red eléctrica
Una empresa de Redeia

Guide for the implementation of power oscillation damping controllers

Version 2

Dirección General de Operación
Dirección de Desarrollo del Sistema
Departamento de Fiabilidad del Sistema Eléctrico

Septiembre 2024

red eléctrica

Control of modifications

Version	Date	Modifications
1.0	-	-
2.0	24/09/2024	Initial version.

red eléctrica

Contents

1 Introduction

Electromechanical oscillations, also known as power oscillations, are a phenomenon of *angle stability of power systems under small perturbations* [1]. Electromechanical oscillations involve generators which oscillate against each other in the power system. Electromechanical oscillations can be seen in the different variables of the power system, such as bus frequencies and voltages, power flows and current flows through the branches of the power system, among others. Electromechanical oscillations can be divided into local oscillations and inter-area oscillations [1], [2]. Local oscillations involve oscillations between groups of coherent generators close to each other and their oscillation frequencies can be around 0,7-2,5 Hz. Inter-area oscillations involve oscillations between groups of coherent generators in remote areas and their oscillation frequencies can be around 0,1-1 Hz. Although traditionally small-signal angle stability in power systems was dominated by the dynamics of synchronous machines [3], in modern power systems power-electronic-based devices could have a significant effect on this stability phenomenon, which has been classified as *converter-driven stability – slow interactions* [4]. Incidents during the past years show the problem of inter-area oscillations in the Continental Europe (CE) power system [5].

One of the most effective ways to damp electromechanical oscillations is by means of supplementary controllers attached in the different devices of the power system:

- Synchronous machines: By means of using Power System Stabilizers (PSS). This group includes synchronous power-generating modules and synchronous condensers.
- Facilities containing power-electronic-based devices, such as Power Park Modules (PPM), Energy Storage Systems (ESS), Flexible Alternating Current Transmission Systems (FACTS), High Voltage Direct Current (HVDC) transmission systems: By means of using Power Oscillation Damping (POD) controllers.

The use of POD controllers in Voltage Source Converters (VSC) with Grid-Following (GFL) control has been studied during the past years. Specifically, examples of POD controllers can be found for wind PPMs [6], [7], [8], [9], [10], [11], solar Photovoltaic (PV) PPMs [12], [13], power converters in general (including energy storage systems) [14], [15], FACTS systems [16], [17], [18], [19], [20], [21], [22] and VSC-HVDC systems [23], [24], [25], [26], [27]. In addition to VSC-based systems with GFL control as the ones mentioned earlier, POD controllers in VSC converters with Grid-Forming (GFM) have also been proposed recently [28]. Finally, it should be mentioned that POD controllers could also be implemented in current-source HVDC systems (LCC-HVDC) [29], [30], [31].

The proposal for review of the European regulation for requirements for generators (Commission regulation EU 2016/631 (RfG) [32]), subject to public consultation by ACER in July 2023, proposes technical requirements for POD controllers. The draft document is known as Requirements for Generators 2 (RfG2) [33]. At national level, the draft proposal of the operation procedure (Procedimiento de Operación, PO) 12.2 [34], submitted to the Ministry for the Energy Transition and Demographic Challenge (Ministerio para la Transición Ecológica y el Reto Demográfico, MITERD) of the Spanish Government in Jun 2022, proposed technical requirements for POD controllers, in line with the current European regulation [32], [35] and the Spanish regulation [36]. These requirements are generic, and no specific implementation of POD controllers are imposed. Independently of the degree of freedom of a particular POD controller, it is important that POD controllers are aligned with the technical capabilities expected from them.

The Spanish System Operator (SO) proposed the creation of a working group (so-called GT_POD)[1] with the different stakeholders from the electrical energy sector to write a specification on the technical capabilities of POD controllers. The objective of this working group was to have a common and agreed vision on this type of controllers, technical specifications and acceptance criteria, potential implementation and particularities depending on the technology.

[1] Working group GT_POD took place between June 2023 and June 2024, and this document was elaborated as a result of this working group.

This document describes the implementation and technical specifications for POD controllers in the following facilities:

- Wind or solar PV PPMs
- Energy Storage Systems (ESS).
- Hybrid facilities.
- HVDC systems.
- FACTS.

This document will use the term *Electricity Storage Module (ESM)* proposed in the draft document of RfG2 [33]. An ESM could be a standalone energy storage system and it could also be included in a hybrid facility. Besides, according to the proposal of [33],an ESM can be of type synchronous power generating modules (SPGM) or of type PPM. POD controllers addressed in this document only include for ESM systems of type PPM and the term *ESM-PPM* will be used along this document to refer to them.

This document describes POD controllers in VSC-based power converters with GFL control, which is the control approach more extended, discussing particular aspects of each type of system. Specific aspects related to the implementation of POD controllers depending on the technology and evaluation of their performance will be discussed in this document. The document mainly focuses on POD controllers applied to PPM and ESM-PPM systems. Finally, technical requirements of POD controllers are summarised.

The document deals with technical capabilities that POD can provide to the power system, but specific design methods of POD are not described. It is important to highlight the relevant role of having correct settings of POD controllers, because they are directly linked to the effectiveness of POD controllers. However, this document does not address specific design methods of POD controllers, because manufacturers should have freedom to choose the design method to determine the settings of POD controllers, as long as they provide the expected technical capabilities to the power system.

The following entities have participated in this working group and in the writing of this document:

- Red Eléctrica: System Operator (coordinator of the working group).
- Ministry for the Energy Transition and Demographic Challenge (MITERD) of the Spanish Government (supervisor of the working group).
- Associations/representative entities of companies of distribution of electrical energy (Utilities): aelec, ASEME, CIDE and UFD.
- Associations of companies of electrical energy storage systems: AEPIBAL and ASEALEN.
- Associations of companies of renewable energies: AEE, APPA Renovables and UNEF.
- Accredited laboratories and accredited certification companies: SGS and Fundación CIRCE.

During the working group, a total of 4 meetings have been held, leading to technical discussions between all the participants. Additionally, the SO and the rest of participants of the working group have presented simulation results, supporting the technical content of this document.

The need for pilot projects at national level as a proof of concept of POD controllers has been raised in the working group. The SO has manifested its support to this type of initiatives and the objective is to execute them during the following years. Currently, there are examples of facilities with POD controllers in the Spanish power system. For example, the 2x1000 MW VSC-HVDC Spain-France interconnector (INELFE-1) [37], in operation since 2015 is equipped with POD controllers [38]. Furthermore, the planning of the Spanish electrical system for period 2020-2026 includes four STATCOMs (4x150 Mvar) with POD controllers connected to different points of the power system [39]. In addition, a pilot project with POD controllers in a wind power park module with energy storage system has been carried out [40]. Regardless of these examples, it is advisable to carry out more pilot projects in the coming years so that POD controllers reach sufficient technological maturity so that the integration of POD controllers is effective and reliable.

Finally, it is emphasized that this is a living document, in the sense that the working group on POD controllers could agree to include modifications to the document in the future if considered necessary, based on industry experience in this type of controllers over the next few years.

2 POD controllers in the proposals for regulation and operation procedures

This section presents the literal text related with POD controllers from the following documents:

- Draft document of *Requirements for Generators 2 (RfG2)* (European regulation).
- Draft document of *Procedimiento de Operación (P. O.) 12. 2 (Operation Procedure 12. 2, at national level in Spain)*.

2.1 POD controllers in the draft document of RfG2

The draft document of the regulation of technical requirements for generators (RfG2) (at the date of writing this document) [33] refers to POD controllers in the following parts:

- Article 21.2.f (type-C generators):
  *With regard to **power oscillations damping control**, if specified by the relevant TSO a power park module shall have a power oscillation damping function which, through the control of the active power, reactive power, or both, helps to attenuate the power oscillations.be capable of contributing to damping power oscillations. The power oscillation damping shall be able to damp inter-area oscillations in the range of, at least, 0,1 Hz – 1,0 Hz. The voltage and reactive power control characteristics of power park modules must not adversely affect the damping of power oscillations.*
- Article 22.2 (type-D generators):
  *2. With regard to **power oscillations damping control**, type D power park modules shall have a power oscillation damping function which helps to attenuate the power oscillations, through the control of the active power, reactive power, or both. The power oscillation damping shall be able to damp inter-area oscillations in the range of, at least, 0,1 Hz – 1,0 Hz. The relevant TSO in co-ordination with the relevant system operator shall have the right to request and approve the tuning of the power oscillation damping by the power-generating facility owner to damp the inter-area oscillation mode based on frequency ranges specified by the relevant TSO in coordination with adjacent TSO or TSOs. The relevant TSO shall have the right to request the tuning of the power oscillation damping by power-generating facility owner to damp the local oscillation mode, in which the power park modules is oscillating against the network. The proposed power oscillation damping control shall be approved by the relevant TSO.*

In turn, the RfG2 states:

- Section “Whereas (3)-(s1)”
  The requirements on electricity storage are considered to be the same as those on power generation modules unless explicitly stated otherwise in this Regulation.

2.2 POD controllers in the draft document of P. O. 12.2

The draft document of the P. O. 12.2 (at the date of writing this document) [34] refers to POD controllers in the following parts (literal text written in Spanish language):

- Módulos de generación de electricidad que no tengan consideración existente – Módulos de generación de electricidad del SEPE – Requisitos de frecuencia – Control de la potencia (sección 5.1.1.1)
  *Los controles de la potencia de despacho (de establecimiento, de limitación, de limitación de rampa, de anti vertido en autoconsumidores o si el módulo de generación de electricidad dispone de un sistema de control que impida que la potencia activa que pueda inyectar a la red supere la capacidad de acceso concedida), se diseñarán de forma que no se impidan las inyecciones transitorias de potencia acumuladas derivadas de la regulación potencia frecuencia (MRPF, MRPFL-O y MRPFL-U) ni, en su caso, de la emulación de inercia, **amortiguamiento de oscilaciones** u otros controles incrementales de la potencia del módulo de generación de electricidad.*

- Módulos de generación de electricidad que no tengan consideración existente - Módulos de generación de electricidad de los SENP - Requisitos de tensión - Amortiguamiento de las oscilaciones de potencia para módulos de parque eléctrico de tipo C y D (sección 5.2.2.4)
  *En el caso de no contribuir al **amortiguamiento de las oscilaciones de potencia**, el diseño de todos sus controles será de tal forma que se asegure que no generarán o contribuirán a desamortiguar **oscilaciones de potencia** entre 0,2 Hz y 2,5 Hz. No obstante, el operador del sistema podrá establecer valores diferentes por subsistema eléctrico. Estos nuevos valores deberán ser comunicados al Ministerio para la Transición Ecológica y el Reto Demográfico que deberá pronunciarse sobre los mismos en el plazo de un mes. Transcurrido ese plazo sin pronunciamiento expreso, éste se entenderá realizado en sentido favorable.*
- Instalaciones híbridas – Modalidad A (sección 10.1)
  *Los equipamientos de almacenamiento de parque eléctrico de tipo C o D deberán disponer de un **sistema POD-Q** (Power Oscillation Damping), módulo destinado a amortiguar oscilaciones mediante potencia reactiva, y **POD-P** (Power Oscillation Damping), módulo destinado a amortiguar oscilaciones mediante potencia activa, tanto en generación como en consumo en su caso. Dependiendo del tipo de almacenamiento y para evitar un envejecimiento prematuro del mismo, el control **POD-P** solo se activará cuando la amplitud de la frecuencia de oscilación supere un umbral definido por el operador del sistema. El control se mantendrá activo hasta que la amplitud de la frecuencia de oscilación permanezca durante 5 minutos por debajo del umbral. En el caso de tecnologías de almacenamiento o sistemas híbridos que permitan este control de manera continua sin un envejecimiento extra, el operador del sistema podrá mantener activo este control de manera continua. La integración de estas funciones podrá ser implementada en un plazo transitorio de 1 año a partir de la entrada en vigor del presente procedimiento.*
- Instalaciones híbridas – Modalidad B (sección 10.2)
  *Si el conjunto es de parque eléctrico de tipo C o D deberá disponer de **POD-Q** (Power Oscillation Damping), módulo destinado a amortiguar oscilaciones mediante potencia reactiva, y **POD-P** (Power Oscillation Damping), módulo destinado a amortiguar oscilaciones mediante potencia activa, tanto en generación como en consumo en su caso en las mismas condiciones que se requiere en la modalidad A.*
- Sistemas HVDC y módulos de generación de electricidad en corriente continua - Requisitos para el SEPE - Requisitos de frecuencia (sección 9.1.1.1)
  Los controles de la potencia de despacho (de establecimiento, de limitación, de limitación de rampa o si el módulo de parque eléctrico en corriente continua dispone de un sistema de control, que impida que la potencia activa que pueda inyectar a la red supere la capacidad de acceso concedida), cumplirán los mismos requisitos de diseño establecidos para los módulos de generación de electricidad del SEPE.
- Sistemas HVDC y módulos de generación de electricidad en corriente continua - Requisitos para los SENP - Requisitos de frecuencia - Capacidad de amortiguación de oscilaciones de potencia (sección 9.2.1.4)
  *Los sistemas HVDC de los SENP deberán amortiguar posibles **oscilaciones electromecánicas** en el rango de frecuencia de 0,2 Hz a 2,5 Hz modificando el correspondiente rango establecido en el apartado 13 del Anexo III de la Orden TED 749/2020 para los sistemas HVDC del SEPE.*
- Sistemas de almacenamiento independiente (sección 11)
  Si el equipamiento de almacenamiento inyecta y absorbe su energía a la red a través de alternadores o convertidores electrónicos propios, y éste no forma parte de una instalación hibrida, cumplirá los requisitos técnicos correspondientes al equipamiento de almacenamiento según la modalidad A establecidos en el apartado 10.

3 POD controllers

This section presents a general description of POD controllers in facilities involving power converters controlled with grid-following (GFL) type, and their implementation following most extended schemes, for illustrative purposes. In order to provide a general description of POD controllers, a generic GFL converter which represents a facility will be considered. This document will refer to this facility in a generic way as *GFL device*.

3.1 Fundamentals

A Voltage Source Converter (VSC) with GFL control (*GFL device*) connected to the power system is considered, as shown in Figure *1*. Active- and reactive-power injections of the GFL device are denoted by P and Q, respectively, and the current injection phasor is denoted as $\bar{I}$. The voltage at the connection point is denoted as $\bar{V} = V\angle\theta$ and the frequency at the connection point as ω (pu). A simple control structure is assumed, to facilitate the analysis:

- Active-power (P) control.
- Reactive-power (Q) control.

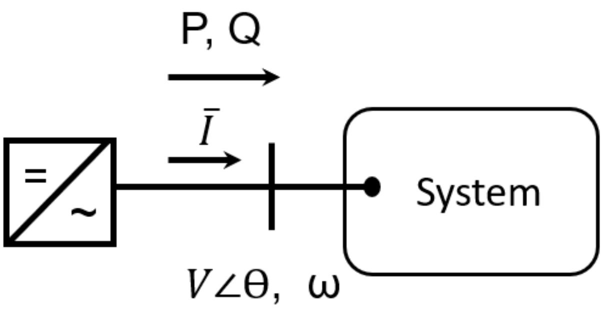

Figure 1*: GFL device.*

The objective of a Power-Oscillation-Damping (POD) controller is to damp electromechanical oscillations in the power system (also known as power oscillations). The GFL device can contribute to the damping of electromechanical oscillations by means of supplementary controllers in two ways:

- Modulation of the active-power injection (POD-P).
- Modulation of the reactive-power injection (POD-Q).

It should be noticed that POD-P controllers are linked to the primary energy source of the power converter. In energy storage systems, a POD-P controller could be implemented with full and guaranteed functionality only if a power and energy operating band is reserved. On the other hand, in an PPM a POD-P control could be implemented with a specific reserve for this application, or with only downstream operation (when there is no primary upward reserve available) or with an additional energy storage system.

In general, different options for POD controllers could exist:

- POD controllers with different input signals. For example, frequency at the connection point, voltage magnitude at the connection point, remote variables (frequency at a remote bus, etc…), or a combination of signals.
- POD controllers with different output signals. POD-P: supplementary active-power set point, supplementary d-axis current set point, etc… POD-Q: reactive-power supplementary set point, supplementary q-axis current set point, supplementary voltage set point, etc…
- POD controllers with different control structures.

However, this document will only describe the most common and established structures for POD controllers. POD-P and POD-Q controllers should be:

- Effective
- Robust

Figure 2 shows a general scheme of POD controllers in GFL devices. POD-P controller has as input signal y_P and as output signal a supplementary set point of the active-power injection ($\Delta P^{ref,POD}$). POD-Q controller has as input signal y_Q and as output signal a supplementary set point of the reactive-power injection ($\Delta Q^{ref,POD}$).

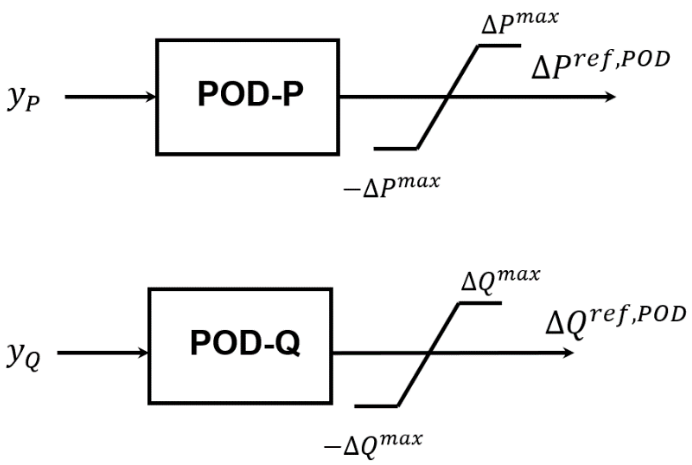

Figure 2: General scheme of POD controllers.

The set-point values of the active- and reactive-power injections are given by:

$$P^* = P_0 + \Delta P^{ref,POD} \quad (1)$$

$$Q^* = Q_0 + \Delta Q^{ref,POD} \quad (2)$$

where:

- P_0 is a constant active-power set-point term.
- Q_0 is a constant reactive-power set-point term.
- $\Delta P^{ref,POD}$ is the supplementary active-power set point provided by the POD-P controller.
- $\Delta Q^{ref,POD}$ is the supplementary reactive-power set point provided by the POD-Q controller.

Independently of the specific aspects of each implementation, the behaviour of POD controllers should have the following general characteristics:

- A POD controller should contribute to the damping of electromechanical oscillations in the power system.
- A POD controller should be focused on small disturbances. This means that, as much as possible, a POD controller should act continuously in the presence of small disturbances, unless otherwise indicated in particular cases due to specific aspects related to the technology of the facility.
- Specific parameters of a POD controller should ensure that its control actions go in the correct direction to contribute to the damping of electromechanical oscillations in the electrical system.
- Specific parameters of a POD controller should ensure that control actions are significant enough to contribute to the damping of electromechanical oscillations of the power system, but guaranteeing that the system is stable.
- The POD controller should have a saturation parameter, to limit the control action when large disturbances occur (ΔP^{max} y ΔQ^{max} in Figure 2).
- The POD controller should have all necessary filtering elements to make it effective for the input signals considered.
- A POD controller should not act in steady state when the input has an average value ("DC component" or "offset").

3.2 Extended schemes of POD controllers

Figure *3* shows the general structure of POD-P and POD-Q controllers in GFL devices, following the most common implementation. It should be clear that the implementation of POD controllers described in this subsection is a possible option based on common schemes for this type of controllers, but this document does not indicate this particular implementation for POD controllers is mandatory. The objectives of including this description of a common implementation of POD controllers in this subsection are the following:

- To show an example of the implementation of a POD controller, following the most common block diagrams and using public information. This is intended to be useful and help the different stakeholders to become familiar with or go deeper into POD controllers, if necessary.
- For illustrative purposes.

The general scheme of the POD controller, following most common implementation (Figure *3*), has the following components:

- Low-pass filter.
- Wash-out filter (high-pass filter).
- Lead/lag filter (phase-compensation filters).
- Controller gain.
- Controller saturation parameters.

Parameters of each bock can be identified in Table 1 with a brief description.

This general structure of POD controllers has been widely studied in the technical literature (see references [14], [18], [41], for example) and it is analogous to the one used in Power System Stabilizers (PSS) in synchronous machines [42].

Following the common practice for POD controllers and PSSs, it is assumed that the parameters of the POD controllers in Figure *3* are written in per unit magnitudes (pu), referred to the nominal apparent power of the device in MVA. It is important to note that the manufacturer has freedom in choosing the per-unit base value in its POD controller, or even in real magnitudes could be used. Hence, the use of a specific base value for pu is not imposed.

POD controllers can be implemented with a symmetrical structure for POD-P and for POD-Q controllers, as in Figure *3*. The POD-P controller has a "-1" in its block diagram, because, for the same input signal, the POD-P controller and the POD-Q controller should have opposite directions, in general. POD-P and POD-Q controllers could be activated simultaneously (POD-PQ).

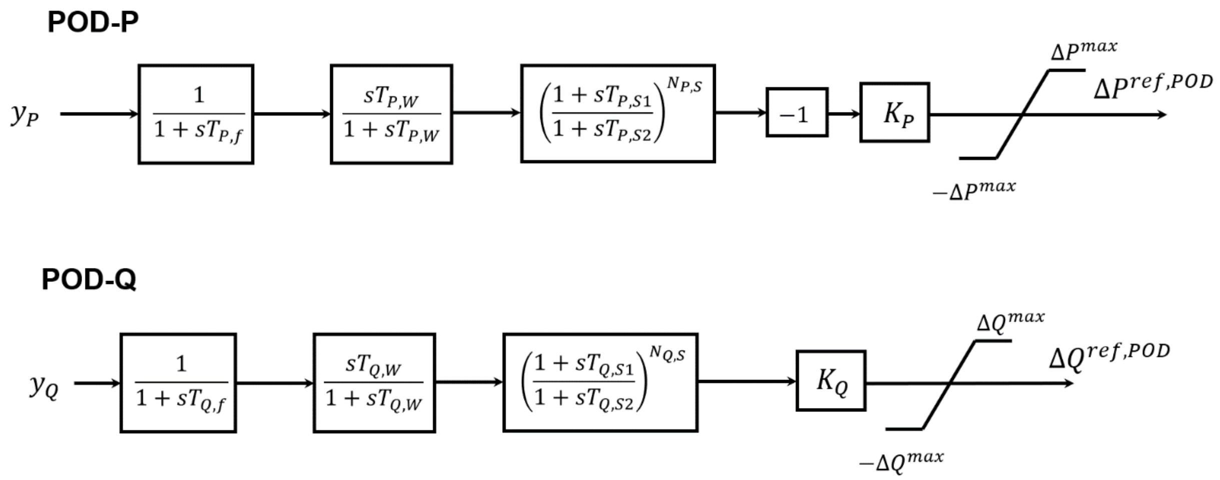

Figure 3: General scheme of POD controllers, following most common implementation.

Supplementary active- and reactive-power set-point values for POD-P and POD-Q controllers, written in the Laplace domain, are given by:

$$\Delta P^{ref,POD} = -K_P \cdot \frac{sT_{P,W}}{1+sT_{P,W}} \cdot \frac{1}{1+sT_{P,f}} \cdot \left(\frac{1+sT_{P,S1}}{1+sT_{P,S2}}\right)^{N_{P,S}} \cdot y_P \qquad (3)$$

$$\Delta Q^{ref,POD} = K_Q \cdot \frac{sT_{Q,W}}{1+sT_{Q,W}} \cdot \frac{1}{1+sT_{Q,f}} \cdot \left(\frac{1+sT_{Q,S1}}{1+sT_{Q,S2}}\right)^{N_{Q,S}} \cdot y_Q \qquad (4)$$

The electromechanical modes of interest must be observable in the input variables of POD-P and POD-Q controllers (y_P and y_Q, respectively), and, in general, there are multiple options that can result in effective and robust POD-P and POD-Q controllers.

One input variable for POD-P and POD-Q controllers that exhibits good robustness properties is the frequency deviation at the connection point:

$$y_P = y_Q = \Delta\omega \text{ (pu)} \qquad (5)$$

where: $\Delta\omega = \omega - \omega_0$ and $\omega_0 = 1$ pu is the nominal frequency of the GFL device. In general, POD gains are assumed to be positive (see the sign criterion). It should be noticed that the options of using the frequency deviation or the frequency as in input signals are equivalent, due to the presence of the high-pass filter (wash-out).

In general, when using the frequency deviation as input signal for POD-P and POD-Q controllers of Figure *3*, gain values are typically positive ($K_P \geq 0$ y $K_Q \geq 0$), although this is not mandatory and it depends on the particular design of POD controllers, on the dynamic response of the facility and its controllers, and on its location.

In GFL converters, the frequency, ω, is measured with a Phase-Locked Loop (PLL) and this signal can be used directly as the input signal of POD controllers, or, alternatively, other methods of frequency estimation could be used.

Table 1 presents a description of the parameters of POD-P and POD-Q controllers and typical values, assuming POD-P and POD-Q controllers using frequency deviation as input signal. In the fourth column, it is indicated whether the parameter is designed/fixed. It should be noted that POD-P and POD-Q controllers could be activated simultaneously (POD-PQ).

Table 1: Parameters of POD-P and POD-Q controllers. Typical values for parameters using the frequency deviation in pu as input signal, for illustrative purposes.

Controller	Parameter	Description	Design/fixed	Comment
POD-P	K_P	Gain	Design	Gain to obtain a reasonable value of damping ratio of the mode or modes of interest in the case study to be analysed. Typical values for a POD-P controller gain using frequency deviation (in pu) as input signal: within the range [-400, 400] pu (pu with respect to the apparent power of the device). Typically, $K_P \geq 0$, although there could be exceptions in particular cases.
	$T_{P,S1}$, $T_{P,S2}$	Lead/lag filters	Design	Required phase compensation. There is also the option of neglecting this filter. In general, a POD-P controller could be effective without the need of this filter if the active-power control of the device is fast enough.
	$N_{P,S}$	Exponent of lead/lag filters	Fixed	Typical values: $N_{P,S} = 1$, $N_{P,S} = 2$ or $N_{P,S} = 3$. Reference value: $N_{P,S} = 2$.
	$T_{P,W}$	Wash-out filter	Fixed	Typical values: within 1-20 s. Reference value: $T_{P,W} = 5$ s.
	$T_{P,f}$	Low-pass filter	Fixed	Typical values: within 0-0,20 s. Reference value: $T_{P,f} = 0{,}1$ s. This parameter could represent a filter implemented in the controller, or it could be a representation of the measurement process of the input signal.
	$\pm\Delta P^{max}$	Saturation parameter	Fixed	Typical values: within 5%-20% (% with respect to the apparent power of the device). Reference value: $\pm\Delta P^{max} = \pm 10$ %.
POD-Q	K_Q	Gain	Design	Gain to obtain a reasonable value of damping ratio of the mode or modes of interest in the case study to be analysed. Typical values for a POD-Q controller gain using frequency deviation (in pu) as input signal: within the range [-400, 400] pu (pu with respect to the apparent power of the device). Typically, $K_Q \geq 0$, although there could be exceptions in particular cases.
	$T_{Q,S1}$, $T_{Q,S2}$	Lead/lag filters	Design	Required phase compensation. There is also the option of neglecting this filter. Not always is true that POD-Q designs without this filter are effective and robust, but this may occur in some cases. Factors that could have influence in the required phase compensation are: how fast the reactive-power controller of the device is and the power system (e.g., SCR, etc..).
	$N_{Q,S}$	Exponent of lead/lag filters	Fixed	Typical values: $N_{Q,S} = 1$, $N_{Q,S} = 2$ o $N_{Q,S} = 3$. Reference value: $N_{Q,S} = 2$.
	$T_{Q,W}$	Wash-out filter	Fixed	Typical values: within 1-20 s. Reference value: $T_{Q,W} = 5$ s.
	$T_{Q,f}$	Low-pass filter	Fixed	Typical values: within 0-0,20 s. Reference value: $T_{Q,f} = 0{,}1$ s. This parameter could represent a filter implemented in the controller, or it could be a representation of the measurement process of the input signal.
	$\pm\Delta Q^{max}$	Saturation parameter	Fixed	Typical values: within 5%-20% (% with respect to the apparent power of the device). Reference value: $\pm\Delta Q^{max} = \pm 10$ %.

3.3 Activation thresholds in POD-P controllers

As stated previously, POD controllers should be targeted at small disturbances and, as far as possible, they should act continuously when subject to small disturbances. In some energy storage technologies, a continuous modulation of the active-power injection, even if small, could degrade their lifetime, based on technical discussions with different manufacturers. For this reason, the use of an activation threshold for the POD-P controller in ESM-PPM systems is allowed. In this way, the POD-P may be activated only when a continuous oscillation in the system is detected with an amplitude greater than or equal to a certain threshold.

Since electromechanical oscillations are well observed at the frequency of the different buses of the system, one option is to use the frequency at the connection point to detect power system oscillations. In this case, a general scheme of the POD-P controller of an ESM-PPM (whether it is stand-alone or part of a hybrid facility) will be as in Figure 4. The POD-P controller will be activated only when a sustained oscillation over time with a certain amplitude is detected in the frequency at the connection point: if its amplitude ($\hat{f}$) is greater than or equal to a specified threshold ($\hat{f}_{thr}$).

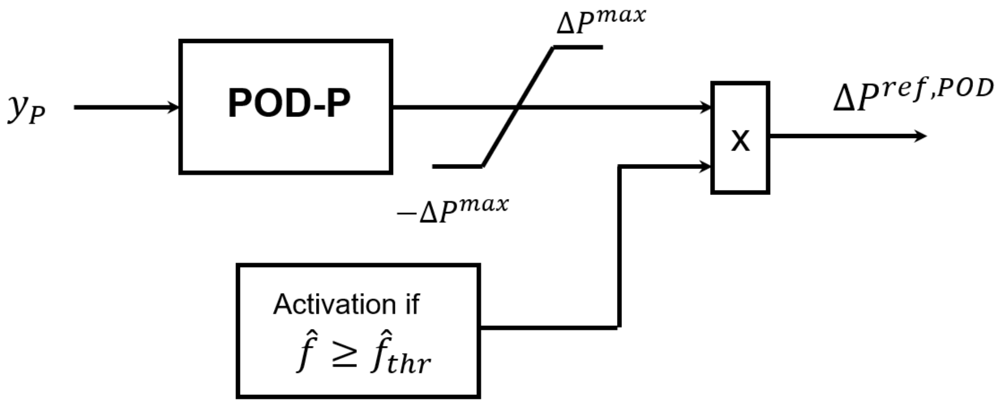

Figure 4: General scheme of a POD-P controller in a ESM-PPM with activation threshold.

The activation threshold of the POD-P controller can be implemented in different ways (specific algorithm for oscillation detection, time rules, sampling windows, hysteresis characteristics for activation/deactivation, etc…). There are no restrictions in implementing the activation threshold of the POD-P controller in ESM-PPM systems using different methods, as long as its correct behaviour is guaranteed and tested.

Typical values for the activation threshold could be around $\hat{f}_{thr} = 0 - 40$ mHz. The proposed reference value is an amplitude of $\hat{f}_{thr} = 15$ mHz. The range of the frequencies of the oscillations to be detected is 0,1-2,5 Hz.

Figure 5 shows an illustrative example of sustained oscillations of 0,2 Hz observed in the frequency: one with an amplitude of $\hat{f} = 5$ mHz, in blue, and another with an amplitude of $\hat{f} = 40$ mHz, in red. The interpretation of the activation threshold $\hat{f}_{thr} = 15$ mHz is also shown in Figure 5. The POD-P controller of the ESM-PPM system would be activated by the oscillation of amplitude $\hat{f} = 40$ mHz (in red), but not by the one of amplitude $\hat{f} = 5$ mHz (in blue). In the example, the mean value of the frequency is 50 Hz, but the mean value of the frequency may be different due to continuous change in the frequencies of the system due to small perturbations.

Finally, it should be mentioned that the use of an activation threshold in POD-P controllers in ESM-PPM systems is allowed, but this does not mean that it is mandatory.

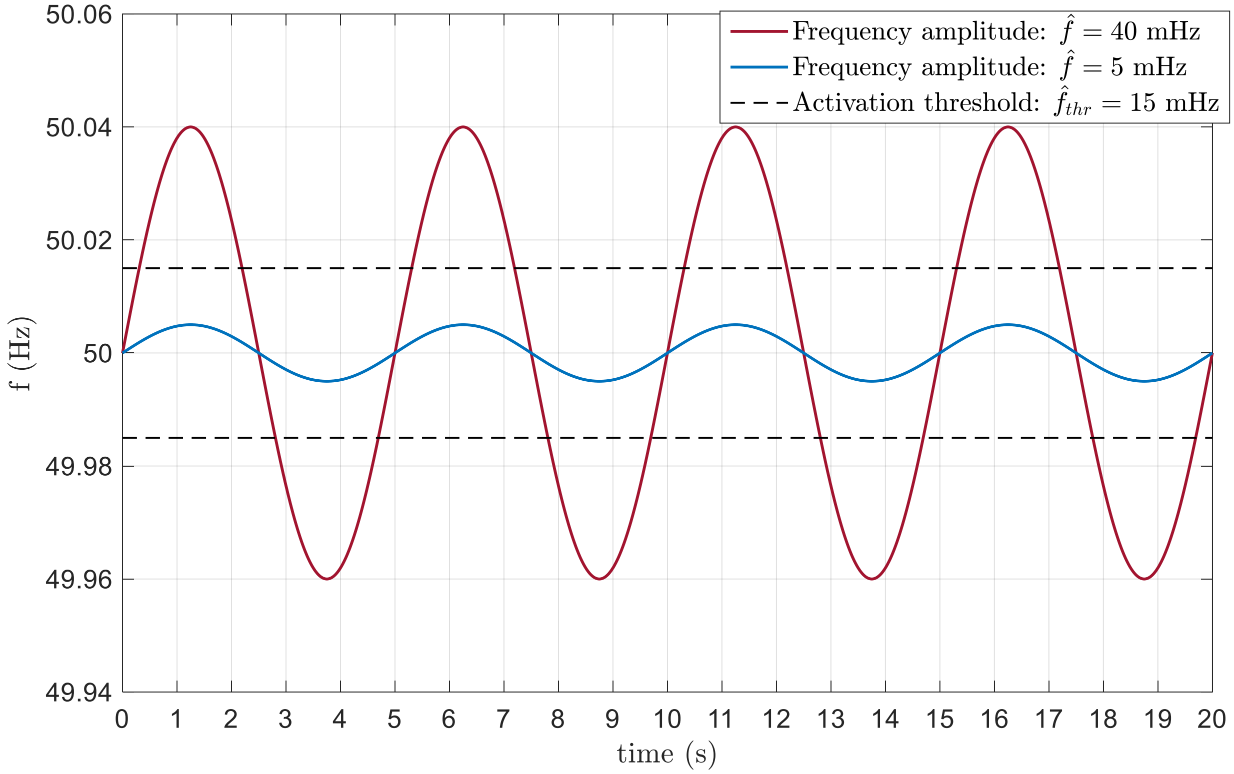

Figure 5: Illustrative example of an oscillation of 0,2 Hz observed in a bus frequency.

4 Oscillation frequency of electromechanical modes

This section discusses aspects related to the oscillation frequency of the electromechanical modes of the power system, with the aim of avoiding confusion related to this aspect and clarifying the acceptance criteria according to the current Spanish Compliance Monitoring Technical Standard (NTS) [43].

In general, a POD controller is designed to contribute to increasing the damping ratio of electromechanical modes of the power system and the main modes of interest are the inter-area modes. In turn, although there are indicative values for the oscillation frequencies of the electromechanical modes (as presented in Section 1), it is not possible to set rigid limits to the oscillation frequencies in real-world power systems. An additional challenge is the uncertainty of how the electromechanical oscillations and their dynamic properties will evolve in power systems with a high content of power-electronic devices; and the responsibility of the SO is to guarantee power system stability.

Taking these aspects into account, the SO considers it necessary to have POD controllers with good performance in the oscillation frequency range of 0,1-2,5 Hz. However, the SO is aware that it is not realistic to expect POD controllers with significant improvements in the entire specified frequency range. Therefore, the following nuances must be taken into account for POD controllers for facilities located in the Peninsular Spanish electrical system (Sistema Eléctrico Peninsular Español, SEPE):

- Electromechanical oscillations within the range 0,1-0,3 Hz: It is expected that POD controllers are effective within this frequency range, since the critical inter-area modes in the Continental European system are within this range [5]. The performance of the POD controller within this frequency range is monitored and accepted according to the criteria proposed in this document and according to the NTS [43].
- Electromechanical oscillations within the range 0,3-1,5 Hz: It is expected that POD controllers provide reasonable results within this frequency range (improvements may be small or, at least, the damping ratio of the electromechanical mode should not be decreased). The performance of the POD controller in this frequency range is monitored and accepted according to the criteria proposed in this document and according to the NTS [43]
- Electromechanical oscillations within the range 1,5-2,5 Hz: It is expected that POD controllers do not excite other modes of the system that could be in this frequency range, but no improvements are expected. It is assumed that the design of the POD controller proposed by the manufacturer is sufficiently robust to guarantee this and that the manufacturer will perform/adopt the necessary simulations and/or measures to ensure this.
- Oscillations of another nature: It is expected that POD controllers do not excite other modes of the system. It is assumed that the design of the POD control proposed by the manufacturer is sufficiently robust to guarantee this and that the manufacturer will perform/adopt the necessary simulations and/or measures to ensure this.

Non-Peninsular Spanish electrical systems (Sistemas Eléctricos No-Peninsulares, SENP) have some particularities, because (a) the oscillation frequencies of the inter-area modes are higher, (b) nowadays electromechanical oscillations are not critical in these systems and (c) due to the small size of this type of systems and the incorporation of non-synchronous generation and power-electronic devices expected in the coming years, there is significant uncertainty about the how the electromechanical modes of these systems will evolve (in nature, damping ratio and oscillation frequency). For the evaluation of POD controllers in the SENP, the evaluation methodology will be the same as the one used for POD controllers in the SEPE, and it may be updated in the coming years if the nature of electromechanical oscillations in this types of systems requires it. Due to the uncertainties above, it is considered necessary that the facilities are equipped with POD controllers, but these shall be deactivated. If in the future it is considered necessary, the SO may request the activation of the POD controllers. The way of evaluating POD controllers in SENP is described in Subsection 5.2. It is emphasized that all the aspects mentioned here are compatible with current regulation (Spanish and European).

5 Evaluation of the behaviour of POD controllers

The evaluation of the behaviour of POD controllers will be performed according to the Spanish Compliance Monitoring Technical Standard (NTS) [43]. Any additional nuances would be proposed to the Compliance Monitoring Working Group (GTSUP) for its evaluation. The synthetic two-area system of the NTS is considered (Figure 6). The synthetic system represents an inter-area oscillation between a synchronous generator in a small coherent area (bus 1) and an equivalent synchronous generator in a larger coherent area (bus 4). This synthetic system allows to represent an electromechanical oscillation with different oscillation frequencies, by adjusting the reactance of line 2-3 ($X_L = X_{23}$). The synthetic two-area system and the methodology for inter-area-oscillation analysis with limited information were proposed in [44], and its application for the analysis of the impact of a PPM on the damping of inter-area oscillations was proposed in [43]. The objective of this synthetic system is to capture the general properties of inter-area oscillations in the Continental Europe power system with limited information.

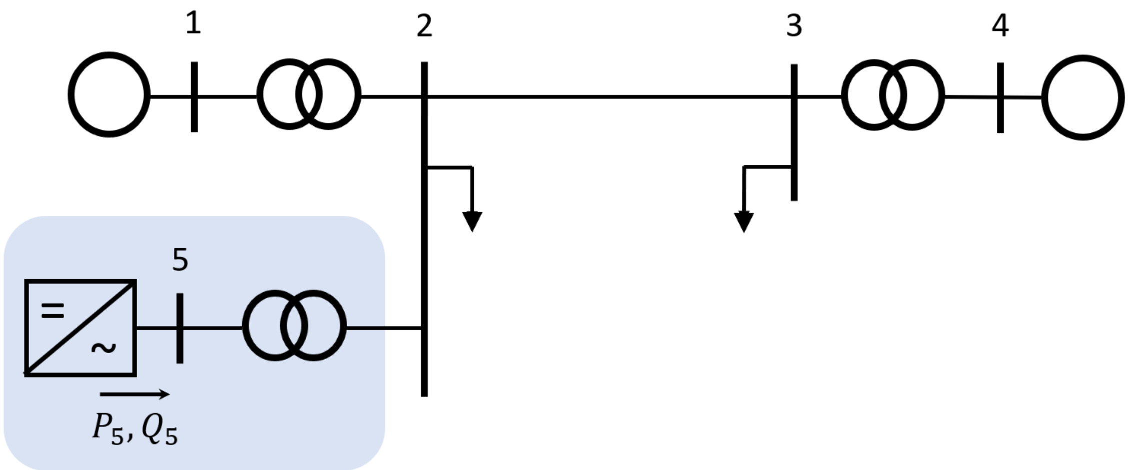

Figure 6: Synthetic two-area system (NTS).

The GFL device is connected to bus 5 and it will have a nominal apparent power of 1500 MVA, following the NTS methodology. All system data can be found in [43]. This simplified system allows to analyse the impact of the GFL device on the damping ratio of the inter-area mode in a two-area system.

A design for POD-P and POD-Q controllers is proposed for a GFL device in this system. For the simulations, the facility must have all its controllers activated, in addition to the POD controllers, following the NTS guidelines [42].

Comparison of different cases:

- Base case results, only synchronous machines connected and without GFL device (B0).
- Base case results where the GFL device is included without POD controllers (B1).
- Base case results where the GFL device with POD-P controller included.
- Base case results where the GFL device with POD-Q controller included.
- Base case results where the GFL device with POD-PQ controller included.
- All the results of the base system where the GFL device is included shall be carried out for
    a. Constant reactive power mode.
    b. Voltage control mode, with a droop constant of the voltage control – reactive power (QV) droop control of 2%, 4% and 7%.

Notice that POD controllers shall be effective in all control modes and operating points of the GFL device. However, for the evaluation of POD controllers, representative cases have been chosen and it is not required to perform the entire list of simulations that are required for the evaluation of other technical capabilities, according to the NTS.

For the analysis, the dynamic models must be appropriate for electromechanical simulations, also known as Root-Mean Square (RMS) type models. That is, taking into account the dynamics of interest in the dynamic models of the devices and representing the electrical grid with algebraic equations. For small-signal stability studies (eigenvalue analysis and frequency-domain methods), the dynamic models must be prepared for linearisation around an operating point.

The particularities of POD controllers depending on the type of facility are explained below:

- PPM systems: the regulations in force as of May 2024 do not require PPM systems to have POD controllers. In the event that a PPM system voluntarily has POD controllers to contribute to the damping of electromechanical oscillations in the power system, the acceptance criteria for POD controllers described in this document will apply.
  It should be mentioned that POD-P and POD-Q controllers could be validated independently. For example, a PPM could have POD-Q only and, therefore, the acceptance criteria would only apply to the POD-Q controller.
- In the case of systems involving energy-storage systems (hybrid facilities (Mode A and Mode B), and stand-alone energy-storage systems), the regulations in force as of May 2024 do not require these controllers either, although the new regulatory proposal for PO 12.2 does consider it: then the acceptance criteria for POD controllers described in this document will apply.

Both, the evaluation methodology and the acceptance criteria for POD controllers proposed in this document will be agreed with the Compliance Monitoring Working Group (GTSUP), once the PO 12.2 or any other regulations requiring this type of controllers have been approved, if necessary.

5.1 Acceptance criteria for POD controllers

In order to determine whether POD controllers contribute to improving the damping of inter-area modes, the cases with POD controllers shall be compared with the base case (with GFL device and without POD controllers, which corresponds to case B1). If the electromechanical modes obtained in the cases with POD controllers have greater damping ratio than the base case, then the performance of the POD controllers would be satisfactory. Notice that the improvement of case B1 (with GFL device and without POD) with respect to case B0 (base case without GFL device) is already covered in the current NTS standard. For this reason, the impact of the POD controllers is compared only with case B1.

The acceptance (or admissibility) criteria for POD controllers proposed in this document are divided into two:

- Acceptance criterion for the robustness of the POD controller.
- Acceptance criterion for the effectiveness of the POD controller.

These acceptance criteria apply both to PPM systems with POD control and to energy-storage systems (ESM-PPM).

5.1.1 Acceptance criterion for the robustness of the POD controller

The POD-robustness acceptance criterion consists of the evaluation of the behaviour of the POD controllers in a range of frequencies of the electromechanical mode, following the methodology and acceptance criteria of the NTS [43].

The behaviour of the POD controllers could be evaluated in two ways, following the guidelines of the NTS:

- Small signal stability analysis (eigenvalues) (procedure and acceptance criteria detailed in sections 5.10.2.1 and 5.10.3.1 of [43], respectively). Acceptance criterion: damping ratio of electromechanical modes greater than or equal to 5%.
- Time-domain simulation (procedure and acceptance criteria detailed in sections 5.10.2.2 and 5.10.3.2 of [43], respectively).

Ideally, it would be expected that when activating the POD controller, the damping ratio of the electromechanical mode would be greater than or equal to the one obtained without POD controller (case B1) for the entire frequency range covered by changing the line reactance from 0,01 pu to 0,6 pu (pu using a power base of 100 MVA). However, there could be some cases in which for a specific value of the line reactance this is not fulfilled, and it is more practical to use only criterion of damping ratio the electromechanical modes greater than or equal to 5%. This means that the POD-robustness acceptance criterion does not quantify the improvement that POD controllers should produce and, except for the way of expressing it, in practice there are no differences with respect to the acceptance criteria for power oscillations in PPMs according to current compliance standards in Spain (NTS).

5.1.2 Acceptance criterion for the effectiveness of the POD controller

Without prejudice to what could be said in the GTSUP and, if applicable, established in the NTS standard [43] as a certification criterion for these controllers, in the absence of this development in the current NTS, the following efficiency criterion is proposed, as a result of the technical discussions and analysis carried out in the GT_POD.

The system in Figure 6 is considered with a line reactance of $X_L = 0{,}6$ pu (base 100 MVA), which corresponds to a frequency range of 0,10-0,25 Hz, approximately. Table 2 summarises the effectiveness acceptance criteria. All the results of the base system where the GFL device is included shall be carried out for voltage control droop constants of 2%, 4% and 7% (droop QV). It is worth to emphasise that, due to the POD-robustness acceptance criteria, the damping ratio of the electromechanical mode must be greater than or equal to 5% for all cases and values of reactance X_L. The POD-effectiveness acceptance criterion can be tested by means of small-signal stability analysis (eigenvalues) or by time-domain simulation.

Unlike the robustness acceptance criterion, the POD-effectiveness acceptance criterion quantifies the improvement on the damping ratio of the electromechanical mode produced by the POD controller. The required improvement is quantified using a single operating point ($X_L = 0{,}6$ pu), since it would be unrealistic to require a specific improvement for the entire frequency range.

The increase in damping ratio of the electromechanical mode required in the POD-effectiveness acceptance criterion, proposed in Table 2, is defined as:

$$\Delta\varsigma_i = \varsigma_i - \varsigma_{B1} \qquad (6)$$

where:

- ς_{B1}: damping ratio of the electromechanical mode obtained in case B1 (%).
- ς_1: damping ratio of the electromechanical mode obtained in the case with POD-P controller (%).
- ς_2: damping ratio of the electromechanical mode obtained in the case with POD-Q controller (%).
- ς_3: damping ratio of the electromechanical mode obtained in the case with the POD-P and POD-Q controllers activated simultaneously (POD-PQ) (%).

It should be noted that the increment values obtained in the damping ratio of the electromechanical mode $\Delta\varsigma_i$ of Table 2 should only be evaluated for the POD controllers that the facility has. For example, if a PPM only has POD-Q controller, but it does not have POD-P controller, the effectiveness acceptance criterion for POD-Q controller ($\Delta\varsigma_2 \geq 5$ %) is required for compliance, but naturally the effectiveness acceptance criteria for POD-P controller or both simultaneously (POD-PQ) (($\Delta\varsigma_1$ and $\Delta\varsigma_3$, respectively) are not required for compliance.

Table 2: Proposed POD-effectiveness acceptance criteria. Two-area system with $X_L = 0{,}6$ pu (which corresponds to an oscillation frequency of de 0,15-0,25 Hz, approximately).

Case	POD-effectiveness acceptance criterion
With POD-P controller	Increment of the damping ratio of the electromechanical mode, $\Delta\varsigma_1$, of at least 5 % compared to case B1: $\Delta\varsigma_1 \geq 5$ %.
With POD-Q controller	Increment of the damping ratio of the electromechanical mode, $\Delta\varsigma_2$, of at least 5 % compared to case B1: $\Delta\varsigma_2 \geq 5$ %.
With POD-PQ controller	Increment of the damping ratio of the electromechanical mode, $\Delta\varsigma_3$, of at least 5 % compared to case B1: $\Delta\varsigma_3 \geq 5$ %.

5.2 Particularities of the evaluation of POD performance in the SEPE and in the SENP systems

The context of electromechanical oscillations in SEPE and SENP systems is different and, therefore, the assessment of POD controllers will have particularities in each case.

On the one hand, inter-area oscillations in the Continental European power system are observed in the SEPE and they are a critical issue nowadays. The most critical inter-area oscillations are within the frequency range 0,1-0,3 Hz. In this case, a facility with POD controller will necessarily be located in the coherent generator area of the SEPE, which oscillates against the other coherent areas of the Continental Europe power system.

On the other hand, SENP systems have different characteristics from each other, and typically the oscillation frequencies of the electromechanical modes are higher than the ones present in the SEPE (they can be within the range 0,8 Hz-2,5 Hz). Nowadays, electromechanical oscillations in SENP systems are not problematic. However, this situation may change in the future, in terms of damping ratio and frequencies of the electromechanical modes, due to the changing nature of this type of systems (due to the incorporation of non-synchronous generation and power-electronic devices). In turn, a facility equipped with POD controller may be located in different coherent areas of the electromechanical oscillations. For these reasons, it is considered necessary that facilities should have POD controllers implemented, but determining their settings today does not guarantee their correct performance in the future.

Along these lines, a reasonable proposal for the evaluation of the behaviour of POD controllers in the SEPE and in the SENP system is as follows:

- SEPE: Evaluation of the behaviour as described at the beginning of Section 5 and with the acceptance criteria of Subsection 5.1.
- SENP: Evaluation of the behaviour as described at the beginning of Section 5 and with the acceptance criteria of Subsection 5.1. But the facility shall always have the POD controller deactivated. If in the future the SO considers it necessary to activate the POD controller of the facility, a study will be jointly defined by the owner of the facility to define the parameters of the POD controllers, with the collaboration of the SO.

5.3 Particularities of the evaluation of POD performance in energy-storage systems

In ESM-PPM systems, the use of an activation threshold for the POD-P controller is allowed. In this case the POD-P controller would be activated when an oscillation of a certain amplitude ($\hat{f}_{thr}$) is detected (see Section 3.3). Independently of this, to test the performance of the POD-P controller when subject to small disturbances it is necessary to run some simulations with the activation threshold deactivated, regardless of whether they actually have it activated or not.

The particularities of the evaluation of the performance of the POD-P controller in ESM-PPM systems are the following:

- Evaluation of the performance as described at the beginning of Section 5 and with the acceptance criteria of Subsection 5.1. For these simulations, the activation threshold of the POD-P controller must be deactivated. This is, the POD-P controller must act continuously for any oscillation amplitude.
- Additional verifications of the time-domain simulation of the synthetic system of Figure 6, with the activation threshold of the POD-P controller activated:
  1. Simulation with a sufficiently small disturbance that does not cause the activation of the POD-P controller.
  2. Simulation with a sufficiently large disturbance that causes the activation of the POD-P controller.

6 Additional considerations

Some additional aspects related to the implementation of POD controllers are discussed below:

- POD controller options: at the PPM/ESM-PPM Power Plant Controller (PPC) level or at the converter (power generation unit, PGU) level.
- POD controller input signals.
- Processing and modelling of POD controller input signal.
- POD-P and POD-Q controller variants.
- POD-Q controller variants.
- POD controller particularities depending on the technology.

6.1 POD controller options: at PPC level or at converter (PGU) level

POD-P and POD-Q controllers can be implemented in two different ways:

- At Power Plant Control level (PPC) level. That is, at a centralised level in the PPM/ESM-PPM.
- At converter level. This is, at PGU level.

6.1.1 POD controller at PPC level

The main characteristics are the following:

- In this case, the supplementary active- and reactive-power references provided by POD-P and POD-Q controllers ($\Delta P^{ref,POD}$ and $\Delta Q^{ref,POD}$, respectively) are added to the references of the active- and reactive-power injections of the PPC of the PPM or ESM-PPM.
- The PPC is responsible for distributing the references for active- and reactive-power injections of the plant (P^* y Q^* de (1) and (2), respectively) between the converters in the park (at PGU level). For this, a communication system is necessary. Communication delays (calculation time + communication latencies) can have an impact on the behaviour of the POD controllers and, therefore, they should be represented in the models and taken into account in the design of POD controllers.
- It is common to use measurements at the connection point of the plant as input signal for POD-P and POD-Q controllers, such as frequency or voltage magnitude at the connection point.
- Usually, the PPC is slower. Therefore, in order to obtain effective POD-P and POD-Q controllers, an appropriate design of the lead/lag filters is required, to obtain an appropriate phase compensation of POD controllers.

6.1.2 POD controller at PGU level

The main characteristics are the following:

- In this case, the supplementary active- and reactive-power references provided by POD-P and POD-Q controllers ($\Delta P^{ref,POD}$ and $\Delta Q^{ref,POD}$, respectively) are added to the references of the active- and reactive-power injections of the converter, at PGU level (i.e., each PGU has its own POD controllers).
- The total active- and reactive-power references of each PGU will be the terms corresponding to the reference sent by the PPC and the term of the POD controller (P^* and Q^* of (1) and (2), respectively).
- Each PGU could use local measurements, such as frequency or voltage module at its AC terminals. Alternatively, they could also use measurements at the connection point of the park, requiring communication, having to take into account the associated delay times, although the former implementation seems more practical.
- It is essential to coordinate POD-P and POD-Q controllers at converter level (PGU) with the PPC, since, if these control layers are not coordinated correctly, the PPC could cancel or attenuate the effect of POD-P and POD-Q controllers at PGU level.
- The cleanest implementation of POD-P and POD-Q controllers at PGU level is when the PPC is controlled in open loop. This is, when the PPC does not have a proportional-integral (PI) regulator with negative feedback of the active- or reactive-power injection (or voltage) measurements. This means

that the distribution of setpoints between the PGU is carried out by a calculation of the setpoints at PPC of the PPM/ESM-PPM level.

6.2 POD controller input signals.

There are different input signal possibilities for POD-P and POD-Q controllers. In references [9], [11], for example, POD-P and POD-Q controllers in wind power parks using different input signals are discussed.

In general, it is an extended practice to choose one of the following input signals for POD-P and POD-Q controllers in GFL converters:

- Frequency (or frequency deviation from the nominal frequency) at the connection point.
- Voltage magnitude at the connection point.

POD-P and POD-Q controllers could have different input signals. The frequency and voltage magnitude will be measured at the connection point. If POD controllers are considered at PPC level, the connection point will be the one of the park at the high voltage side. If POD controllers are considered at converter level (PGU), the connection point will be the AC terminal of the converter.

Input signals which are considered appropriate for POD-P and POD-Q controllers could be used, if their effectiveness and robustness are proven. However, the SO has a preference for the use of frequency signals as input signal for both POD-P and POD-Q controllers, due to the robustness properties they provide to the controllers, in the context of interest:

- Inter-area oscillations in the Continental Europe power system.
- Iberian Peninsula: coherent area of synchronous generators at one edge of the inter-area oscillations of interest.
- Devices with POD-P and POD-Q controllers in located in the Iberian Peninsula.

Reference [41] studied POD-P and POD-Q controllers using frequency and voltage input signals, discussing the main aspects of each option. Most relevant properties of POD-P and POD-Q controllers using frequency or voltage signals as input are presented below:

- POD controllers using frequency measurement as input signal:
  - POD-P controllers are typically more effective than POD-Q controllers when frequency signals are used as input signal.
  - Frequencies at the edges of the inter-area oscillation have a high observability.
  - Frequencies at points close to the centre of the inter-area oscillation have a low observability.
  - The observability factors of the inter-area mode at the frequencies at the system buses at the two edges of an inter-area oscillation have a significant phase shift (opposite phase between the two opposite points of the oscillation).
- POD controllers using voltage-magnitude measurement as input signal:
  - POD-Q controllers can be more effective than POD-P controllers when voltage signals are used as input signals for such controllers.
  - POD-Q controllers using voltage as input signal could be more effective than POD-Q controllers using frequency as input signal, if the design is appropriate and depending on the system topology.
  - Observability factors of the inter-area mode in voltages at buses of the system can have high magnitude at mid-points of the inter-area oscillation.
  - Observability factors of the inter-area mode in voltages at buses in the system (in magnitude and phase) strongly depend on the network topology, power flows in the system and the location of voltage control elements in the system (e.g. connected generators, etc…).

For the reasons stated above and in particular due to their robustness properties, the SO has preference for the use of frequency input signals for POD-P and POD-Q controllers. Although, as already indicated above, any option of POD controller is valid as long as its correct performance is proved and agreed with the SO.

The frequency input signal can be the frequency at the connection point (if the POD controllers are implemented at PPC level), the frequency at the AC terminal of each converter (if the controllers are implemented at PGU level) or even a frequency signal from a remote bus of the system could be used as input signal. In general, if the frequency is used as input signal for POD controllers, any of these variants is allowed. If the input signal from a remote bus is used, the SO must be informed of this circumstance.

6.3 Processing and modelling of POD controller input signal

The model of POD-P and POD-Q controllers shall contain a realistic representation of the processing of the input signals (y_P and y_Q), including measurement filters and communication delays (if any).

For example, if the measurement process of the input signal can be approximated by a first-order filter with a time constant of 80 ms (i.e. $1/(1 + sT_m)$ with $T_m = 0{,}08$ s), this transfer function should be included in the dynamic models of POD-P and POD-Q controllers.

If these dynamics were not taken into account in the models, the designs of POD-P and POD-Q controllers may be inappropriate, and this could lead to wrong conclusions. This effect could be represented properly in the model by using an approximation, if the dynamic behaviour represents the reality with sufficient accuracy.

6.4 POD-P and POD-Q controller variants

In general, effective POD-P and POD-Q controllers may be of different nature. For example:

- Different block diagrams.
- Different input signals (for example, frequency, voltages, power flows through a line).
- Input signals with local measurements or remote measurements.
- POD controllers with different output signals:
    - POD-P: supplementary reference for the active-power injection, direct-axis current, etc…
    - POD-Q: supplementary reference for reactive-power injection, transverse-axis current, or voltage, etc…
- Fixed or adaptive parameters.
- Different variants of POD-Q controller implementation when the GFL device is in voltage control mode. This aspect is related to the POD-Q controller output signal. Because it may be more common, this aspect is addressed separately in Section 6.5.

In general, the SO will consider valid any variant of POD-P and POD-Q controllers as long as that their effectiveness and robustness are guaranteed (see Section 5.1).

- POD-P and POD-Q controllers based on the general structure described in this document using the frequency at the connection point (or frequency deviation at the connection point with respect to the nominal frequency) as input signal and complying with the technical requirements: they will be accepted by the SO.
- POD-P and POD-Q controllers based on other variants or other input signal: they shall be submitted to the SO with the corresponding studies. The SO will analyse both the POD controllers and the studies, to determine their acceptance.

6.5 POD-Q controller variants

The POD-Q controller in Figure *3* is valid not only for a GFL device with control of the reactive-power injection at the connection point, but also when a GFL device controllers the voltage magnitude at the connection point, as long as the voltage control loop has an intermediate calculation of a reactive-power setpoint, the implementation is correct and it is ensured that the voltage control and the POD-Q controller do not interact.

Alternatively, if the GFL device is controlling the voltage module at the connection point, an alternative to the one shown above for the POD-Q controller is to include a supplementary voltage reference instead of a reactive-power reference. This controller can keep the name POD-Q (implementation 2) or, eventually, it could be known by the name POD-V, but it is for the same application. In this case (Figure 7), the total voltage reference would be given by:

$$V^{*} = V_0 + \Delta V^{ref,POD} \quad (7)$$

$$\Delta V^{ref,POD} = K_V \cdot \frac{sT_{V,W}}{1+sT_{V,W}} \cdot \frac{1}{1+sT_{V,f}} \cdot \left(\frac{1+sT_{V,S1}}{1+sT_{V,S2}}\right)^{N_{V,S}} \cdot y_V \quad (8)$$

where: V^{*} is the voltage reference of the GFL device, V_0 is a constant value, $\Delta V^{ref,POD}$ is the supplementary voltage reference of the POD-Q control (implementation 2 or POD-V) and y_V is its input signal.

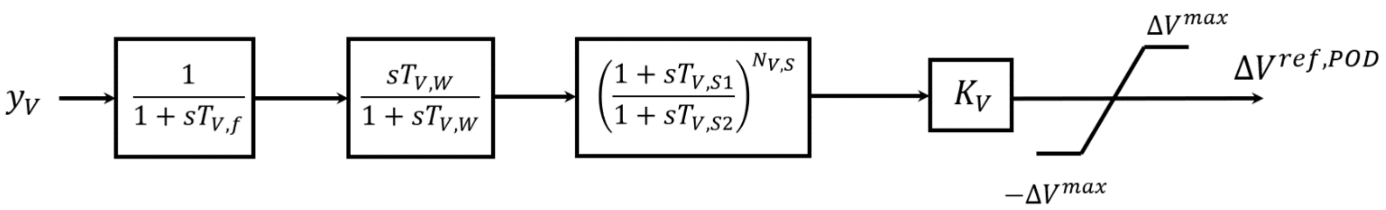

Figure 7: POD-Q controller with implementation 2 (POD-V).

It should be noticed that, like the POD controllers in Subsection 3.2, this particular implementation is presented with illustrative purposes and there may be different implementations that would also be acceptable.

If this option is chosen, its correct design and effectiveness must be guaranteed.

6.6 POD controller particularities depending on the technology.

Technical requirements for POD-P and POD-Q controllers are summarised below, according to the status of the regulations as of May 2024:

- PPM: According to the current regulations, it is required to the PMM (types C and D) to not produce negative effects on the damping of inter-area oscillations (Orden TED-749-20) [36]. It is not required explicitly to the PPM to be equipped with POD-P and/or POD-Q controllers, but it could have these controllers voluntarily or if needed to comply with the requirement of not producing negative effects to the damping of inter-area oscillations.
  In the proposed European regulation RfG2 [33], it is required to the PPM (type D) to have POD controllers implemented: either only POD-P, or only POD-Q or both (POD-PQ). In type-C PPMs, POD controllers could be required if specified by the relevant TSO.
  In case the PPM has POD-P and/or POD-Q controllers, these shall fulfil the technical functionalities as described in this document.
- Electricity storage module (ESM): according to the proposal of P. O. 12.2 [34], the electric energy storage system (types C and D), whether it is stand alone or a part of a hybrid installation, shall be equipped with POD-P and POD-Q controllers. Depending on the energy-storage technology and to avoid its premature degradation, the POD-P controller will only be activated when the amplitude of the frequency oscillation exceeds a threshold defined by the SO (all details described in [34]). This is in line with the proposed European regulation RfG2 [33].
  In the proposed European regulation RfG2 [33], it is required to the ESM-PPM (type D) to have POD controllers implemented: either only POD-P controller, or only POD-Q controller, or both (POD-PQ) (since it is explicitly stated that the requirements for PPM apply also to ESM-PPM). In type-C ESM-PPMs, POD controllers could be required if specified by the relevant TSO.
  In case the ESM-PPM has POD-P and/or POD-Q controllers, these shall fulfil the technical functionalities as described in this document.
- HVDC systems: POD-P and POD-Q controllers are required as mandatory (Orden TED-749-20) [36].
- FACTS: It is treated as an additional component of a power-generating module (ACPGM). Therefore, technical requirements related to power oscillations are applied in an aggregated way to a PPM (do not decrease the damping ratio of the inter-area oscillation), as described above. For example, it could happen that a POD controller is attached in a FACTS device which is integrated in the PPM. In this case, POD-P and POD-Q controllers shall fulfil the technical functionalities as described in this document.

7 Main ideas (summary) of the proposal for technical specifications of POD controllers

Technical specifications for the POD controllers, for compliance with technical requirements of the regulation, are summarised below:

- Technical requirements according to the European regulations [32], [33], [35], Orden TED-749-20 [36] and the draft of the new P. O. 12.2 [34].
- POD controllers can be implemented according to the proposal of this document (following the most common and accepted block diagrams and using the frequency (or frequency deviation with respect to the nominal frequency) as input signal, as described in Section 3). The frequency input signal can be the frequency at the connection point (if POD controllers are implemented at PPC level), the frequency at the AC terminal of the converter (if the controllers are implemented at PGU level) or even the frequency signal of a remote bus could be used as input signal.
  Also, other variants of POD controllers other than those described in this document can be implemented. However, the correct behaviour of POD controllers shall be guaranteed, and the proposal must be accepted by the SO.
- POD controllers can be implemented at plant control level (PPC) or at converter level (PGU). In any case, the correct behaviour of POD controllers shall be guaranteed.
- The evaluation of the behaviour of POD controllers will be carried out according to the NTS standard [43] regulations (Section 5 of this document). In case of using other variants of POD controllers and in case that additional tests are needed due to limitations in the extractable conclusions of the NTS synthetic system when using these variants, complementary studies that guarantee the correct behaviour of the POD controllers would be accepted.
- Technical specifications: Saturation parameters of POD controllers shall comply with the technical specifications described in Table 3. These technical specifications apply to any POD-control variant, including other schemes different than the ones described in this document. It should be highlighted that these specifications apply to saturation parameters, but they are not related to the concept of active- and reactive-power reserve of the facility.
  If the most common implementation of POD-P and POD-Q controllers (Figure *3*) is used with the frequency deviation in pu as input signal, then POD-controller parameters shall be consistent with those in Table 4.
- In the case of POD-P controllers in energy-storage systems (see Section 3.3), the threshold of the frequency-oscillation amplitude defined by the SO from which the POD-P controller will be activated shall be adjustable and $\hat{f}_{thr} \leq 15$ mHz (amplitude of the sinusoidal signal with respect to the mean value, not peak-peak amplitude) for oscillations detected between 0,1-2,5 Hz (see Section 4 for more information on oscillation frequencies of electromechanical modes). Notice that an activation threshold of $\hat{f}_{thr} \leq 15$ mHz means that the POD-P controller will only be activated for oscillations in the frequency with amplitude $\hat{f} > 15$ mHz. The activation threshold shall be implemented with all control elements needed to ensure its correct operation (for example, hysteresis characteristic or timing for activation/deactivation, etc.), although the specific details of these aspects are not specified here, since there are different ways of doing it. The SO may request to modify the value of the activation threshold upon express notification. This is included in Table 3.
- In facilities in the SEPE, POD controllers shall be activated all the time, unless otherwise indicated by the SO. In facilities in the SENP, POD controllers shall be deactivated. In the future, if considered necessary to guarantee the reliability and security of the power system, the SO may request to activate the POD controllers of facilities in the SENP.

Table 3: Technical specifications for POD controller parameters in PPMs and ESM-PPMs.

Controller	Comment	Parameter	Recom-mended/manda-tory
POD-P	POD-P controller according to the scheme of Figure 2.	Saturation parameter ΔP^{max}: adjustable and within the range 0-20 %. (% with respect to the nominal apparent power in MVA). Reference value: $\Delta P^{max} = 10$ %. Mandatory value: $\Delta P^{max} \geq 10$ %, unless a lower value is specified by the SO. Subject to reserve availability.	Mandatory
	Only for ESM-PPM. POD-P controller, according to the scheme of Figure 4.	Activation threshold $\hat{f}_{thr}$: adjustable and within the range $\hat{f}_{thr} = 0 - 40$ mHz. Reference value: $\hat{f}_{thr} = 15$ mHz. Mandatory value: $\hat{f}_{thr} \leq 15$ mHz, unless a lower value is specified by the SO.	Mandatory
POD-Q	POD-Q controller according to the scheme of Figure 2. (implementation 1)	Saturation parameter ΔQ^{max}: adjustable and within the range 0-20 %. (% with respect to the nominal apparent power in MVA). Reference value: $\Delta Q^{max} = 10$ %. Mandatory value: $\Delta Q^{max} \geq 10$ %, unless a lower value is specified by the SO. Subject to reserve availability.	Mandatory
	POD-Q controller variant applied to a voltage reference (POD-V) according to (7). (implementation 2)	Parameter ΔV^{max}: adjustable and within the range 0-10 %. Reference value: $\Delta V^{max} = 5$ %. Mandatory value: $\Delta V^{max} \geq 5$ %, unless a lower value is specified by the SO. Subject to reserve availability.	Mandatory

Table 4: Parameters of POD-P and POD-Q controllers, according to most common implementation (Figure 3), using the frequency deviation in pu as input signal.

Control	Parameter	Description	Comment	Recommended/mandatory
POD-P	K_P	Gain	Range [-400, 400] pu (pu con with respect to the nominal apparent power Typically, $K_P \geq 0$, although there could be exceptions in particular cases. It shall be tuned.	Recommended
	$T_{P,S1}$, $T_{P,S2}$	Lead/lag filters	They shall be tuned.	Recommended
	$N_{P,S}$	Exponent of lead/lag filters	Typical values: $N_{P,S} = 1$, $N_{P,S} = 2$ or $N_{P,S} = 3$. Reference value: $N_{P,S} = 2$.	Recommended
	$T_{P,W}$	Wash-out filter	Typical values: within 1-20 s. Reference value: $T_{P,W} = 5$ s.	Recommended
	$T_{P,f}$	Low-pass filter	Typical values: within 0-0,20 s. Reference value: $T_{P,f} = 0{,}1$ s.	Recommended
	$\pm\Delta P^{max}$	Saturation parameter	Typical values: within 5%-20% (% with respect to the apparent power of the device). Reference value: $\Delta P^{max} = 10$ %. Mandatory value: $\Delta P^{max} \geq 10$ %, unless a lower value is specified by the SO.	Mandatory
	$\hat{f}_{thr}$	Activation threshold	Only for ESM-PPM Typical values within $\hat{f}_{thr} = 0 - 40$ mHz. Reference value: $\hat{f}_{thr} = 15$ mHz. Mandatory value: $\hat{f}_{thr} \leq 15$ mHz, unless a lower value is specified by the SO.	Mandatory
POD-Q	K_Q	Gain	Range [-400, 400] pu (pu con with respect to the nominal apparent power Typically, $K_Q \geq 0$, although there could be exceptions in particular cases. It shall be tuned.	Recommended
	$T_{Q,S1}$, $T_{Q,S2}$	Lead/lag filters	They shall be tuned.	Recommended
	$N_{Q,S}$	Exponent of lead/lag filters	Typical values: $N_{Q,S} = 1$, $N_{Q,S} = 2$ o $N_{Q,S} = 3$. Reference value: $N_{Q,S} = 2$.	Recommended
	$T_{Q,W}$	Wash-out filter	Typical values: within 1-20 s. Reference value: $T_{Q,W} = 5$ s.	Recommended
	$T_{Q,f}$	Low-pass filter	Typical values: within 0-0,20 s. Reference value: $T_{Q,f} = 0{,}1$ s.	Recommended
	$\pm\Delta Q^{max}$	Saturation parameter	Typical values: within 5%-20% (% with respect to the apparent power of the device). Reference value: $\Delta Q^{max} = 10$ %. Mandatory value: $\Delta Q^{max} \geq 10$ %, unless a lower value is specified by the SO.	Mandatory

8 Disclaimer

The System Operator publishes this document for the purpose of facilitating the understanding and implementation of power oscillation damping controllers. This document has no regulatory value. The information is intended to be up-to-date and accurate, but the System Operator declines all responsibility for the information contained in this document. Such information is of a general nature and does not refer to the specific circumstances of any particular subject and does not constitute professional or legal opinions.

The System Operator declines all responsibility for losses suffered as a result of decisions, actions or omissions based on the information published in this document. In particular, the System Operator declines all responsibility for economic losses or indirect damage, including, without limitation, any commercial loss or loss of profit, resulting directly or indirectly from, or related to, the publication of this document by the System Operator, and the use that may be made of this document.

It should be noted that there is no guarantee that the information disseminated in this guide accurately reproduces official texts. Only the texts of the Spanish and European regulations, as published in the "Boletín Oficial del Estado" and in the Official Journal of the European Union), respectively, are considered authentic.

In the event of any possible confusion in the interpretation of any specific aspect between the Spanish and English versions of this guide, the reference document is the one written in Spanish.

The latest updated edition of this guide is available in the customer area ("área de clientes") of the corporate website *www.ree.es*.

9 Contact information

Any doubts or queries that may arise from this guide, as well as doubts or incidents in the platform, shall be created and sent through Red Eléctrica's Customer Services Platform ("Portal de Servicios a Clientes") (www.ree.es), in the "Contact us" module ("Contacta con nosotros").

Address:

Red Eléctrica – Redeia
Dirección General de Operación
Dirección de Desarrollo del Sistema
Paseo Conde de los Gaitanes, 177
28109 Alcobendas, Madrid, España
Telephone: 91 659 91 19

10 References

[1] P. Kundur, Power System Stability and Control, New York, NY, USA: McGraw-Hill (Inc.), 1994.

[2] M. Klein, G. J. Rogers and P. Kundur, "A Fundamental Study of Inter-Area Oscillations in Power Systems," *IEEE Transactions on Power Systems,* vol. 3, no. 6, pp. 914-921, 1991.

[3] P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou, H. Hill, A. Stankovic, C. Taylor, T. Van Cutsem and V. Vittal, "Definition and classification of power system stability," *IEEE Transactions on Power Systems,* vol. 19, no. 3, pp. 1387-1401, 2004.

[4] N. Hatziargyriou, J. Milanovic, C. Rahmann, V. Ajjarapu, C. Canizares, I. Erlich, D. Hill, I. Hiskens, I. Kamwa, B. Pal, P. Pourbeik, J. Sanchez-Gasca, A. Stankovic, T. Van Cutsem, V. Vittal and C. Vournas, "Definition and classification of power system stability - Revisited & Extended," *IEEE Transactions on Power Systems,* vol. 36, no. 4, pp. 3271-3281, 2021.

[5] ENTSO-E, "Analysis of CE inter-area oscillations of 1st December 2016," ENTSO-E SG SPD REPORT, Brussels, Belgium, 2017.

[6] C. Martinez, G. Joos and B. T. Ooi, “Power System Stabilizers in Variable Speed Wind Farms,” in *Proc. IEEE/PES General Meeting*, Calgary, AB, Canada, 2009.

[7] L. Sigrist and L. Rouco, "Design of damping controllers for doubly fed induction generators using eigenvalue sensitivities," in *Proc. IEEE/PES Power Systems Conference and Exposition*, Seattle, WA, USA, 2009.

[8] J. L. Domínguez-García, O. Gomis-Bellmunt, F. D. Bianchi and A. Sumper, "Power oscillation damping supported by wind power: A review," *Renewable and Sustainable Energy Reviews,* vol. 16, no. 7, pp. 4994-5006, 2012.

[9] J. L. Domínguez-García, F. D. Bianchi and O. Gomis-Bellmunt, "Control Signal Selection for Damping Oscillations With Wind Power Plants Based on Fundamental Limitations," *IEEE Transactions on Power Systems,* vol. 28, no. 4, pp. 4274-4281, 2013.

[10] S. De Rijcke, N. Hamann, A. Harjula, J. Seppanen, A. Kuusela and I. Luukkonen, "Damping Power System Oscillations by Wind Power Plants," in *Proc. 15th Wind integration Workshop (WIW 2016)*, Vienna, Austria, 2016.

[11] L. Petersen, P. H. Nielsen, G. C. Tarnowski and T. Lund, "Addressing power oscillations damping requirements for wind power plants," in *Proc. 20th International Workshop on Large-Scale Integration of Wind Power into Power Systems as well as on Transmission Networks for Offshore Wind Power Plants (WIW 2021)*, Berlin, Germany, 2022.

[12] R. Shah, N. Mithulananthan and K. Y. Lee, "Large-Scale PV Plant With a Robust Controller Considering Power Oscillation Damping," *IEEE Transactions on Energy Conversion,* vol. 28, no. 1, pp. 106-116, 2013.

[13] N. Jankovic, J. Roldan-Perez, M. Prodanovic and L. Rouco, "Centralised Multimode Power Oscillation Damping Controller for Photovoltaic Plants with Communication Delay Compensation," *IEEE Transactions on Energy Conversion,* vol. 39, no. 1, pp. 1-9, 2024.

[14] N. Jankovic, J. Roldan-Perez and M. Prodanovic, "Power Oscillation Damping using Converter-Interfaced generators under Constrained Active and Reactive Powers," in *Proc. IEEE/PES Innovative Smart Grid Technologies Europe (ISGT Europe)*, Espoo, Finland, 18-21 October, 2021.

[15] N. Jankovic, J. Roldan-Perez, M. Prodanovic, J. A. Suul, S. D’Arco and L. Rouco Rodriguez, "Power oscillation damping method suitable for network reconfigurations based on converter interfaced generation and combined use of active and reactive powers," *International Journal of Electrical Power and Energy Systems* , vol. 149, no. 109010, pp. 1-10, 2023.

[16] N. Martins and L. T. G. Lima, "Determination of suitable locations for power system stabilizers and static var compensators for damping electromechanical oscillations in large scale power systems," *IEEE Transactions on Power Systems,* vol. 5, no. 4, pp. 1455-1469, 1990.

[17] L. Rouco, "Coordinated design of multiple controllers for damping power system oscillations," *Electric Power Systems Research,* vol. 23, pp. 517-530, 2001.

[18] A. R. Messina, H. Hernández, E. Barocio, M. Ochoa and J. Arroyo, "Coordinated application of FACTS controllers to damp out inter-area oscillations," *Electric Power Systems Research,* vol. 62, pp. 43-53, 2002.

[19] B. Kalyan Kumar, S. N. Singh and S. C. Srivastava, "Placement of FACTS controllers using modal controllability indices to damp out power system oscillations," *IET Generation, Transmission and Distribution,* vol. 1, no. 2, pp. 209-217, 2007.

[20] N. Mithulananthan, C. A. Canizares, J. Reeve and G. J. Rogers, "Comparison of PSS, SVC, and STATCOM controllers for damping power system oscillations," *IEEE transactions on power systems,* vol. 18, no. 2, pp. 786-792, 2003.

[21] M. Lahtinen, T. Rauhala, H. Kuist, P. Peltola and P. Halonen, “Static Var Compensator enhancing the operational reliability of Finnish transmission network,” in *CIGRE Session, paper B4-206*, Paris, France, 2010.

[22] K. Uhlen, L. Vanfretti, M. M. de Oliveira, A. B. Leirbukt, V. H. Aarstrand and J. O. Gjerde, “Wide-Area Power Oscillation Damper Implementation and Testing in the Norwegian Transmission Network,” in *Proc. IEEE/PES General Meeting*, San Diego, CA, USA, 22-26 July, 2012.

[23] Y. Pipelzadeh, B. Chaudhuri and T. C. Green, " Control coordination within a VSC HVDC link for power oscillation damping: A robust decentralized approach using homotopy," *IEEE Transactions on Control Systems Technology,* vol. 21, no. 4, pp. 1270-1279, 2012.

[24] M. Hadjikypris and V. Terzija, "Active power modulation assisting controller scheme implemented on a VSC-HVDC link establishing effective damping of low frequency power oscillations," in *Proc. IEEE International Energy Conference (ENERGYCON)*, Cavtat, Croatia, 13-16 May, 2014.

[25] M. A. Elizondo, R. Fan, H. Kirkham, M. Ghosal, F. Wilches-Bernal, D. Schoenwald and J. Lian, "Interarea Oscillation Damping Control Using High-Voltage DC Transmission: A Survey," *IEEE Transactions on Power Systems,* vol. 33, no. 6, pp. 6915 - 6923, 2018.

[26] J. Renedo, A. Garcia-Cerrada, L. Rouco and L. Sigrist, "Coordinated Design of Supplementary Controllers in VSC-HVDC Multi-Terminal Systems to Damp Electromechanical Oscillations," *IEEE Transactions on Power Systems,* vol. 36, no. 1, pp. 712-721, 2021.

[27] Y. Xing, E. Kamal, B. Marinescu and F. Xavier, “Advanced control to damp power oscillations with VSC-HVDC links inserted in meshed AC grids,” *International Transactions on Electrical Energy Systems,* vol. 31, no. 12, pp. 1-16, 2021.

[28] J. L. Rodriguez-Amenedo and S. Arnaltes Gómez, "Damping Low-Frequency Oscillations in Power Systems Using Grid-Forming Converters," *IEEE Access,* vol. 9, pp. 158984-158997, 2021.

[29] R. L. Cresap, W. A. Mittelstadt, D. N. Scott and C. W. Taylor, “Operating experience with modulation of the pacific HVDC intertie,” *IEEE Transactions on Power Apparatus and Systems,* Vols. PAS-97, no. 4, pp. 1053-1059, 1978.

[30] T. Smed and G. Andersson, “Utilising HVDC to Damp Power Oscillations,” *IEEE Transactions on Power Delivery,* vol. 8, no. 2, pp. 620-627, 1993.

[31] B. J. Pierre, F. Wilches-Bernal, D. A. Schoenwald, R. T. Elliott, D. J. Trudnowski, R. H. Byrne and J. C. Neely, "Design of the Pacific DC Intertie Wide Area Damping Controller," *IEEE Transactions on Power Systems,* vol. 34, no. 5, pp. 3594-3604, 2017.

[32] European Union, "COMMISSION REGULATION (EU) 2016/631 of The European Parliament and of The Council: establishing a network code on requirements for grid connection of generators," Official Journal of the European Union, Brussels, Belgium, 2016.

[33] ACER, “Amendments for Commission Regulation (UE) 2016/631 (RfG) - Draft,” (https://www.acer.europa.eu/electricity/connection-codes, último acceso 9-5-2024), Brussels, Belgium, December, 2023.

[34] Red Eléctrica, «Procedimiento de Operación (PO) 12.2 - Borrador: Instalaciones conectadas a la red de transporte y equipos de generación, consumo, almacenamiento y sistemas HVDC: requisitos,» 2021.

[35] European Union, "COMMISSION REGULATION (EU) 2016/1447 of The European Parliament and of The Council: establishing a network code on requirements for grid connection of high voltage direct current systems and direct current-connected power park modules," Official Journal of the European Union, Brussels, Belgium, 2016.

[36] Ministerio para la Transición Ecológica y el Reto Demográfico, Gobierno de España, “Orden TED/749/2020, de 16 de julio, por la que se establecen los requisitos técnicos para la conexión a la red necesarios para la implementación de los códigos de red de conexión,” Boletín Oficial del Estado, número 208, España, 2020.

[37] J. Bola, R. Rivas, Fernández-Alonso, G. Pérez, J. Hidalgo, L. M. Coronado, C. Longás, S. Sanz, G. Lemarchand, J. Roguin and D. Glaise, “Operational experience of new Spain-France HVDC interconnection,” in *Proc. CIGRE Session, paper B4-117*, Paris, France, 2016.

[38] J. Renedo, A. Diaz-García, G. Torresan, E. Lorenzo Cabrera, A. Cordón, S. Sanz Verdugo, J. Peiró, J. Pérez Castro, G. Calvo, A. Hernández Sautua, A. Petit, H. Oukhayi, S. Akkari and H. Saad, "Tests on the POD-P controller of INELFE Spain-France VSC-HVDC interconnector," in *Proc. CIGRE B4 International SC Meeting and Colloquium, paper B4-1145*, Vienna, Austria, 11-15 Sep, 2023.

[39] Red Eléctrica, "Plan de desarrollo de la Red de Transporte de Energía Eléctrica: Período 2021-2026," https://www.planificacionelectrica.es (último acceso 25-01-2023), España, 2022.

[40] E. Rakhshani, J. M. Ruiz, E. Dominguez, M. Sojo, M. Lasa, A. Molina, G. Quiñonez, S. Martínez Villanueva and M. Lorenzo Sotelo, "Proyecto RES+: Sistema de almacenamiento híbrido como soporte a parques renovables que permiten una amplia gama de servicios de red avanzados en sistemas grid following: Experiencia a escala real en España," in *", Proc. I Edición Congreso de Redes Inteligentes (FutuRed)*, Madrid, España, 14 diciembre, 2022.

[41] L. Rouco, F. L. Pagola, A. Garcia-Cerrada, J. M. Rodríguez-García and R. M. Sanz, "Damping of electromechanical oscillations in power systems with superconducting magnetic energy storage systems: location and controller design," in *Proc. 12th Power Systems Computation Conference (PSCC)*, Dresden, Germany, 19-23 August , 1996.

[42] M. Klein, G. J. Rogers, S. Moorty and P. Kundur, "Analytical investigation of factors influencing power system stabilizers performance," *IEEE Transactions on Energy Conversion ,* vol. 7, no. 3, pp. 382-390, 1992.

[43] Red Eléctrica, Aelec, Grupo Naturgy, Cide, Aseme, «Norma técnica de supervisión de la conformidad de los módulos de generación de electricidad según el Reglamento UE 2016/631,» https://www.esios.ree.es/es/pagina/codigos-red-conexion (último acceso 1-5-2024), España, 2022.

[44] J. Renedo, L. Sigrist and L. Rouco, "Design of power system stabilizers to damp low frequency inter-area oscillations with limited information," in *Proc. 13th IEEE/PES PowerTech Conference*, Milano, Italy, 23-27 June, 2019.

red eléctrica

Una empresa de Redeia