\text{ref}}=[P_{\text{ref}}, Q_{\text{ref}}, V_{dc,ref}]^{T}$; $u_{\text{in}}=[u_{\text{in},28}, u_{\text{in},28}]^{T}$ where $u_{\text{in},28}$ and $u_{\text{in},28}$ indicate the x-axis and y-axis components of B28 bus voltage, respectively; $A_{\text{tf},k}$, $B_{\text{ref},k}$ and $B_{\text{ref},k}$ represent the state matrix, input matrix of reference control values and bus voltage, respectively; $k=a$, $b$, and $c$ indicate the matrices belonging to the Scenarios A, B, and C, respectively.

The linearized equations of the TOD and POD controllers in Fig. 3 can be written as,

$$\begin{align*}
\Delta x_{\text{pod}} &= A_{\text{pod,k}} \Delta x_{\text{pod}} + B_{\text{pod,k}} \Delta v_{\text{pod}} \\
\Delta y_{\text{pod,k}} &= C_{\text{pod,k}} \Delta x_{\text{pod}} \\
\Delta x_{\text{pod}} &= A_{\text{pod,k}} \Delta x_{\text{pod}} + B_{\text{pod,k}} \Delta v_{\text{pod}} \\
\Delta y_{\text{pod,k}} &= C_{\text{pod,k}} \Delta x_{\text{pod}}
\end{align*}$$

(10)  

(11)

where $x_{\text{pod}}$ and $x_{\text{pod}}$ are the vectors of state variables of the TOD and POD controllers, respectively; $A_{\text{pod,k}}$, $B_{\text{pod,k}}$ and $C_{\text{pod,k}}$ denote the state matrix, input matrix, and output matrix of TOD controller, respectively; $A_{\text{pod,k}}$, $B_{\text{pod,k}}$ and $C_{\text{pod,k}}$ are defined similarly.

Combining (9) ~ (11) gets the linearized model of OWF with TOD and POD control in WECS, which is,
\[
\Delta x_W = A_{W,k} \Delta x_W + K_{v,k} \Delta v_d + B_{v,k} \Delta v_{ref} + B_{u,k} \Delta u_{in} \tag{12}
\]
where \(x_W = [x_{W,d}, x_{W,q}, x_{pod}]^T\), \(v_d = [v_{not}, v_{pod}]^T\).

\[
A_{W,k} = \begin{bmatrix}
A_{W,k} & 0 & 0 \\
0 & A_{pod,k} & 0 \\
0 & 0 & B_{pod,k}
\end{bmatrix}, 
B_{v,k} = \begin{bmatrix}
0 \\
0 \\
B_{pod,k}
\end{bmatrix}
\]
and \(B_{u,k} = \begin{bmatrix}
B_{ref,k} \\
0 \\
0
\end{bmatrix}\).

\(B_{v,k} = [0, 0, 0]^T\) and \(B_{u,k} = [B_{in,k}, 0, 0]^T\). In the state matrix \(A_{W,k}\), \(G_{pod,k} = B_{ref,k} X_{pod,k}\), and \(G_{pod,k} = B_{ref,k} X_{pod,k}\). If \(k = a\), we have \(B_{1,k} = \begin{bmatrix}1, 0, 0 \end{bmatrix}^T\). If \(k = b\), we have \(B_{1,k} = [0, 0, 1]^T\) and \(B_{2,k} = [1, 0, 0]^T\).

<table>
<thead>
<tr>
<th>Module</th>
<th>State variables</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSC</td>
<td>(i_{dc}, i_{ac})</td>
<td>converter ac side current</td>
</tr>
<tr>
<td></td>
<td>(i_{q}, i_{d})</td>
<td>converter dc side current</td>
</tr>
<tr>
<td></td>
<td>(u_{dc}, u_{ac})</td>
<td>transformer T1 primary side current</td>
</tr>
<tr>
<td></td>
<td>(x_{d}, x_{q})</td>
<td>capacitor voltage in the harmonic filter</td>
</tr>
<tr>
<td>GSC</td>
<td>(V_{dc}, V_{ac})</td>
<td>DC-link voltage</td>
</tr>
</tbody>
</table>

**TABLE I**

**DESCRIPTIONS OF THE STATE VARIABLES OF A PMSG-BASED WIND FARM**

\[\Delta \dot{x} = A \Delta x + B \Delta u \]

The elements in the vector \(i_{W}M\) for the B28 bus are equal to the corresponding currents injected by OWF and the rest elements are zero. Also, elements in \(u_{in}\) in (12) are included in the vector \(u_{W}\). Therefore, \(i_{W}M = C_{1}\times x_{W}\) and \(u_{W} = C_{2}\times x_{W}\), respectively, in which \(C_{1}\) and \(C_{2}\) are output matrices.

Based on (14), the relationship between \(i_{W}\) and \(u_{W}\) can be further expressed as

\[\Delta v_{ref} = Y_N \Delta u_{W} + G_w \Delta x_{W} + G_N \Delta x_{W} \tag{15}\]

Combining (12), (13), (15) and (16) can obtain the unified linearized model of an OWF and AC grid integrated system with TOD and POD control, which is illustrated as the block diagram shown in Fig. 5.

**Fig. 5.** Block diagram of the linearized model of a wind farm and AC grid integrated system with the TOD and POD control.

**Fig. 6.** System responses to the DC-link voltage step-change under the linearized model and Simulink model: (a) \(v_{dc}\), the DC-link voltage, (b) \(\omega_c\), the angular speed difference between the PMSG rotor and WT rotor, (c) \(i_{in}\), MSC ac side q-axis current, and (d) \(\delta_{RC}\), the rotor angle difference between the 8th SG and \(8^\text{th}\) SG in the AC grid.

In Fig. 5, \(A_{W,k} = A_{W,k} + B_{u,k} \times C_{2}\times A_{1}\); \(B_{W} = B_{u,k} \times A_{2}\); \(A_{2} = \begin{bmatrix} A_{2} + B_{u,k} A_{2} \\ B_{u,k} A_{2} \end{bmatrix}\); \(B_{pod,k} = K_{pod,k} X_{pod,k}\); \(B_{pod,k} = K_{pod,k} X_{pod,k}\); \(A_{1} = (Y_{N} - Y_{N})^{-1} X_{pod,k}\), \(A_{2} = (Y_{N} - Y_{N})^{-1} X_{pod,k}\). The linearized...
equation of the entire system can be further expressed as
\[ \Delta x_{sys} = A_{sys,k} \Delta x_{sys} + B_{sys,k} \Delta v_{ref} \]  
(17)
where \( x_{sys} \) is the vector of state variables of the entire system, and \( x_{sys} = [x, w, z]^T \).
\[ A_{sys,k} = \begin{bmatrix} A_{xw,k} & B_{xw,d,k} & B_{xg} & B_{pod,k} \\ B_{sw} & A_{xg} & 0 & 0 \end{bmatrix}, \quad B_{sys,k} = \begin{bmatrix} B_{xw,k} \\ 0 \end{bmatrix} \]

It can be derived from (8) that \( \Delta P_{ref} = 3k_{opt} \omega_{wt}^2 \Delta \omega_{wt} \) in MPPT, while \( \Delta P_{ref} = (P_{max} - k_{opt} \omega_{wt}^2) \Delta \omega_{wt} (\omega_{max} - \omega_{wt}) \) in DPO. Thus data in the second row of \( A_{sys,k} \) should be corrected accordingly for these two operation statuses.

D. Validation of the Linearized Model

The linearized model of the entire system (17) is developed in MATLAB m-code, and its accuracy is verified through the Simulink-based time-domain simulation model. When the WECS adopts Scenario C and operates under the wind speed of 9 m/s, the reference DC-link voltage \( V_{dc} \) of the WECS is subject to a step increase from 1.0 to 1.1 p.u. at 25 s. Fig. 6 compares the system responses between the linearized model and the Simulink model, which indicates that the results of the linearized model are consistent with those of the Simulink model, thus the accuracy of the derived linearized equations in section III is validated.

IV. MODAL ANALYSIS

The objective of the modal analysis is to analyze the interaction between the torsional and power oscillations, and to tune the TOD and POD controllers to damp these oscillations at the same time. To fully evaluate the impact of the operation statuses of WECS on the POD and TOD, typical wind speeds \( V_w = 9 \) m/s, 11 m/s and 13 m/s correspond to MPPT, DPO and MXP in (8), respectively, are considered in each scenario. The eigenvalues (\( \lambda = \sigma_i \pm j\omega_i \)), right eigenvector (\( \phi_i \)) and left eigenvector (\( \psi_i \)) of the matrix \( A_{sys,k} \) in (17) are obtained by the eig command in MATLAB. The frequency and damping ratio of a mode (\( \lambda_i \)) are calculated as, \( f_i = \omega_i / 2\pi \) and \( \zeta_i = -\sigma_i / (\sqrt{\sigma_i^2 + \omega_i^2} \times 100 \%) \), respectively. The participation factor (PF) of the \( k \)th state variable in the \( i \)th mode is computed by \( PF_{ki} = |\phi_{ik}| \psi_i | \). While the normalized participation factor (NPF) is used to present the results, which is given as \( NPF_{ki} = PF_{ki} / \max(PF_{ki}) \).

Fig. 7. Oscillatory modes of the WECS without the TOD and POD control, (a) frequency ranges from 10~1400 Hz, and (b) frequency ranges from 0~10 Hz.

A. System Related Oscillatory Modes

When neither of the controllers is activated, the oscillatory modes of the WECS under the MXP status within the three scenarios are plotted in Fig. 7. This figure shows that most of the modes have frequencies in the range of 10~1400 Hz, and their damping ratios are sufficient for the stable operation of the WECS. Additionally, several modes with frequencies ranging from 0 to 2 Hz are observed and damped well except for one mode located close to the right plane, which has participation states from \( T_s, \omega_m \) and \( \omega_{ms} \), and is identified as the torsional mode. The eigenvalues of the torsional mode in different scenarios are further demonstrated in TABLE II. It shows the torsional mode is stable, but with a low damping ratio in each scenario. The torsional oscillation frequency ranges from approximately 1.26 to 1.27 Hz, which agrees with the calculated result of 1.28 Hz based on (2).

For the AC grid, there are 9 power oscillation modes, as illustrated in TABLE III. All the modes are stable apart from mode P2, and most modes are lightly damped due to the negligence of PSS. Two power oscillation modes decided by the 8th and 9th SGs are selected as the targeted modes to be damped from the OWF, in which one (P2) is unstable and another (P1) is stable but with a low damping ratio. Thus the rotor angle difference between the 8th and 9th SGs (\( \omega_{gd} - \delta_{g} \)) is selected as the input signal of the POD controller in each scenario.

It can be found that the frequencies of the power oscillation mode P2 in TABLE III and the torsional oscillation mode in TABLE II are very close in this system configuration, which implies severe interactions between both types of oscillations may be induced. For convenience, the torsional mode in TABLE II and the modes P1 and P2 in TABLE III are subsequently referred to as mode 1, mode 2, and mode 3, respectively.

TABLE II

<table>
<thead>
<tr>
<th>Scenario</th>
<th>The eigenvalue of the torsional mode</th>
<th>Participating states</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-0.27±j 7.95</td>
<td>( T_s, \omega_m )</td>
</tr>
<tr>
<td>B</td>
<td>-0.29±j 7.95</td>
<td>( T_s, \omega_m )</td>
</tr>
<tr>
<td>C</td>
<td>-0.21±j 7.95</td>
<td>( T_s, \omega_m )</td>
</tr>
</tbody>
</table>

TABLE III

<table>
<thead>
<tr>
<th>Mode</th>
<th>Damping ratio (%)</th>
<th>Major Participating states</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>0.26±j 9.02</td>
<td>( \delta_{yb}, \omega_{yb}, \delta_w )</td>
</tr>
<tr>
<td>P2</td>
<td>0.03±j 8.00</td>
<td>( \omega_{yb}, \delta_w, \delta_{yb} )</td>
</tr>
<tr>
<td>P3</td>
<td>-0.30±j 9.14</td>
<td>( \omega_{yb}, \delta_w, \delta_{yb} )</td>
</tr>
<tr>
<td>P4</td>
<td>-0.40±j 8.98</td>
<td>( \omega_{yb}, \delta_w, \delta_{yb} )</td>
</tr>
<tr>
<td>P5</td>
<td>-0.23±j 8.03</td>
<td>( \omega_{yb}, \delta_w, \delta_{yb} )</td>
</tr>
<tr>
<td>P6</td>
<td>-0.58±j 6.51</td>
<td>( \omega_{yb}, \delta_w, \delta_{yb} )</td>
</tr>
<tr>
<td>P7</td>
<td>-0.20±j 6.87</td>
<td>( \omega_{yb}, \delta_w, \delta_{yb} )</td>
</tr>
<tr>
<td>P8</td>
<td>-0.22±j 7.43</td>
<td>( \omega_{yb}, \delta_w, \delta_{yb} )</td>
</tr>
<tr>
<td>P9</td>
<td>-0.17±j 8.73</td>
<td>( \omega_{yb}, \delta_w, \delta_{yb} )</td>
</tr>
</tbody>
</table>

B. Analysis Results of the Scenario A

Based on the eigenvalue sensitivity approach [35], there exist optimal phase compensations for the TOD and POD controllers. The optimal parameters for Scenario A are \( T_{od,a} = T_o,a = 0.02 \) s, \( T_{od,a} = 0.17 \) s, and \( T_{od,a} = 0.02 \) s. Then the effectiveness of the TOD and POD controllers depends on their gains \( K_{od,a} \)
and $K_{\text{pod,a}}$.

The root loci of the oscillatory modes that determine the torsional and power oscillations in the Scenario A are illustrated in Fig. 8. For the case that $K_{\text{tod,a}}$ is fixed at 0, and $K_{\text{pod,a}}$ ranges from 0 to 2, in steps of 0.08, the relevant eigenvalues under three operation statuses (MPPT, DPO and MXP) are plotted in Fig. 8(a). It is observed that mode 1 moves toward the left-half plane before $K_{\text{pod,a}}$ surpassing a certain value ($K_{\text{pod,a}}=1.2$) under each operation status. In contrast, the damping ratio of the mode 2 will continue to be enhanced during the same process. As for the mode 3, which is unstable when $K_{\text{pod,a}}=0$, migrates slowly toward the left-half plane as $K_{\text{pod,a}}$ increases, and the maximum damping ratio of the mode 3 is around 3.7%, which remains unsatisfied compared to the modes 1 and 2. Considering the fact that the mode 2 is sufficiently damped and the mode 3 becomes insensitive to the further increase of $K_{\text{pod,a}}$ when its value reaches 1.2, $K_{\text{pod,a}}$ is chosen to be 1.2 to obtain maximum damping of mode 1. For $K_{\text{pod,a}}=1.2$, if $K_{\text{tod,a}}$ increases from 0 to 4, in steps of 0.16, it can be seen from Fig. 8(b) that the mode 2 moves to the left, and its damping ratio increases significantly. However, the modes 1 and 3 migrate towards the right-half plane, and the mode 3 even enters into the unstable zone when $K_{\text{tod,a}}$ reaches the peak under each operation status.

![Fig. 8. Root loci of the oscillatory modes of interest in the Scenario A, (a) $K_{\text{tod,a}}=0$ and $K_{\text{pod,a}}$ ranges from 0 to 2, and (b) $K_{\text{pod,a}}=1.2$ and $K_{\text{tod,a}}$ increases from 0 to 4.](image)

The corresponding NPFs of the participating states in those modes are plotted in Fig. 9. When $K_{\text{tod,a}}=0$ and $K_{\text{pod,a}}$ ranges from 0 to 2, it shows in Fig. 9(a) that the torsional oscillation (with participating states $T_1$ and $\omega_m$) interacts with the power oscillation (with participating states $\delta_{d8}, \omega_{g8}, \delta_{r9}$ and $\omega_{r9}$) in the oscillatory modes 1 and 3, and such interaction is most significant as $K_{\text{pod,a}}$ increases to a certain value ($K_{\text{pod,a}}=0.4$). However, the interaction of these two types of oscillations becomes weak as the further increase of $K_{\text{pod,a}}$. The reason behind this phenomenon is when the eigenvalue that determines the power oscillation moves closer to the eigenvalue that determines the torsional oscillation, their interaction will become stronger and vice versa. When $K_{\text{pod,a}}=1.2$ and $K_{\text{tod,a}}$ ranges from 0 to 4, it shows in Fig. 9(b) that the interaction of the torsional and power oscillations becomes stronger in modes 2 and 3 as $K_{\text{tod,a}}$ increases, because both the TOD and POD signals superimpose in the active power control loop in this scenario.

According to the results presented in Figs. 8 and 9, it concludes in the Scenario A that the TOD will counteract the POD. From the perspective of POD, the gain of the TOD controller should be as small as possible. However, the gain of the TOD controller should be large enough to suppress the torsional oscillation. Thus, the choice of the gain of the TOD controller is a trade-off between the suppression of torsional oscillation and the damping of power oscillation, and this value is set to be 2 in this study. Due to the interaction of the torsional and power oscillations, they cannot be damped satisfactorily at the same time as a lightly damped mode (mode 3) exists in this scenario.

![Fig. 9. Participating states and the corresponding NPFs in the oscillatory modes of interest in the Scenario A under the MXP status: (a) $K_{\text{tod,a}}=0$ and $K_{\text{pod,a}}$ ranges from 0 to 2, and (b) $K_{\text{pod,a}}=1.2$ and $K_{\text{tod,a}}$ increases from 0 to 4.](image)

C. Analysis Results of the Scenario B

The optimized parameters of the phase compensators in the TOD and POD controllers for the Scenario B are $T_{1,b}=T_{2,b}=0.02$ s, and $T_{3,b}=T_{4,b}=0.02$ s.

For $K_{\text{tod,b}}=0$, if $K_{\text{pod,b}}$ is varied from 0 to 4, in steps of 0.16, it is observed in Fig. 10 (a) that the mode 1 almost stays still while the mode 2 moves to the left continuously. The mode 3 also migrates toward the left-half plane but it will move back once $K_{\text{pod,b}}$ surpasses a certain value ($K_{\text{pod,b}}=3.2$) under each operation status. Thus, the value of $K_{\text{pod,b}}$ is chosen to be 3.2 to maximize the damping ratio of the mode 3. Then the results of increasing $K_{\text{tod,b}}$ from 0 to 6, in steps of 0.24, are illustrated in Fig. 10 (b) which shows that the modes 1 and 3 migrate toward the left-half plane, whereas the mode 2 changes very little. Although $K_{\text{tod,b}}$ can be further increased, it is found that
the mode 1 only shifts slightly and the damping of the mode 3 is sufficiently enough.

![Root loci of the oscillatory modes of interest in the Scenario B](image)

**Fig. 10.** Root loci of the oscillatory modes of interest in the Scenario B, (a) \(K_{\text{pod,b}}=0\) and \(K_{\text{pod,b}}\) ranges from 0 to 4, and (b) \(K_{\text{pod,b}}=3.2\) and \(K_{\text{pod,b}}\) increases from 0 to 6.

The optimized parameters of the phase compensators in the TOD and POD controllers for the Scenario C are \(T_{1,c}=0.02\) s, \(T_{2,c}=0.17\) s, \(T_{3,c}=0.17\) s, and \(T_{4,c}=0.02\) s.

For \(K_{\text{pod,c}}=0\), if \(K_{\text{pod,c}}\) ranges from 0 to 2, in steps of 0.08, it can be seen from Fig.12(a) that the damping ratio of the mode 3 increases first and then weakens as \(K_{\text{pod,c}}\) exceeds a certain value (MPPT and DPO: \(K_{\text{pod,c}}=1.36\), MXP: \(K_{\text{pod,c}}=1.2\)). The damping of mode 1 experiences an upward trend in MPPT and DPO while remains almost stable in MXP. In contrast, the mode 2 continues to move toward the left-half plane, and its damping improves more significantly. Choosing the value of \(K_{\text{pod,c}}\) as 1.2 and increasing \(K_{\text{pod,c}}\) from 0 to 10, it is observed in Fig. 12(b) that the damping of the mode 1 will be enhanced drastically, while the damping ratios of the modes 2 and 3 fluctuate in a small range.

![Root loci of the oscillatory modes of interest in the Scenario C](image)

**Fig. 12.** Root loci of the oscillatory modes of interest in the Scenario C, (a) \(K_{\text{pod,c}}=0\) and \(K_{\text{pod,c}}\) ranges from 0 to 2, and (b) \(K_{\text{pod,c}}=1.2\) and \(K_{\text{pod,c}}\) increases from 0 to 10.

![Participating states and the corresponding NPFs](image)

**Fig. 11.** Participating states and the corresponding NPFs in the oscillatory modes of interest in the Scenario B under the MXP status, (a) \(K_{\text{pod,b}}=0\) and \(K_{\text{pod,b}}\) ranges from 0 to 4, and (b) \(K_{\text{pod,b}}=3.2\) and \(K_{\text{pod,b}}\) increases from 0 to 6.

The explanation for these phenomena is that the power oscillation only interacts with torsional oscillation when their eigenvalues are close in the Scenario B.

Therefore, for the Scenario B, we select an optimal gain of the POD controller (\(K_{\text{pod,b}}=3.2\)) to maximize the damping ratio of the lowest damped power oscillation mode (mode 3), and use a large gain of the TOD controller (\(K_{\text{pod,b}}=6\)) to enhance the damping of the torsional oscillation and weaken its interaction with the power oscillation.

**D. Analysis Results of the Scenario C**

The participating states and the corresponding NPFs are illustrated in Fig. 11. When \(K_{\text{pod,b}}=0\) and \(K_{\text{pod,b}}\) increases to a certain value (\(K_{\text{pod,b}}\approx 1.1\)), Fig. 11(a) shows that the torsional oscillation interacts with power oscillation in the oscillatory modes 1 and 3. However, this interaction disappears as \(K_{\text{pod,b}}\) is further increased. When \(K_{\text{pod,b}}=3.2\), Fig. 11(b) shows that the strongest interaction of the torsional and power oscillations occurs in the modes 1 and 3 as \(K_{\text{pod,b}}\) increases to around 3 and 4, respectively. However, such interaction becomes weak as \(K_{\text{pod,b}}\) is further increased.
1 and 3 is the strongest as \( K_{\text{pod,c}} \) increases to 5, but such interaction can be avoided in the mode 3 and becomes less significant in the mode 1 as \( K_{\text{pod,c}} \) reaches 10. The reason for those phenomena is the same as that in the Scenario B.

According to the results presented in Figs. 12 and 13, in the Scenario C, an optimal gain of the POD controller (\( K_{\text{pod,c}}=1.2 \)) is selected to obtain the maximum damping ratio of the power oscillation mode (mode 3), and a large gain of the TOD controller (\( K_{\text{tod,c}}=10 \)) is selected to improve the damping of the torsional oscillation and weaken its interaction with the power oscillation.

### E. Stability Performances of the Three Scenarios

Based on the modal analysis results, the parameters of the TOD and POD controllers are determined and listed in TABLE IV. Since the effectiveness of the TOD or POD controller is similar under the three different operation statuses. Therefore, this table only presents the details of the torsional and power oscillation modes under MXP status. This table shows that the damping ratios of the modes 1–3 are improved in each scenario compared to the values without the TOD and POD controllers that are presented in TABLE II and III. It should be noted that the participating states in the modes 1–3 shown in TABLE IV are different from those shown in TABLEs II and III due to the interactions of torsional and power oscillations after incorporating the TOD and POD controllers into the WECS.

For the Scenarios B and C, the damping ratios of the torsional and power oscillations can be improved simultaneously to satisfactory values, i.e., more than 25% for torsional oscillation and 8% for power oscillation. However, for the Scenario A, no matter how the parameters of the TOD and POD controllers are adjusted, a lightly damped oscillatory mode (mode 3), which has participation from the states of the drivetrain and SGs, still exists.

### TABLE IV

Parameters of the TOD and POD Controllers and Stability Performances Under the Three Scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>TOD controller</th>
<th>POD controller</th>
<th>Eigenmodes of interest, damping ratios, and major participating states with corresponding NPF in bracket under the MXP status</th>
</tr>
</thead>
</table>
| A        | \( T_1=0.01 \) s, \( T_2=0.02 \) s, \( T_3=0.017 \) s. | \( T_c=5 \) s, \( T_1=0.17 \) s, \( T_2=0.02 \) s, \( K_{\text{pod,c}}=1.2 \). | 1) Mode 1: –0.63±j8.80; 7.1 %; \( \delta_{\text{ref}}(1.0), \omega_{\text{ref}}(1.0), \omega_{\text{ref}}(0.3), \delta_{\text{ref}}(0.3), \theta_{\text{ref}}(0.2) \) and \( T_1(0.2) \),
2) Mode 2: –2.59±j8.59; 28.9 %; \( \delta_{\text{ref}}(1.0), \omega_{\text{ref}}(1.0), \omega_{\text{ref}}(0.4), T_2(0.6), \delta_{\text{ref}}(0.3) \) and \( \omega_{\text{ref}}(0.3) \),
3) Mode 3: –0.21±j8.00; 2.6 %; \( T_1(1.0), \omega_{\text{ref}}(0.9), \omega_{\text{ref}}(0.5), \delta_{\text{ref}}(0.1) \) and \( \omega_{\text{ref}}(0.1) \). |
| B        | \( T_1=0.01 \) s, \( T_2=0.02 \) s, \( T_3=0.016 \) s. | \( T_c=5 \) s, \( T_1=0.02 \) s, \( T_2=0.02 \) s, \( K_{\text{pod,c}}=3.2 \). | 1) Mode 1: –0.93±j8.34; 11.1 %; \( \delta_{\text{ref}}(1.0), \omega_{\text{ref}}(1.0), \omega_{\text{ref}}(0.6) \) and \( \delta_{\text{ref}}(0.6) \),
2) Mode 2: –1.09±j9.00; 12.0 %; \( \delta_{\text{ref}}(1.0), \omega_{\text{ref}}(1.0), \omega_{\text{ref}}(0.4) \) and \( \omega_{\text{ref}}(0.4) \),
3) Mode 3: –2.48±j8.28; 28.7 %; \( \omega_{\text{ref}}(1.0), T_2(0.9), \delta_{\text{ref}}(0.3) \) and \( \omega_{\text{ref}}(0.3) \). |
| C        | \( T_1=0.01 \) s, \( T_2=0.02 \) s, \( T_3=0.017 \) s. | \( T_c=5 \) s, \( T_1=0.17 \) s, \( T_2=0.02 \) s, \( K_{\text{pod,c}}=1.2 \). | 1) Mode 1: –2.09±j8.05; 25.1 %; \( T_1(1.0), \omega_{\text{ref}}(0.9), \delta_{\text{ref}}(0.3), \omega_{\text{ref}}(0.3) \) and \( \delta_{\text{ref}}(0.1) \) and \( \omega_{\text{ref}}(0.1) \),
2) Mode 2: –1.14±j9.10; 12.4 %; \( \delta_{\text{ref}}(1.0), \omega_{\text{ref}}(1.0), \omega_{\text{ref}}(0.8) \) and \( \delta_{\text{ref}}(0.8) \),
3) Mode 3: –0.74±j8.35; 8.8 %; \( \delta_{\text{ref}}(1.0), \omega_{\text{ref}}(1.0), \omega_{\text{ref}}(0.8) \) and \( \delta_{\text{ref}}(0.8) \). |

### V. Simulation Results and Discussion

To investigate the dynamic performances of the studied system with the TOD and POD control, detailed time-domain simulation models based on Fig.4 (which includes the control Scenarios A, B, and C in WECS) were built in Simulink. In the models, the main parameters of WECS and SGs are presented in Appendix A and B, respectively. In the AC grid, the governor and AVR are included in each SG model, and the power loads remain steady throughout the simulations. The base active power of the OWF is 400 MW, and the base DC-link voltage of WECS is 7500V. Under the wind speeds \( V_w=9 \) m/s, 11 m/s and 13 m/s, the steady output active power of the OWF are 0.54, 0.90 and 1.0 p.u., respectively. We mention that if the active power of WECS exceeds the maximum allowable value after superimposing the modulated component from POD, it should decrease the reference power for the duration of the POD event to guarantee the safe operation of the system in the real-world application. In this study, assuming the maximum allowable active power of the WECS is 1.1 p.u., and the output reactive power of the WECS is controlled to be 0 throughout the simulations. In addition, the DC-link voltage remains to be large enough even though it might be dropped by 0.1 p.u. during TOD and POD, to prevent the overmodulation of the converters. During simulation, a temporary single-phase-to-ground short circuit fault occurs in B26 at 15 s, and the fault is cleared after 0.16 s. The PSSs in the SGs are disabled at 15 s in each scenario.

### A. Verification of the Necessity of TOD and POD Control

Fig. 14 plots the dynamics of the drivetrain when the wind speed steps up from 9 m/s to 13 m/s at 5 s. Without the TOD control in WECS, poorly damped torsional oscillation with a
frequency of approximately 1.26 Hz is observed in each scenario after this disturbance, and the frequency value matches the eigenvalue result in TABLE II. However, with the TOD controller shown in TABLE IV, the torsional oscillation can be damped efficiently. It should be noted that the POD controller is disabled in each scenario during those simulations.

Fig. 15 shows that without the PSSs and POD control, an unstable oscillation mode with a frequency of approximately 1.30 Hz is monitored in the AC grid after the short circuit fault, which agrees with the result presented in TABLE III. Apparently, the power oscillation shown in Fig. 15(a) is caused by the instability of the rotor angles between the 8th SG and 9th SG in two areas shown in Fig. 15(b). Therefore, the following results will use the oscillation of $\delta_{g9}$ to represent the power oscillation.

The simulation results of damping the power oscillation and the induced torsional oscillation in each scenario are as follows.

Fig. 14. The angular speed difference between the PMSG rotor and WT rotor with and without the TOD control, (a) Scenario A, (b) Scenario B, and (c) Scenario C.

Fig. 15. Power oscillation in AC grid without the PSSs and POD control when $V_{dc}$=13 m/s. (a) $P_{ac}$: total active power flow from B29 to B26 and B28, and (b) $\delta_{89}$: rotor angle difference between the 8th SG and 9th SG.

B. Simulation Results within the Scenario A

The transient responses of the system within Scenario A are illustrated in Fig. 16, and the parameters of the POD and TOD controllers are consistent with the ones in TABLE IV. It can be seen from Fig. 16(a) that the oscillatory amplitude of $\omega_m$ increases gradually and then decreases due to the interaction between the torsional and power oscillations, the maximum deviation of $\omega_m$ ranges approximately from −0.05 to +0.05 p.u. under all the three types of wind speeds. Fig. 16(b) illustrates that the oscillation of $\delta_{g9}$ cannot be completely damped out for more than 25 seconds, which is the same as $\omega_m$. According to the results shown in the TABLE IV, the states $\omega_m$, $\delta_{g8}$ and $\delta_{g9}$ participate in modes 1~3, in which the damping ratios of modes 1 and 2 are more than 7%, while the damping ratio of mode 3 is only 2.6%. Hence, the oscillations of $\omega_m$ and $\delta_{g9}$ at the later stage are mainly determined by the mode 3, which is poorly damped. Fig. 16(c) and (d) show that the maximum deviation from the steady-state value of the active power is ±0.1 p.u., and the one of the DC-link voltage is around ±0.03 p.u. during this transient process.

Fig. 16. Transient responses of the studied system within the Scenario A, (a) $\omega_m$: angular speed of the PMSG, (b) $\delta_{g9}$: rotor angle difference between the 8th SG and 9th SG, (c) $P_{ac}$ output power of the WECS, and (d) $V_{dc}$: DC-link voltage of the WECS.

Fig. 17. Impacts of different gains of the TOD controller on the torsional and power oscillations within the Scenario A when $V_{dc}$=13 m/s.

Fig. 17 plots the responses of $\omega_m$ and $\delta_{g9}$ in the Scenario A with different gains of the TOD controller. It is observed that a larger value of $K_{tod,a}$ could suppress the amplitude of torsional oscillation, but counteract the effect of the POD and even causes the torsional and/or power oscillations unstable. The reason for this phenomenon can be explained by the modal analysis results presented in Fig. 8(b) where mode 3 moves towards the right plane as $K_{tod,a}$ increases, and it becomes unstable when $K_{tod,a}=4$. As Fig. 9(b) illustrates, states $\omega_m$ and $\delta_{g9}$ are major contributors to the mode 3, which means both torsional and power oscillations will lose stability. Although the effect of POD can be improved if the TOD controller is disabled ($K_{tod,a}=0$), the maximum fluctuation range of $\omega_m$ reaches ±0.07 p.u., which will bring high mechanical stress to
the WT’s drivetrain.

If the drivetrain employs a one-mass shaft model and assumes the WECS contains POD but no TOD control, the results in Fig.18 show that the torsional oscillation will not be excited by the POD because the one-mass model cannot reflect torsional oscillation dynamics. In addition, as there is no interaction between the torsional and power oscillations within the one-mass model, the power oscillation can be damped out faster than using the two-mass model.

![Fig. 18. Torsional and power oscillations as the drivetrain employs the one-mass or two-mass shaft model and WECS contains POD but no TOD control within the Scenario A when \(V_w = 13\) m/s.](image)

**Fig. 18.** Torsional and power oscillations as the drivetrain employs the one-mass or two-mass shaft model and WECS contains POD but no TOD control within the Scenario A when \(V_w = 13\) m/s.

**C. Simulation Results within the Scenario B**

Fig. 19 depicts the responses of the studied system within the Scenario B, and the parameters of the POD and TOD controllers are consistent with the ones in TABLE IV. It can be seen from Fig. 19 (a) that \(\omega_m\) remains stable during the POD event. Meanwhile, the oscillation of \(\delta_{8,9}\) in Fig. 19(b) can be damped out effectively in approximately 6 seconds after the fault disturbance throughout the three different wind speeds. However, large overshoots (or undershoots) of the output active power are observed in Fig. 19(c) due to the discharging (or charging) of the DC-link capacitors of WECS. The maximum range of deviation from steady state value is –0.40–+0.20 p.u. for \(V_w = 13\) m/s, –0.35–+0.25 p.u. for \(V_w = 11\) m/s, and –0.40–+0.45 p.u. for \(V_w = 9\) m/s, which may be undesirable to the TSOs. Fig. 19(d) shows that the DC-link voltage fluctuates in the range of 0.9–1.1 p.u. due to the output limiter in the POD controller.

![Fig. 19. Transient responses of the studied system within the Scenario B.](image)

**Fig. 19.** Transient responses of the studied system within the Scenario B.

Fig. 20 compares the torsional and power oscillations when only changing the gain of the TOD controller in the Scenario B. The results indicate that the torsional oscillation will not be excited by the POD controller and the gain of the TOD controller has almost no impact on the effect of POD in this scenario. Nonetheless, the gain of the TOD controller should remain large enough to depress the torsional oscillation caused by wind speed or MSC’s power fluctuations.

![Fig. 20. Impacts of different gains of the TOD controller on the torsional and power oscillations within the Scenario B during POD event when \(V_w = 13\) m/s.](image)

**Fig. 20.** Impacts of different gains of the TOD controller on the torsional and power oscillations within the Scenario B during POD event when \(V_w = 13\) m/s.

![Fig. 21. Impacts of the capacitance of the DC-link capacitor on the power oscillation within the Scenario B when \(V_w = 13\) m/s.](image)

**Fig. 21.** Impacts of the capacitance of the DC-link capacitor on the power oscillation within the Scenario B when \(V_w = 13\) m/s.

It is worth noting that the POD efficiency in the Scenario B depends on the capacitance of the DC-link capacitor. As

![Fig. 22. Transient responses of the studied system within the Scenario C.](image)

**Fig. 22.** Transient responses of the studied system within the Scenario C.
shown in Fig. 21, the effect of POD is reduced as the capacitance value decreases, the reason is that the adjustable energy for POD and the capacitance value of the DC-link capacitors are positively correlated.

D. Simulation Results within Scenario C

Fig. 22 presents responses of the studied system within the Scenario C, and the parameters of the POD and TOD controllers are consistent with the ones in TABLE IV. It shows in Fig. 22(a) that the torsional oscillation could be excited by the POD controller, and the maximum fluctuation range of $\omega_n$ is approximately $\pm 0.03$ p.u.. In addition, Fig. 22(a) and (b) demonstrate that oscillations of $\omega_m$ and $\delta_{g8,9}$ can be damped out successfully throughout the three different wind speeds in approximately 8 and 7 seconds, respectively. It is worth noting that the parameters of the POD controller in this scenario are the same as the ones in the Scenario A, whereas the POD controller performs better. Since the outputs of the TOD and POD controllers are limited to $\pm 0.1$ p.u., the maximum deviation from the steady-state value of the output active power and DC-link voltage can be controlled to be $\pm 0.1$ p.u., as shown in Fig. 22(c) and (d), respectively.

![Fig. 23. Impacts of different gains of the TOD controller on the torsional and power oscillations within the Scenario C when $K_{pod,c}=1.2$ and $V_c=13$ m/s.](image)

![Fig. 24. Impacts of different gains of the POD controller on the torsional and power oscillations within the Scenario C when $K_{pod,c}=1.2$ and $V_c=13$ m/s.](image)

The impacts of different gains of the TOD and POD controllers on the torsional and power oscillations in Scenario C are illustrated in Figs. 23 and 24. It shows in Fig. 23 that increasing $K_{pod,c}$ can enhance the damping of the torsional oscillation and suppress the maximum oscillatory amplitude of $\omega_m$. However, the impact of the TOD controller on the power oscillation is negligible. It is observed in Fig. 24 that the damping of power oscillation weakens when $K_{pod,c}$ becomes too small ($K_{pod,c}=0.4$) or too large ($K_{pod,c}=2$), which coincides well with the eigenvalue results in Fig. 12(a). In addition, since the torsional oscillation is excited by the POD controller, the premise that the torsional oscillation can be damped out in this scenario is that the power oscillation decays to zero.

As the Scenario C utilizes the electrostatic energy of the DC-link capacitors to suppress the torsional oscillation, the TOD efficiency depends on the capacitance of the DC-link capacitor. It shows in Fig. 25 that the effect of TOD will be reduced as the capacitance value decreases, while POD efficiency remains unaffected during the same process.

![Fig. 25. Impacts of the capacitance of the DC-link capacitor on the torsional and power oscillations within the Scenario C when $V_c=13$ m/s.](image)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Completion time for TOD and POD</th>
<th>Oscillatory amplitudes of the crucial variables in WECS during POD</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$T_{POD}, T_{TOD}&gt;25$ s</td>
<td>1) $\omega_n$: $\pm 0.05$ p.u.; 2) $P_{d}$: $\pm 0.1$ p.u.; 3) $V_{dc}$: $\pm 0.03$ p.u.</td>
</tr>
<tr>
<td>B</td>
<td>$T_{POD}$: 6 s</td>
<td>1) $\omega_n$: almost 0 p.u.; 2) $P_{d}$: $-0.40 \pm 0.45$ p.u.; 3) $V_{dc}$: $\pm 0.1$ p.u.</td>
</tr>
<tr>
<td>C</td>
<td>$T_{POD}$: 7 s, $T_{TOD}$: 8 s</td>
<td>1) $\omega_n$: $\pm 0.03$ p.u.; 2) $P_{d}$: $\pm 0.1$ p.u.; 3) $V_{dc}$: $\pm 0.1$ p.u.</td>
</tr>
</tbody>
</table>

E. Discussion

The time-domain simulation results within the three scenarios are in good agreement with the modal analysis results. Based on the simulation results shown in Figs. 16, 19 and 22, the dynamic performances of the WECS within the three scenarios are compared in TABLE V. When the oscillatory frequency of the torsional mode is close to the frequency of the power oscillation mode, the torsional oscillation can be excited by the POD controller in the Scenarios A and C. In comparison, the torsional and power oscillations in the Scenario C can be damped out much faster than those in the Scenario A. The reason is that the Scenario A relies on the kinetic energy of WT rotors to damp both the torsional and power oscillations, and the TOD can counteract the effect of the POD in this case. However, the Scenario C utilizes the electrostatic energy of the DC-link capacitors to suppress the torsional oscillation while the kinetic energy of WT rotors to damp the power oscillation. Due to the relative independence of the energy sources for TOD and POD, the interaction of the torsional and power oscillations can be better handled by reasonable tuning of the TOD and POD controllers.

The POD efficiency in the Scenarios B and C are similar, but POD will not induce torsional oscillation in the Scenario B, because it utilizes the electrostatic energy of DC-link capacitors to damp the power oscillation while the kinetic energy of WT rotors to suppress the torsional oscillation.
Although the POD controller in the Scenario B has the smallest impact on the WT’s drivetrain, the output active power of the WECS experiences the largest overshoots and undershoots compared with the other two scenarios, which makes the Scenario B less attractive.

In addition, according to the results shown in Figs. 21 and 25, the capacitance value of the DC-link capacitors and the effect of POD in the Scenario B (or the effect of TOD in the Scenario C) are positively correlated. But in general, the TOD in the Scenario C is less sensitive to the change of capacitance value than the POD in the Scenario B.

VI. CONCLUSIONS

In this paper, three possible scenarios of incorporating both TOD and POD controllers into the PMSG-based WECS are investigated for the first time. A model of a PMSG-based OWF connected to the IEEE 39-bus AC grid has been developed and utilized to study the stability and dynamic performances of the WECS under three scenarios.

Considering the frequency of torsional oscillation coincides with the frequency of power oscillation, the interaction of the two types of oscillations and the stability performances of the three scenarios are analyzed through modal analysis. The major findings are: 1) Torsional oscillation interacts with power oscillation when their eigenvalues are close; 2) As the gain of the POD controller is fixed, such interaction will be further enhanced as the gain of the TOD controller increases in the Scenario A, while the opposite outcomes occur in the Scenarios B and C; 3) The general rule for tuning the POD and TOD controllers is to select an optimal gain for the POD controller to maximize the damping ratio of the power oscillation mode and keep the gain of the TOD controller as large as possible in the Scenarios B and C, while in the Scenario A the choice of the gain of the TOD controller is a trade-off between the suppression of torsional oscillation and the damping of power oscillation; 4) The damping ratios of the torsional and power oscillations in the Scenarios B and C can be improved simultaneously to satisfactory values, but the Scenario A cannot.

Furthermore, the dynamic performances of the WECS within each scenario are illustrated by time-domain simulation studies. By comparison, the Scenario C achieves a better balance between oscillatory amplitudes of the crucial variables in WECS and the suppression of torsional and power oscillations. Hence, it is recommended as the optimal scenario for WECS to damp both the torsional and power oscillations, especially when their frequencies are close. Future work could focus on evaluating the POD-induced mechanical stress on the drivetrain and PMSG of the real WTs.

VII. APPENDIX

A. PMSG-based WECS Data

\[ P_{eq}=10 \text{ MW}; \quad R_m=89.15 \text{ m} \Omega; \quad \omega_n=1.0053 \text{ rad/s}; \quad \rho=1.225 \text{ kg/m}^3; \]
\[ H_m=5.8 \text{ s}; \quad K_e=100 \text{ p.u.} / \text{s}; \quad D_m=1.0 \text{ p.u.}; \quad C_d=20 \text{ mF}; \]
\[ V_{dc}=7500 \text{ V}; \quad \alpha_{opt}=0.5 \text{ p.u.}; \quad \omega_{opt}=1.0 \text{ p.u.}; \quad \omega_{max}=1.1 \text{ p.u.}; \]
\[ P_{max}=1.0 \text{ p.u.}; \quad k_{opt}=0.7; \quad \text{Number of pole pairs: 100}; \quad \text{Rated voltage of PMSG: 3470 V}; \quad \text{Ratio of transformer T1: 3.4 kV/ 66 kV.} \]

B. Parameters of the SGs in AC Grid

The parameters of the SGs based on the nominal power of 1000 MVA are shown in TABLE A1.

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<thead>
<tr>
<th>No.</th>
<th>H</th>
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<th>x2</th>
<th>x3</th>
<th>x4</th>
<th>x5</th>
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<th>x7</th>
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</tr>
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</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, U.K.

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He has extensive industrial experience in the field of electrical power system engineering including power system modelling, simulation, analysis, planning, and control. He was a Senior Power Systems and Consulting Engineer with GECOL, Libya, from 1999 to 2013.

He worked as a research fellow at the School of Engineering, University of Warwick, UK, from 2017 to 2021. His research interests include power system analysis, and operations, renewable generation integration and control, and smart grids. In 2021, he joined the National Grid ESO, UK, where he is currently a power system engineer.