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International Workshop on Dynamic Stability Challenges of the Future Power Grids (DynPOWER 2026)

Guidelines for the implementation of power oscillation damping controllers in power converters

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Contents

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Electromechanical oscillations in power systems

Electromechanical oscillations

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- Electromechanical oscillations (or power oscillations): phenomenon of angle stability under small disturbances
- They are related to oscillations between generators among the power system
  - » Synchronous generators.
  - » Non-synchronous generators could have a significant impact on the damping ratio of electromechanical oscillations.
- Frequency range of electromechanical oscillations: 0.1-2.5 Hz (aprox.).
  - » Local oscillations: 0.7-2.5 Hz (aprox.)
  - » Inter-area oscillations: 0.1-1 Hz (aprox.)

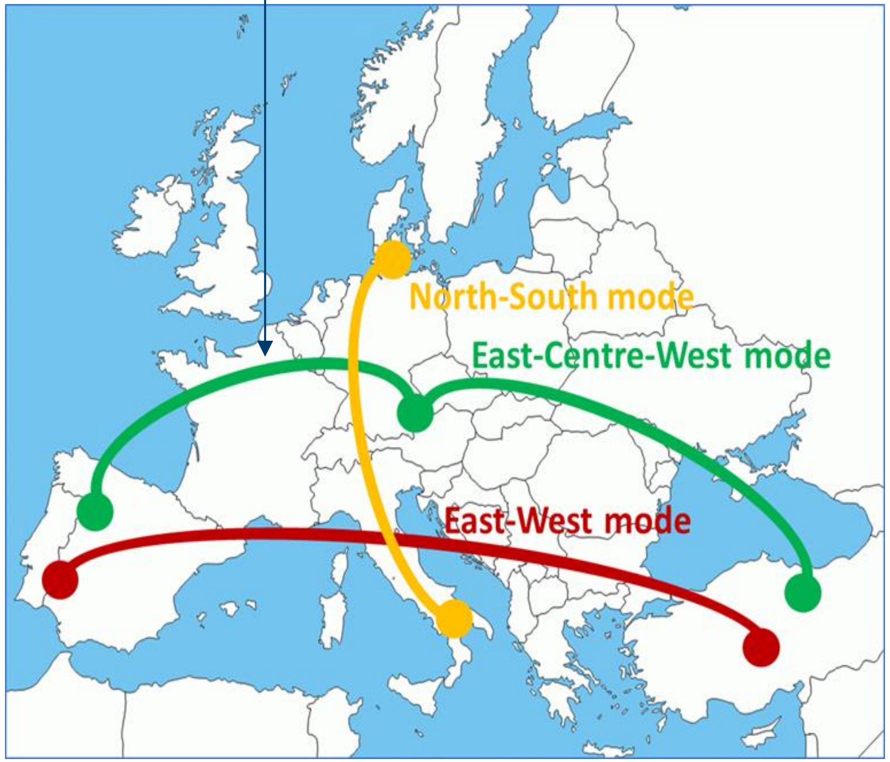
Electromechanical oscillations

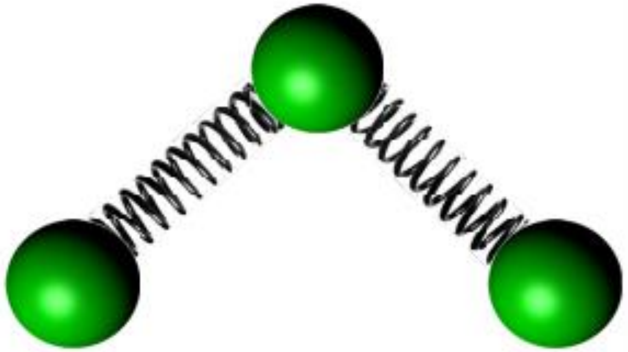
- Methods to improve the damping of electromechanical oscillations
  - Synchronous machines: Power System Stabilizers (PSS).
  - Power-electronic devices: Power Oscillation Damping (POD) controllers.

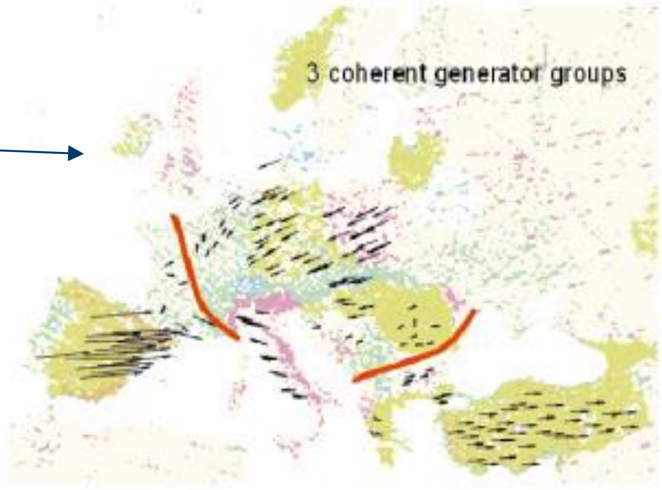
- Facilities involving power-electronic devices
  - Wind or solar photovoltaic (PV) power park modules (PPM).
  - Energy storage systems of type PPM (ESM-PPM): Stand-alone or hybrid facilities.
  - High Voltage Direct Current (HVDC) systems.
  - Flexible Alternating Current Transmission Systems (FACTS).

Inter-area oscillations in the Continental Europe power system

- Inter-área modes
  - North-South mode (0.2-0.3 Hz)
  - East-West mode (0.1-0.16 Hz)
  - East-Centre-West mode (0.1-0.28 Hz)





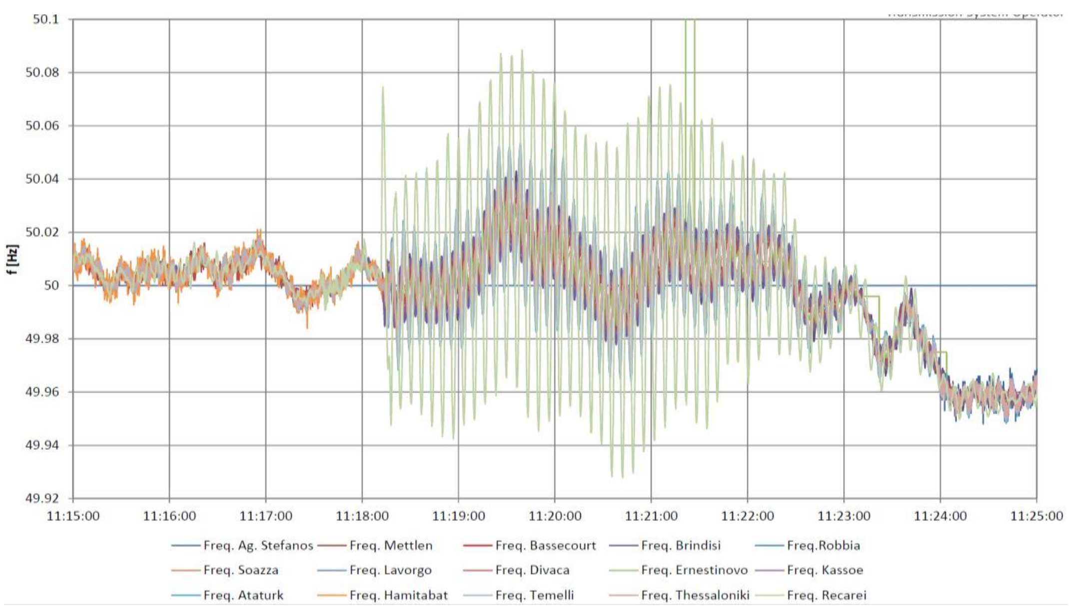


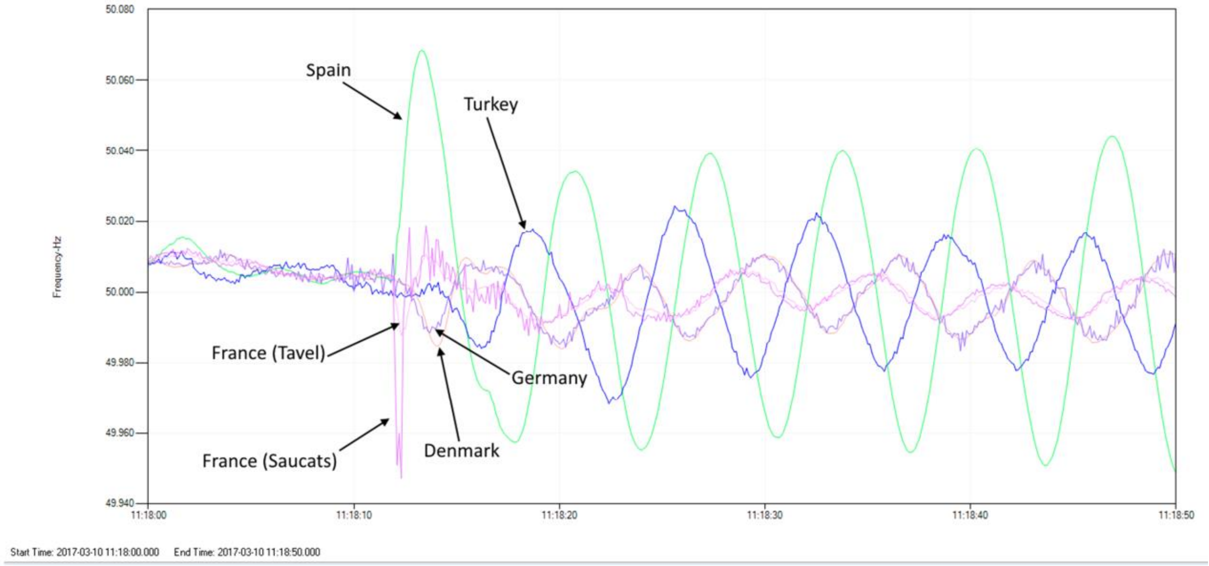
E. Grebe, J. Kabouris, S. López Barba, W. Sattinger, W. Winter, “Low frequency oscillations in the interconnected system of Continental Europe”, Proc. IEEE/PES General Meeting, 2010, pp. 1-7

Inter-area oscillations in the Continental Europe power system

- Incident of 1st December 2016
  - » East-Centre-West, with an oscillation frequency of 0.15 Hz, with negative damping ratio during a certain time
  - » This incident highlighted the relevance of electromechanical oscillations in the Continental Europe (CE) power system and of the security measures to guarantee power system stability.

Frequencies in the CE power system





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

Inter-area oscillations in the Continental Europe power system

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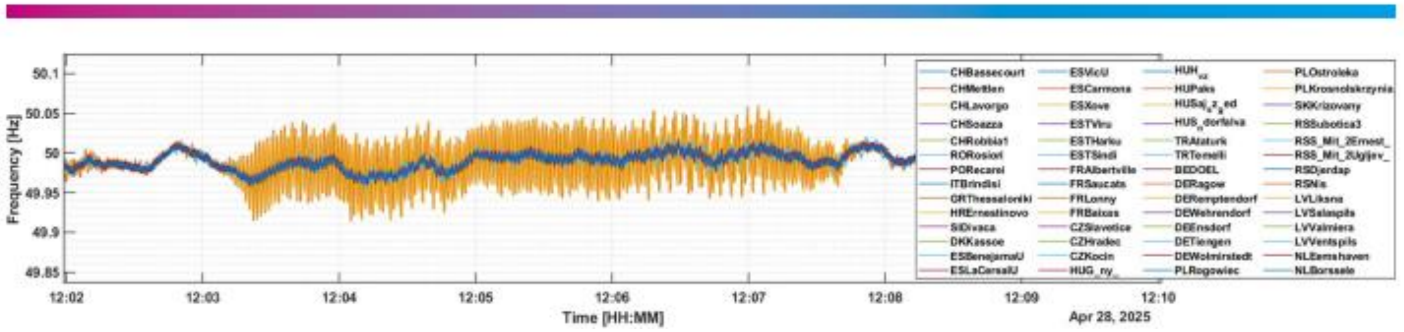
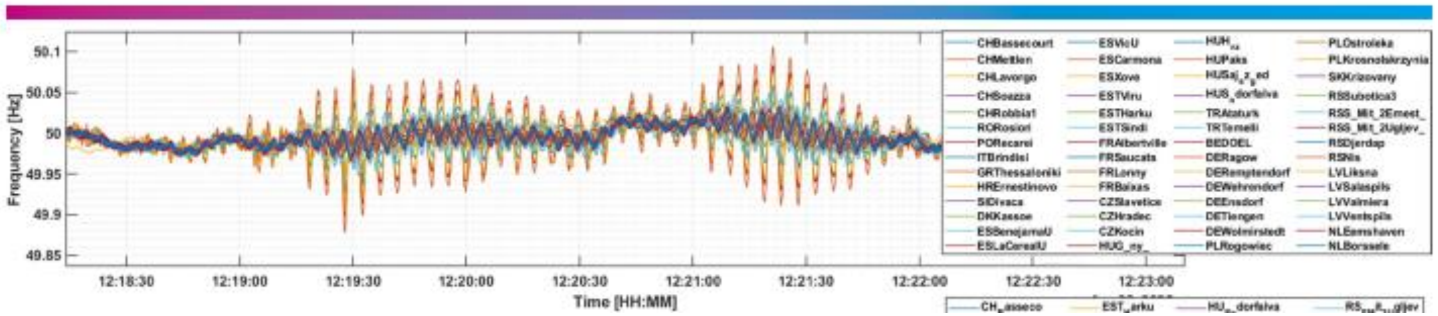
- 28th April 2025 – multifactorial event

Frequencies in the CE power system

0.63 Hz oscillation linked to a certain area (not an inter-area oscillation) (12:03pm-12:08pm)



0.2 Hz inter-area oscillation (12:19pm-12:22pm)



Figures from [A].

[A] ICS Investigation Expert Panel, "Grid Incident in Spain and Portugal on 28 April 2025 – Factual Report," October 2025.
[B] ICS Investigation Expert Panel, "Grid Incident in Spain and Portugal on 28 April 2025 – Final Report," March 2026.

Power oscillation damping controllers (POD) in power converters

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- POD controllers in power converters can be an effective solution to damp electromechanical oscillations
- Key idea: *a POD controller without a proper tuning is nothing*.

- POD controllers in two different contexts:
  - POD controllers in facilities owned by the Transmission System Operator (TSO)
    - POD tuning is carried out together by the supplier and the TSO, according to power system needs
    - Data of the large-scale power system available
  - POD controllers in facilities owned by other stakeholders
    - POD controllers in the context of massive integration of power converters (PPMs, EMS-PPMs, etc…)
    - In general, stakeholders do not have access to the dynamic model of the large-scale power system due to confidentiality (data of critical infrastructure, third parties' data, etc…)
    - Challenge: In the context of massive integration of power converters, How can we guarantee that they are implemented with a proper POD?
    - Need: Guidelines for the implementation of POD controllers, compliance criteria and collaboration between the different stakeholders of the power system.

Working group: Implementation of POD controllers (Spain)

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- Working group at Spanish National level (so-called GT_POD) for guidelines for the implementation of Power Oscillation Damping (POD) controllers
  - Took place between June 2023 – June 2024:
  - Participants: Different stakeholders of the electrical energy sector in Spain (Spanish Government, TSO, DSOs, generation, manufacturers, etc…)
  - Objectives:
    - Specification of the technical capabilities of POD controllers (document).
    - Have a common and agreed vision on this type of controllers, their technical specifications and acceptance criteria, their potential implementation and their particularities depending on the technology.
    - Evaluation of the performance of POD controllers (simulations).
    - Alignment with regulatory proposals at National and European level (NC RfG2).
  - POD controllers in:
    - Power Park Modules (PPM)
    - Electricity Storage Modules (ESM) of type PPM (ESM-PPM): standalone or hybrid facilities.
    - The document only deals with POD controllers in power converters with grid-following (GFL) control mode.

Working group: Implementation of POD controllers (Spain)

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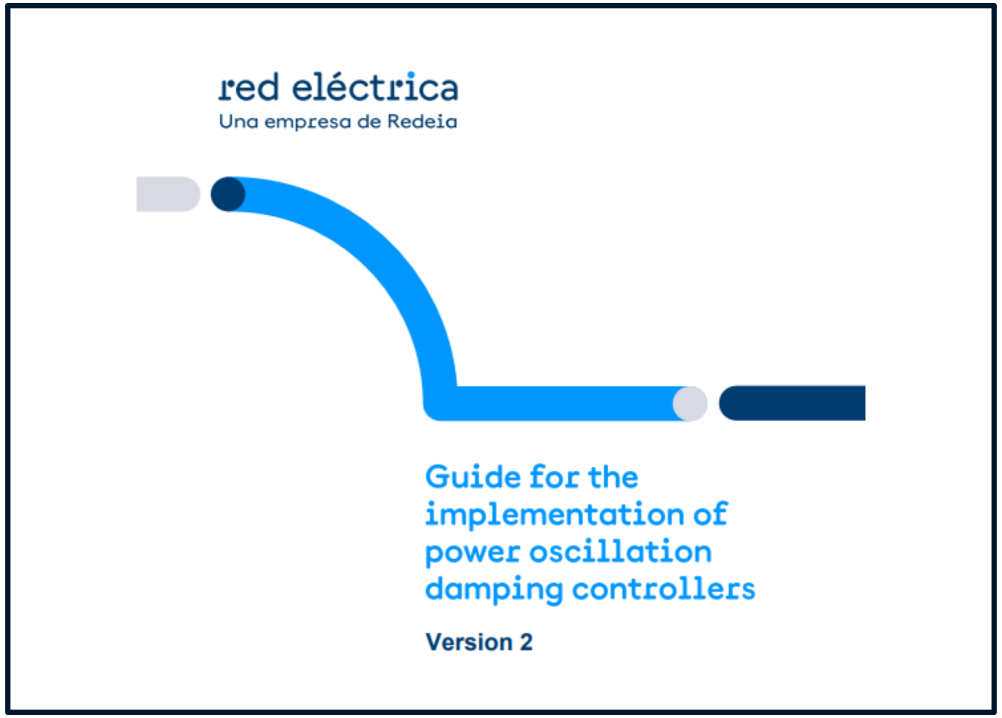
- Document **“Guide for the implementation of power oscillation damping controllers”** published in June-2024.
  - » ENG: “Guide for the implementation of power oscillation damping controllers” (**GT_POD guide**, for short)
  - » https://www.ree.es/sites/default/files/12_CLIENTES/Documentos/GT_POD_guia_implementacion_controles_POD_EN.pdf



Red Eléctrica (Coordinator), “Guide for the implementation of power oscillation damping controllers,” https://www.ree.es/sites/default/files/12_CLIENTES/Documentos/GT_POD_guia_implementacion_controles_POD_EN.pdf (last access: 3-9-2026), Sep , Spain, 2024.

See also:
J. Renedo, M. Martín Almenta, S. Martínez Villanueva, A. Díaz-García, A. Cordón, D. Gotti, “Guidelines for the implementation of power oscillation damping controllers in power converters,” Proc. CIGRE Paris Session, C4-PS1, Paper ID 11445, Paris, France, 23-28 August 2026, pp. 1-15.

Technical requirements of POD controllers according to regulation

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	European regulation	Spanish regulation
PPM	The PPM (type D) shall be equipped with POD controllers: either only POD-P, or only POD-Q or both (POD-PQ) (NC RfG2 draft [C]). The PPM (type C): The TSO may request POD controllers, as above.	Currently: The PPM (types C and D) shall not have a negative impact on the damping of power oscillations. No explicit POD controllers are required mandatory (Orden TED-749-20 [B]). Proposed by the TSO: The PPM (types C and D) shall be equipped with POD-P and POD-Q controllers (draft [D]).
ESM-PPM	The ESM-PPM (type D) shall be equipped with POD controllers: either only POD-P, or only POD-Q or both (POD-PQ) (NC RfG2 draft [C]). The ESM-PPM (type C): The TSO may request POD controllers, as above.	The ESM-PPM (types C and D) shall be equipped with POD-P and POD-Q controllers (draft [D]).
HVDC	The HVDC system shall be capable of contributing to the damping of power oscillations in connected AC networks. Not explicit POD controllers are required [A].	HVDC systems shall be equipped with POD-P and POD-Q controllers (Orden TED-749-20 [B]).
FACTS	No explicit requirement of POD controllers for FACTS.	They are treated as additional components of the power-generating module (ACPGM), according to NTS standard. Therefore, technical requirements of power oscillation damping apply to the aggregated PPM/ESM-PPM (no not decrease the damping ratio of power oscillations).

[A] 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.

[B] 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.

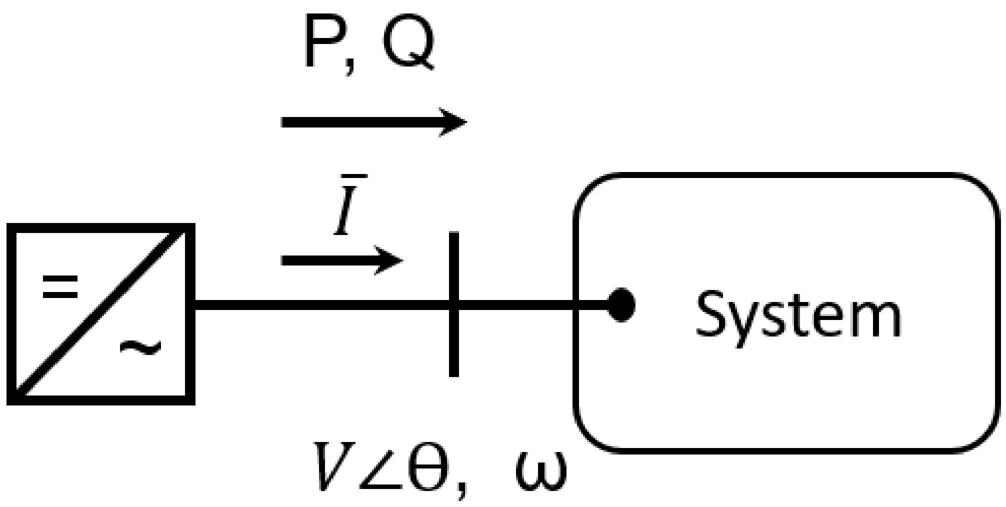
[C] European Commission, “Network code on requirements for grid connection of generators – revision (draft),” (https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/14165-Network-code-on-requirements-for-grid-connection-of-generators-revision_en, last access 4-9-2024), Brussels, Belgium, July, 2026 (NC RfG2 – draft).

[D] Gobierno de España, “Proyecto de Real Decreto por el que se establecen requisitos mínimos de diseño equipamiento, funcionamiento y seguridad de las instalaciones que se conecten a las redes de transporte y distribución de energía eléctrica.,” Ministerio para la Transición Ecológica y el Reto Demográfico (MITERD), www.miteco.gob.es (accessed 9-4-2026), Spain, Feb. 2026.

POD controllers

POD controllers

- A grid-following (GFL) device connected to the grid is considered
  - Generic power converter (specific aspects related to technology or POD-controller implementation are treated separately).
  - Active (P)- and reactive (Q)-power control is assumed for illustrative purposes



POD controllers

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- POD controllers
  - » Active-power modulation (POD-P)
  - » Reactive-power modulation (POD-Q)
  - » Simultaneous active- and reactive-power modulation (POD-PQ)

- POD-P and POD-Q controllers should be:
  - » Effective
  - » **Robust**

- In general, POD-P and POD-Q controllers could have:
  - » Different input signals (frequency deviation, voltage, remote signals, etc…)
  - » Different control structures
  - » Technical capabilities of POD controllers should be **technology agnostic** and **tuning-method agnostic**

POD controllers

- POD-P and POD-Q controllers
  - Reference for P injection: $P^* = P_0 + \Delta P^{ref,POD}$
  - Reference for Q injection: $Q^* = Q_0 + \Delta Q^{ref,POD}$

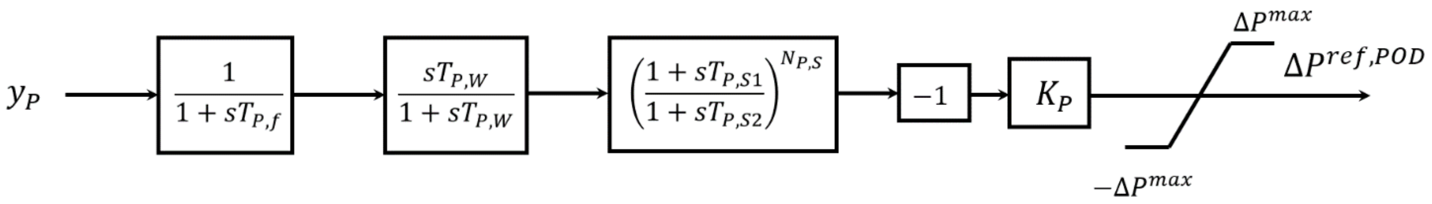
  - A common option for the input signal of POD-P and POD-Q controllers is the frequency deviation at the connection point:

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

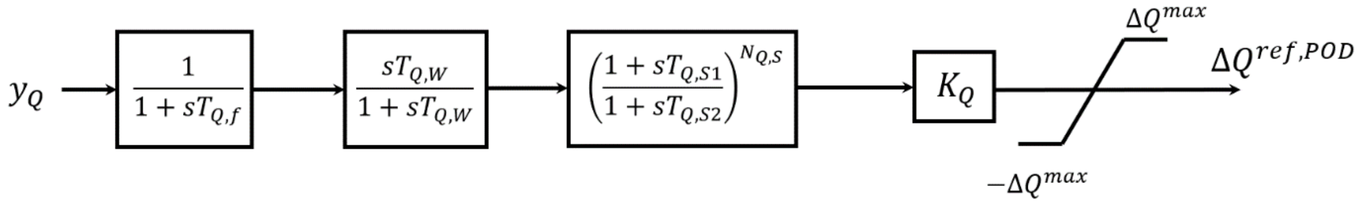
where: $\Delta\omega = \omega - \omega_0$ with $\omega_0 = 1$ pu

Commonly-used block diagrams

POD-P



POD-Q



An activation threshold is allowed for POD-P controllers in ESM-PPM systems: Amplitude an oscillation seen in the bus frequency greater than a certain threshold (to reduce charge/discharge cycles)

POD controllers

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- POD-P control. Parameters. Input signal: $y_P = \Delta\omega$ (pu).

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: $\pm\Delta P^{max} = \pm 10$ %.
	$\hat{f}_{thr}$	Activation threshold	Fixed	Only for ESM-PPM Typical values within $\hat{f}_{thr} = 0 - 40$ mHz. Reference value: $\hat{f}_{thr} = 15$ mHz.

POD controllers

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- POD-Q control. Parameters. Input signal: $y_Q = \Delta\omega$ (pu)

Controller	Parameter	Description	Design/fixed	Comment
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 in some cases, yes. Factors that could have influence in the required phase compensation are: how fast the reactive-power controller of the device is and the grid (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: $\pm\Delta Q^{max} = \pm 10$ %.

Additional considerations.

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- POD-controller options
  - » At Power Park Controller (PPC) level
  - » At converter level (Power Generation Unit, UGE)

- POD-controller input signals
  - » Frequency (or frequency deviation)
  - » Voltage magnitude
  - » Remote signals
  - » Other measurements (power flow, current, etc…)

Input signal for POD-P and POD-Q controllers preferred, due to its robustness properties.

- Signal processing and delays of the POD-controller input signals and modelling
  - » In case that it has relevant impact, dynamic models of POD-P and POD-Q controllers shall include a realistic representation of the signal processing and delays of the input signal.

Additional considerations.

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- POD-P and POD-Q controller variants
  - » Different block diagrams
  - » Different input signals (frequency, voltage, etc…)
  - » Input signal: local or remote measurements.
  - » Parameters: fixed or adaptive
  - » Different variants

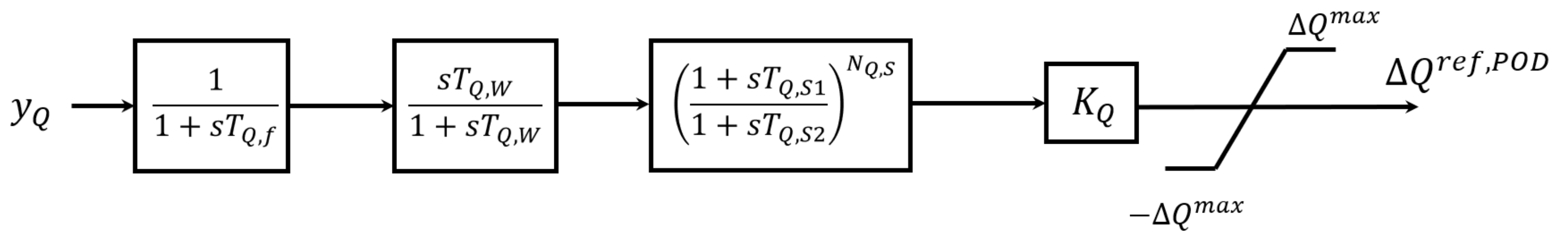
- In general, the Spanish System Operator (SO) will consider valid any variant of POD-P and POD-Q controllers as long as that their effectiveness and robustness are guaranteed
  - » POD controllers following the proposed guidelines and compliance with technical specifications: They will be accepted by the Spanish SO.
  - » POD controllers based on other variants: The Spanish SO will analyze both the POD controllers and the studies, to determine their acceptance.

- Specific aspects related to power modules connected to the Iberian Peninsula (SEPE) or the Spanish Islands (SENP), or specific aspects of ESM-PPMs are detailed in the GT_POD guide.

Additional considerations.

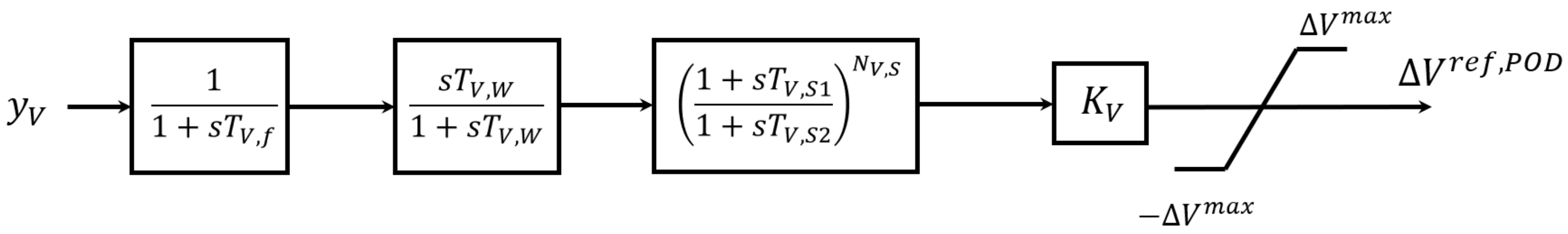
- POD-Q-controller variants in voltage control mode (V-mode)
  - » POD-Q - Option 1: Discussed previously: V setpoint is traduced in a Q setpoint

POD-Q (Opción 1)



  - » POD-Q - Option 2: Another option POD-Q in voltage control mode (V-mode). Supplementary setpoint directly included into the voltage set point (POD-V)

POD-Q (Opción 2, POD-V)



Technical specifications for POD controllers

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- POD-controller parameters shall be consistent with the ranges described in Table 4 of GT_POD document. In addition, POD-controller parameters shall comply with technical specification of the following table:

Control	Comment	Parameter
POD-P	POD-P controller according to the general scheme.	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.
	Only for ESM-PPM. POD-P controller, according to the general scheme.	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.
POD-Q	POD-Q controller according to the general scheme. (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.
	POD-Q controller variant applied to a voltage reference (POD-V) (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.

Evaluation of the performance of POD controllers

Evaluation of the performance of POD controllers.

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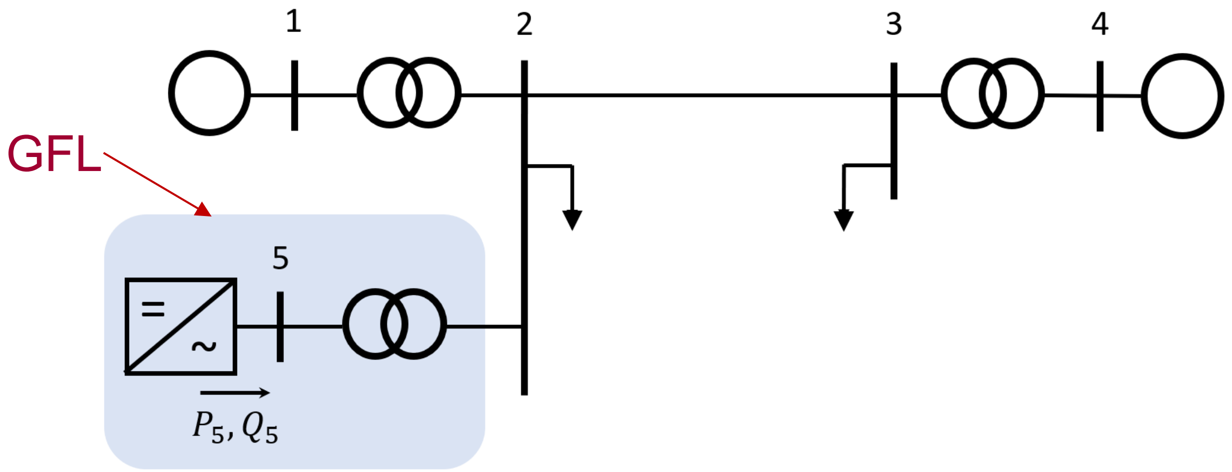
- According to the Spanish Compliance Monitoring Technical Standard (Norma Técnica de Supervisión, **NTS**)
  - **Proposal to include specific evaluation for POD controllers in the NTS (to be evaluated by GTSUP working group).**
- Two-area synthetic system (NTS)
- Comparison of the following cases
  - B0: Base case, only synchronous generators (SG) and without GFL.
  - B1: Base case, with GFL without POD controllers.
  - B2: Base case, with GFL with POD-P controller.
  - B3: Base case, with GFL with POD-Q controller.
  - B4: Base case, with GFL with POD-P and POD-Q controllers (POD-PQ).



Line reactance, $X_L = X_{23}$, is used to change the frequency of the electromechanical oscillation: range $X_L = 0{,}01 - 0{,}6$ pu.

NTS:

[J] Red Eléctrica de España, Aelec, Grupo Naturgy, Cide, and Aseme, “Technical standard for monitoring the compliance of power generating modules according to EU regulation 2016/631,” 2022.

Evaluation of the performance of POD controllers.

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- Two possibilities for simulation
  - Small-signal stability analysis (eigenvalues)
  - Time-domain simulation

- Acceptance criteria for POD controllers (non-binding)
  - **Acceptance criterion 1**: Acceptance criterion for the **robustness of the POD controller**.
  - **Acceptance criterion 2**: Acceptance criterion for the **effectiveness of the POD controller**.

It is important to highlight that the method to evaluate the performance of POD controllers and compliance criteria presented in this paper has not regulatory value, it is just part of the guidelines for good practices of the implementation of POD controllers proposed in the guide for the implementation of power oscillation damping controllers [A].

[A] Red Eléctrica (Coordinator), “Guide for the implementation of power oscillation damping controllers,” https://www.ree.es/sites/default/files/12_CLIENTES/Documentos/GT_POD_guia_implementacion_controles_POD_EN.pdf (last access: 3-4-2025), Sep , Spain, 2024.

Evaluation of the performance of POD controllers.

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- **Acceptance criterion 1: Acceptance criterion for the robustness of the POD controller**
  - Small signal stability analysis (eigenvalues) (procedure and acceptance criteria detailed in sections 5.10.2.1 and 5.10.3.1 of [A], 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 [A], respectively).

- Line reactance: range $X_L = 0.01 - 0.6$ pu

[A] NTS:
Red Eléctrica de España, Aelec, Grupo Naturgy, Cide, and Aseme, “Technical standard for monitoring the compliance of power generating modules according to EU regulation 2016/631,” 2022.

Evaluation of the performance of POD controllers.

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- **Acceptance criterion 2: Acceptance criterion for the effectiveness of the POD controller**

- Line reactance: range $X_L = 0.6$ pu (which corresponds to an oscillation frequency of de 0.15-0.25 Hz, approximately).

Case	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: $\Delta\varsigma_3 \geq 5$ %.

$$\Delta\varsigma_i = \varsigma_i - \varsigma_{B1}$$

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) (%).

Numerical example

Numerical example

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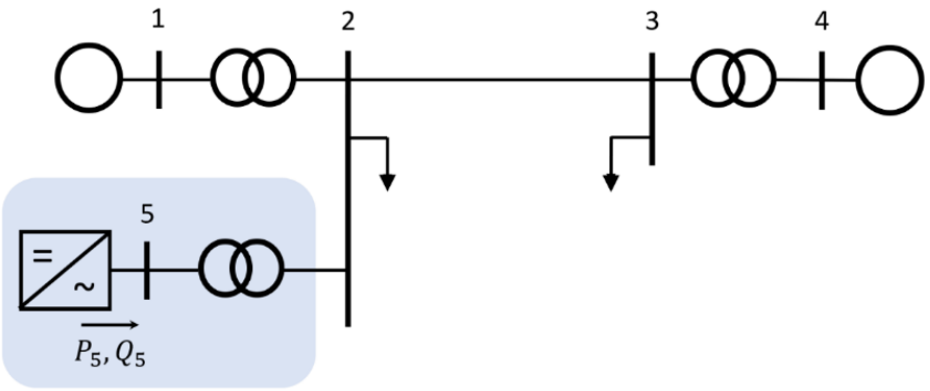
- Synthetic two-area system (NTS)
- Generic model of a GFL-VSC connected to bus 5 (1500 MVA)
- Fundamental analysis for illustrative purposes
  - » Small-signal stability analysis (eigenvalues)
  - » Time-domain simulation
- Proposed synthetic two-area test system for compliance evaluation of POD controllers: synthetic test system and methodology proposed in [A] and in the Spanish technical standard for monitoring compliance (NTS) [B].



Generator	S_B (MVA)	P_G (MW)
1	1500.00	1350.00
4	4000.00	3900.00
5	1500.00	1350.00
Load	P_L (MW)	Q_L (Mvar)
2	2600.00	0.00
3	4000.00	0.00

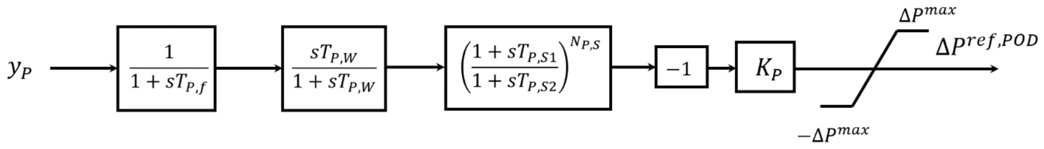
[A] J. Renedo, L. Sigrist and L. Rouco, "Design of power system stabilizers to damp low frequency inter-area oscillations with limited information," in Proc. 13th IEEE/PES PowerTech Conference, Milano, Italy, 23-27 June 2019, pp. 1-6.

[B] Red Eléctrica, Aelec, Grupo Naturgy, Cide, Aseme, "Technical standard for monitoring the compliance of power generating modules according to EU Regulation 2016/631," https://www.esios.ree.es/es/pagina/codigos-red-conexion (last access 23-10-2024), Spain, 2021.

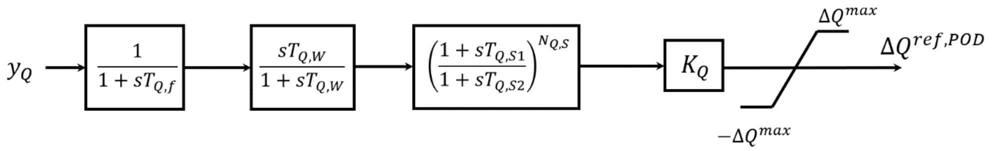
Numerical example

- Comparison
  - B1: Base case: VSC-5 connected and without POD controllers.
  - B2: VSC-5 connected and with POD-P controller.
  - B3: VSC-5 connected and with POD-Q controller.
  - B4: VSC-5 connected and with POD-P and POD-Q controllers.

POD-P



POD-Q



$y_P = y_Q = \Delta\omega$ (pu) donde: $\Delta\omega = \omega - \omega_0$ con $\omega_0 = 1$ pu

- Data
  - System: NTS document [A]
  - POD controllers (Table)

POD-P		POD-Q	
Input: y_P	Frequency deviation: $\Delta\omega = \omega - \omega_0$ (pu)	**Input: y_Q**	Frequency deviation: $\Delta\omega = \omega - \omega_0$ (pu)
K_P	200 pu	K_Q	200 pu
$T_{P,S1}$	0.94	$T_{Q,S1}$	0.49 s
$T_{P,S2}$	1.07 s	$T_{Q,S2}$	1.02 s
$N_{P,S}$	2	$N_{Q,S}$	2
$T_{P,f}$	0.1 s	$T_{Q,f}$	0.1 s
$T_{P,W}$	5 s	$T_{Q,W}$	5 s
$\pm\Delta P^{max}$	±0.1 pu	$\pm\Delta Q^{max}$	±0.1 pu

[A] NTS:
Red Eléctrica de España, Aelec, Grupo Naturgy, Cide, and Aseme, “Technical standard for monitoring the compliance of power generating modules according to EU regulation 2016/631,” 2022.

Numerical example – Sc-A – G1: PSS ON - Test system used for compliance criteria

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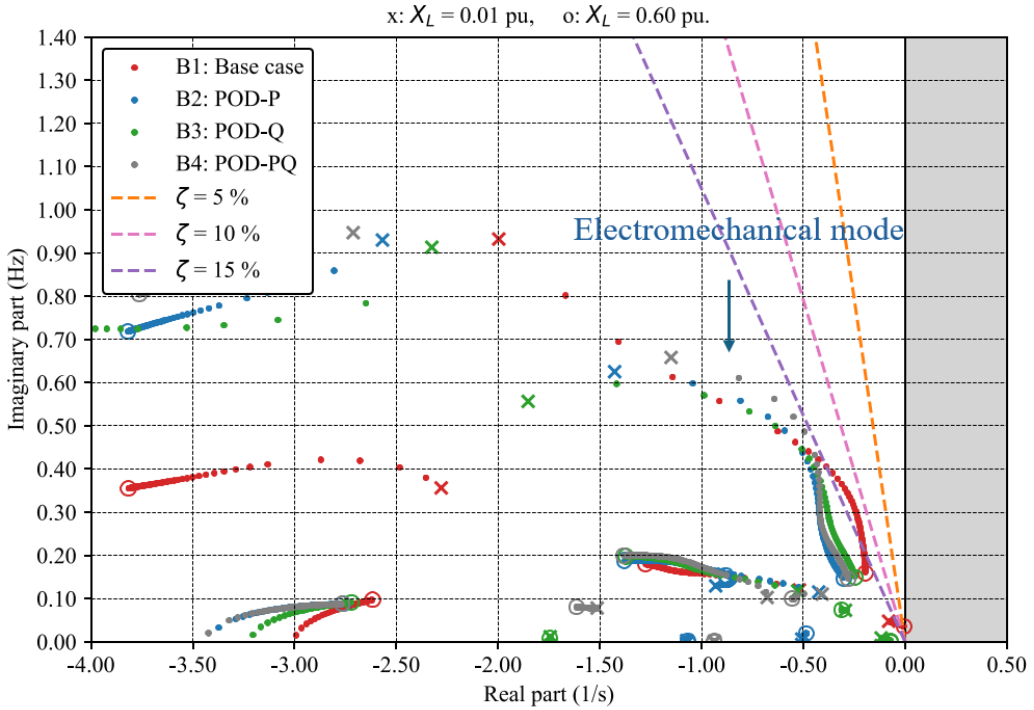
- Small-signal stability analysis (eigenvalues)

POD controllers are effective and robust



	B1: Base case		B2: POD-P		B3: POD-Q		B4: POD-PQ	
X_L (pu)	ζ (%)	f_{mode} (Hz)	ζ (%)	f_{mode} (Hz)	ζ (%)	f_{mode} (Hz)	ζ (%)	f_{mode} (Hz)
0,01	32.26	0.93	40.23	0.93	37.56	0.91	41.47	0.95
0,10	15.83	0.42	18.43	0.38	17.36	0.39	17.62	0.38
0,40	13.55	0.25	26.64	0.21	22.43	0.22	25.53	0.21
0,60	19.17	0.16	31.19	0.15	25.22	0.15	29.18	0.15

$$X_L = 0.6\ pu$$

Case	ς_i (%)	ς_{B1} (%)	$\Delta\varsigma_i$(%)
B2: POD-P	31.19	19.17	12.02
B3: POD-Q	25.22	19.17	6.05
B4: POD-PQ	29.18	19.17	10.01

Numerical example – Sc-A – G1: PSS ON - Test system used for compliance criteria

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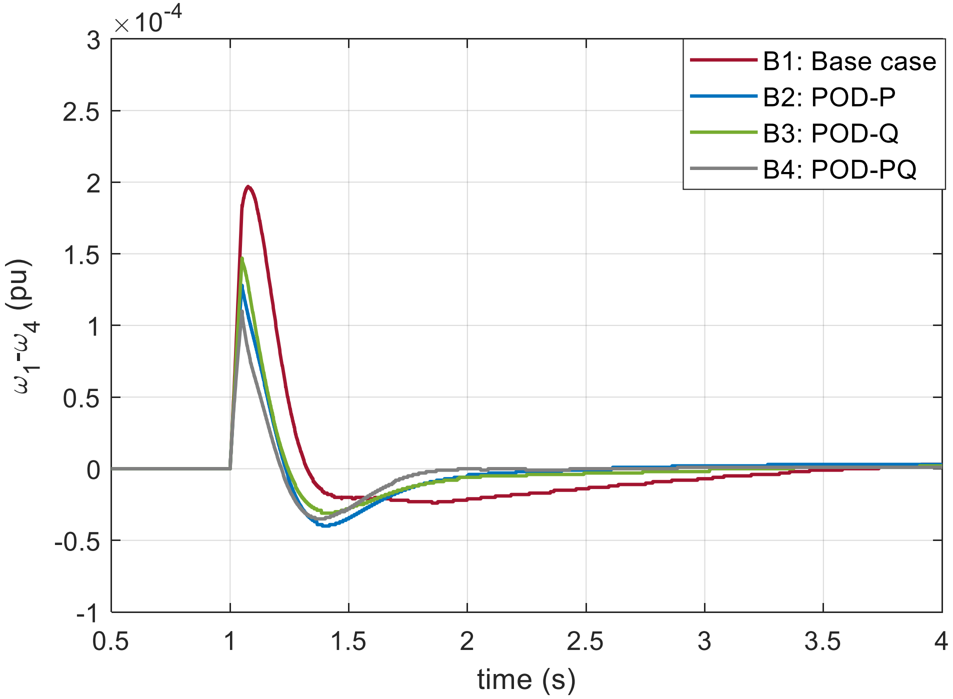
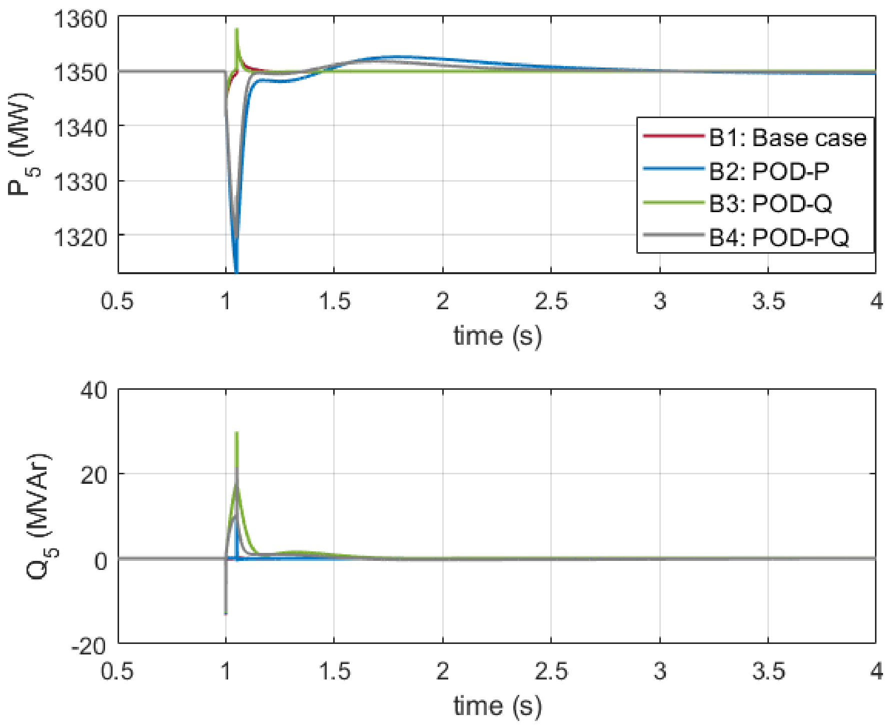
- Time-domain simulation
  - » Small disturbance: Three-phase-to-ground fault with high impedance, cleared after 50ms

POD controllers are effective and robust

Difference of speeds of generators



P and Q injections of VSC-5

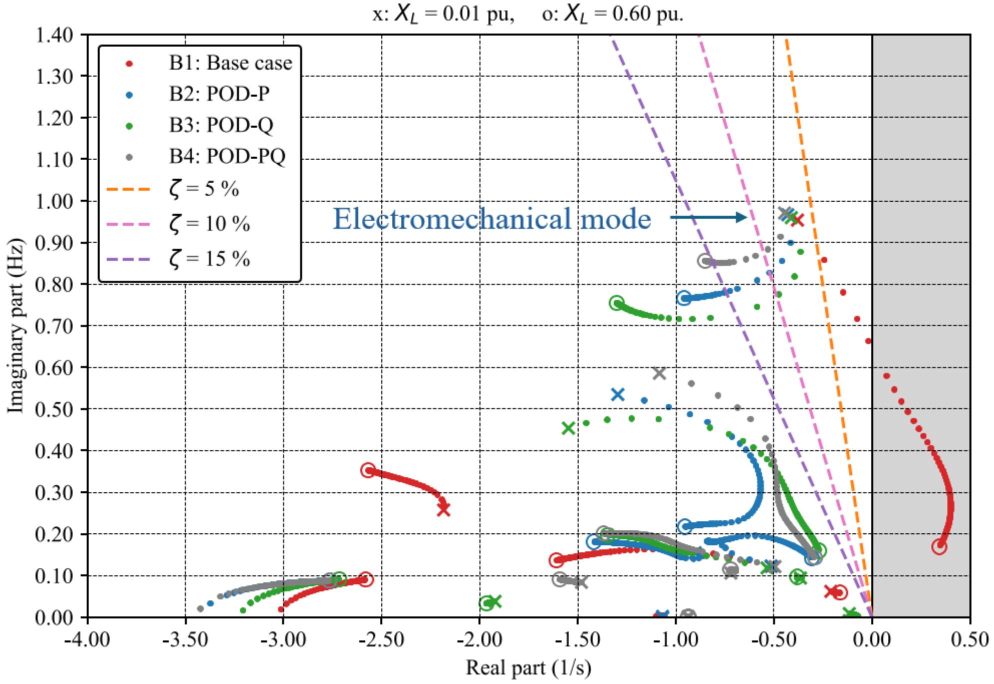


Numerical example – Sc-B – G1: PSS OFF - Test system not used for compliance criteria (just for illustrative purposes)

red eléctrica

- Small-signal stability analysis (eigenvalues)

POD controllers are effective and robust



X_L (pu)	B1: Base case		B2: POD-P		B3: POD-Q		B4: POD-PQ	
	ς (%)	f_{mode} (Hz)	ς (%)	f_{mode} (Hz)	ς (%)	f_{mode} (Hz)	ς (%)	f_{mode} (Hz)
0,01	6.33	0.95	7.05	0.97	6.81	0.96	7.29	0.97
0,10	-5.89	0.49	24.66	0.39	23.00	0.41	20.81	0.38
0,40	-21.77	0.29	45.84	0.20	24.09	0.24	29.07	0.21
0,60	-30.75	0.17	32.61	0.14	26.02	0.16	30.86	0.14

$$X_L = 0.6\ pu$$

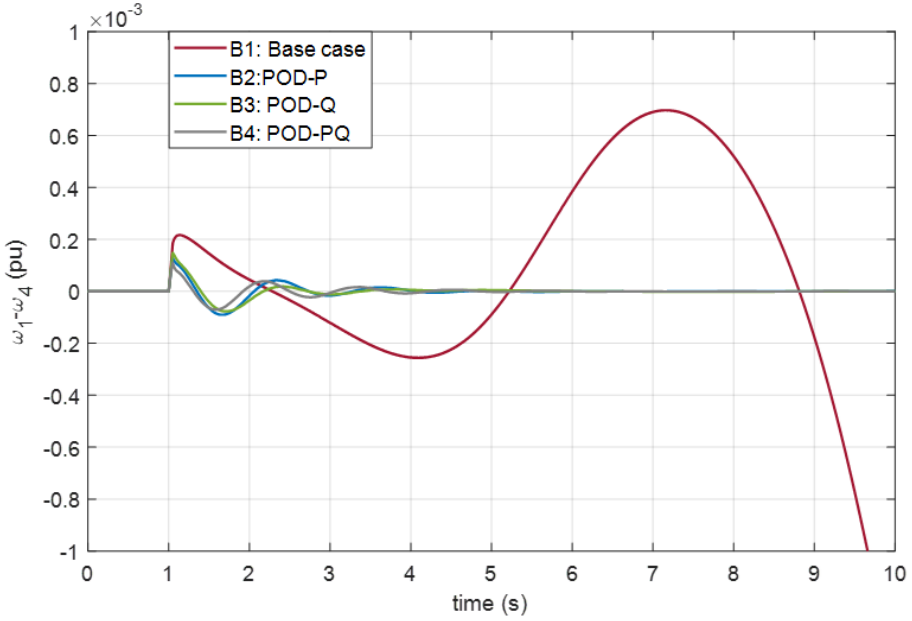
Case	ς_i (%)	ς_{B1} (%)	$\Delta\varsigma_i$(%)
B2: POD-P	32.61	-30.75	63.36
B3: POD-Q	26.02	-30.75	56.77
B4: POD-PQ	30.86	-30.75	61.61

Numerical example – Sc-B – G1: PSS OFF - Test system not used for compliance criteria (just for illustrative purposes)

- Time-domain simulation
  - » Small disturbance: Three-phase-to-ground fault with high impedance, cleared after 50ms

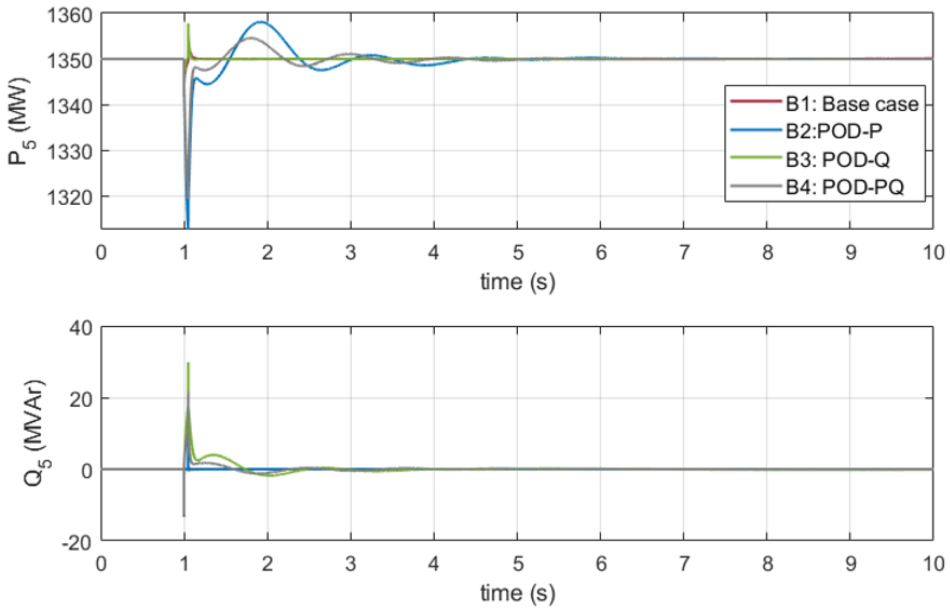
POD controllers are effective and robust

Difference of speeds of generators



(a)

P and Q injections of VSC-5



(b)

Case study: large-scale power system

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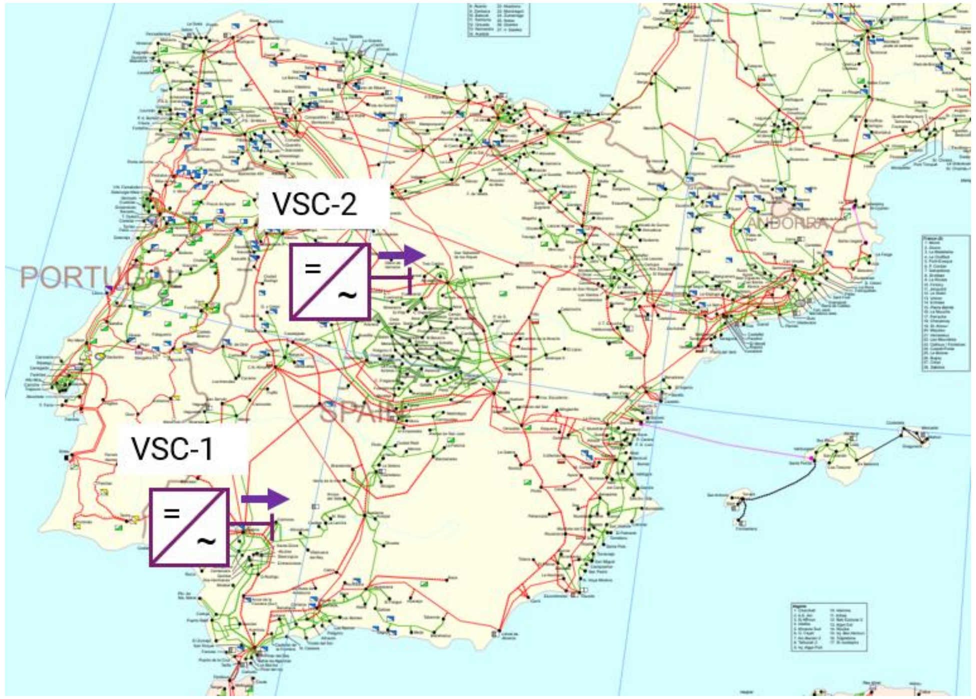
- Two generic VSC converters with GFL control located in arbitrary buses in the Iberian Peninsula power system are considered:
  - » VSC-1 (200 MVA): Located in the southern area of the Iberian Peninsula power system (Carmona 400 kV).
  - » VSC-2 (200 MVA): Located in the central area of the Iberian Peninsula power system (La Cereal 400 kV).
- POD controllers tuned using the NTS synthetic system and tested in the large-scale power system
- Analysis
  - » Scenario selected for the analysis (callibrated to obtain a critical scenario)
  - » Small-signal analysis and non-linear time-domain simulation
  - » PowerFactory-DIgSILENT (RMS models)
  - » Operating point VSC1 & 2: P=Q=0

These two locations of the VSCs were selected arbitrarily, just for illustration purposes in this study and just because they have Phasor Measurement Units (PMU) and their frequencies are often monitored

Key question: *If a POD controller in a power converter is tuned using appropriate synthetic systems, methodologies and compliance criteria, is it still effective when the power converter is connected to a large-scale power system?*



Map from www.entsoe.eu/

Case study: large-scale power system

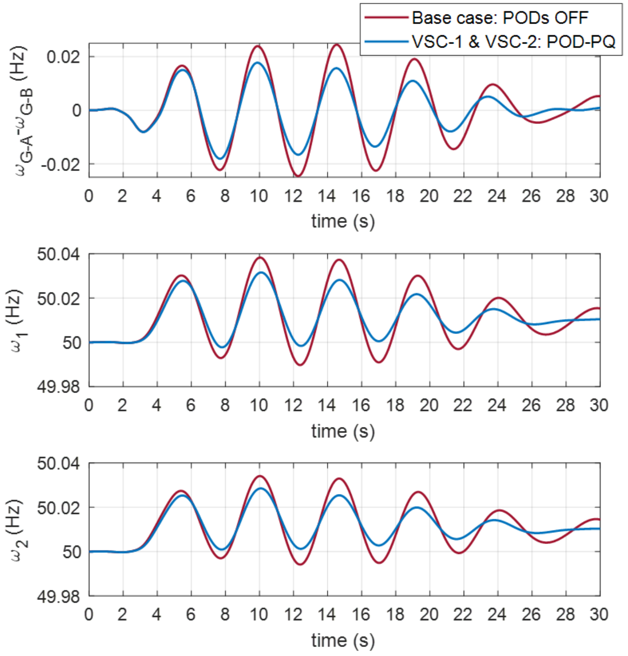
- Results

Small-signal stability analysis (eigenvalues)

Case	ς (%)	f_{mode} (Hz)
Base case: PODs OFF in VSC-1 and VSC-2	1.16	0.20
VSC-1: POD-P	2.56	0.24
VSC-1: POD-Q	1.36	0.20
VSC-1: POD-PQ	2.64	0.24
VSC-2: POD-P	2.18	0.24
VSC-2: POD-Q	1.39	0.20
VSC-2: POD-PQ	2.26	0.24
VSC-1 & VSC-2: POD-PQ	3.17	0.24

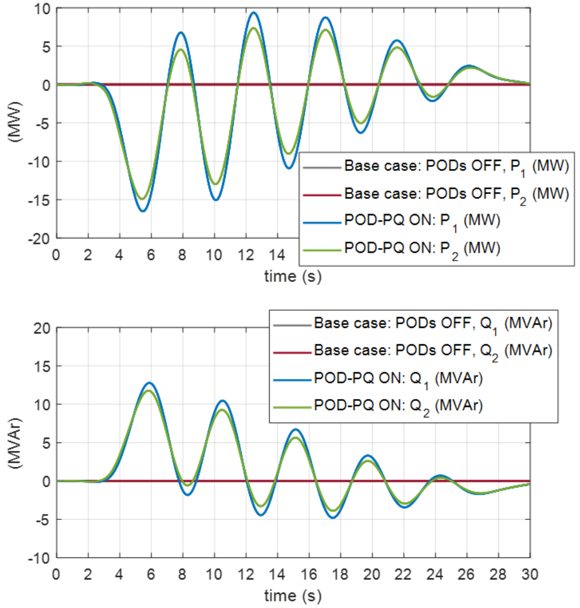
POD controllers are effective and robust

Difference of speeds of generators & frequencies



(a)

P and Q injections of VSCs 1&2



(b)

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INELFE-1 VSC-HVDC link: 2x1000MW Interconnection between France and Spain – POD controllers

INELFE-1 VSC-HVDC link: 2x1000MW Interconnection between France and Spain

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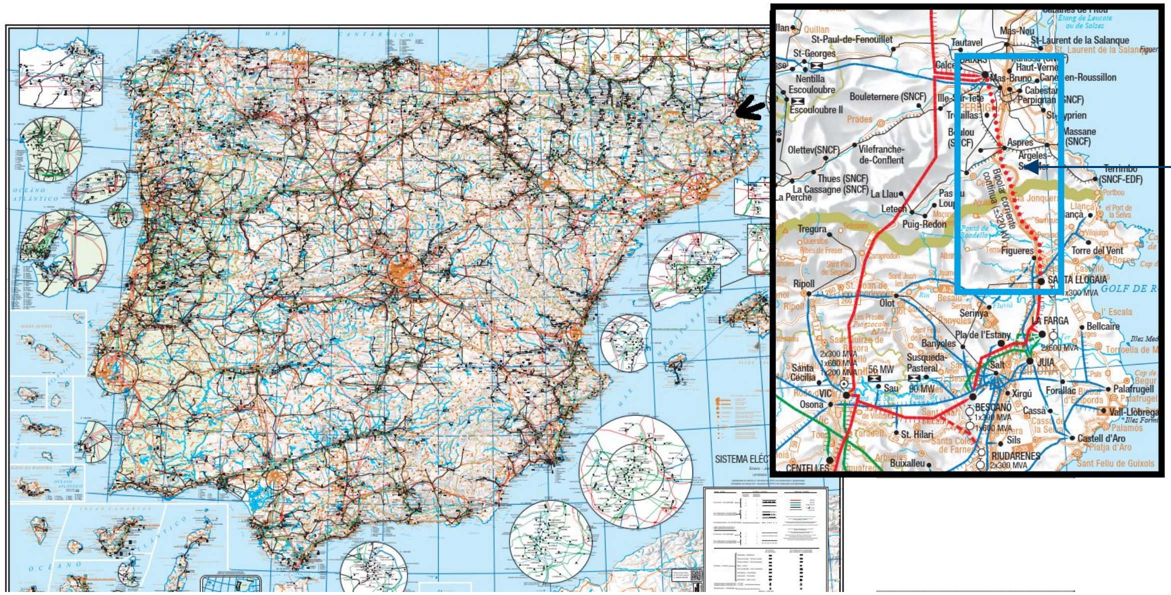

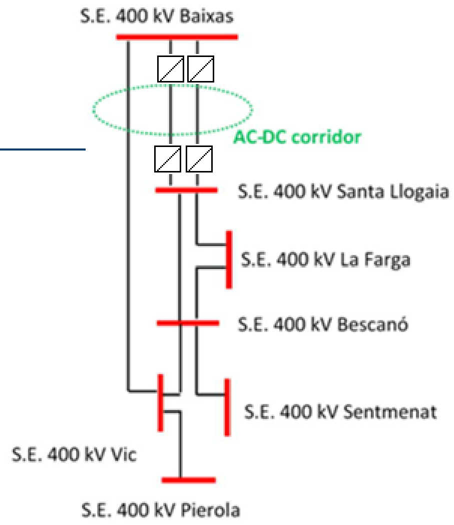

The VSC-HVDC system is equiped with Power Oscillation Damping (POD) controllers, for active-power and reactive-power modulation (POD-P and POD-Q)

Example of a POD controller in a facility owned by the Transmission System Operator (TSO).

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Two operatgion modes:

Constant active power control (CPC)

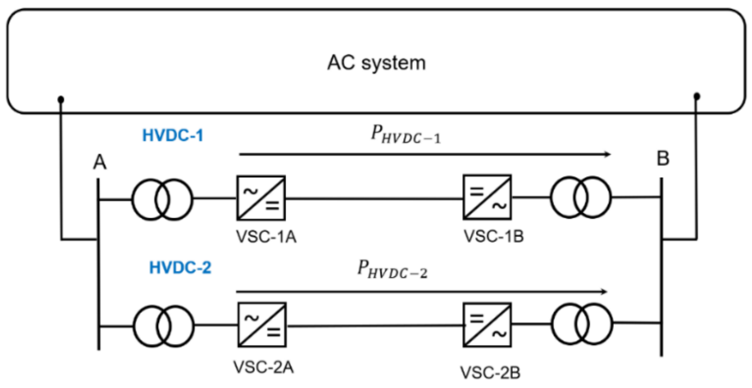
$$P^*_{HVDC-i} = P_0 + \boxed{\Delta P^{ref,POD}}$$

Angle difference control (ADC)

$$P^*_{HVDC-i} = P_0 + \Delta P^{ref,ADC} + \boxed{\Delta P^{ref,POD}}$$

$$\Delta P^{ref,ADC} = \frac{K}{1 + s\tau}(\delta_A - \delta_B)$$

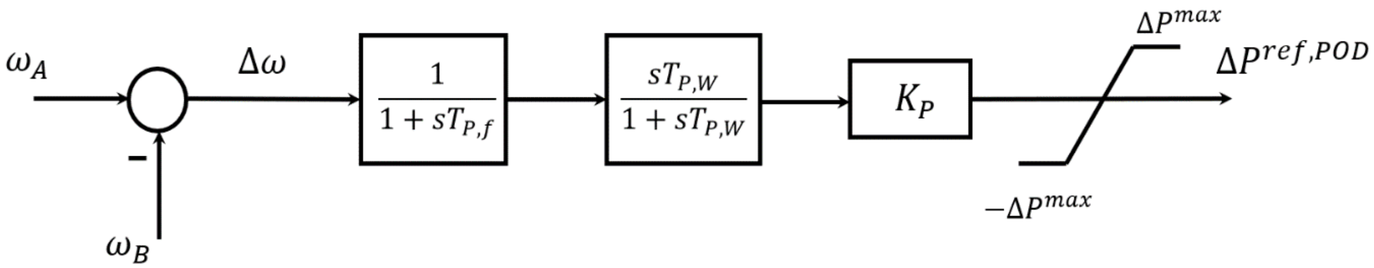
Originally, the control system had a logic condition to disable POD-P controller when using ADC



Parameter	Description	Value
P_0	Constant active-power set point	0 MW
K	Gain of ADC	180 MW/deg
τ	Time constant of ADC	50 s

POD-P controller

Supplementary controller used to damp electromechanical oscillations by means of active-power modulation through the VSC-HVDC link



Para meter	Description	Value
K_P	Controller gain	Original: 500 MW/Hz New: 2500 MW/Hz
$T_{P,f}$	Time constant of the low-pass filter	0.15 s
$T_{P,W}$	Time constant of the wash-out filter	2.5 s
$\pm\Delta P^{max}$	Saturation parameter	$\pm$100 MW

Parameters per link

Modifications made on POD-P controller (during 2022)

- Increase of the gain of POD-P controller from K=500 MW/Hz/link to K=2500 MW/Hz/link, in order to make it more effective
- Modifications in the logic rules in order to allow the activation of POD-P controller when operating the HVDC link in Angle Difference Control (ADC)

This is feasible, because ADC is operated as a slow control ($\tau = 50$ s)

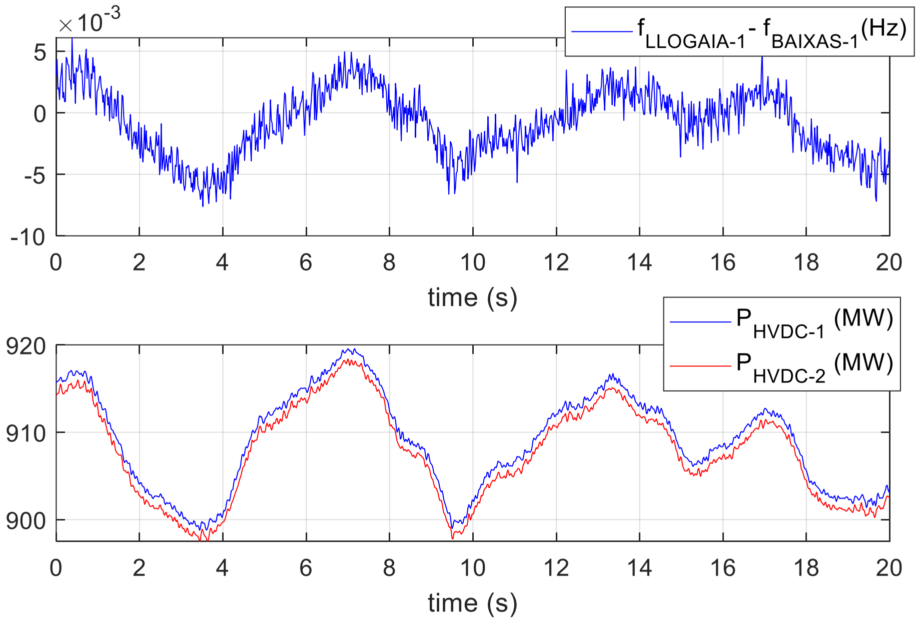
Validation:

Power system studies
Hardware-in-the-loop tests
Field tests

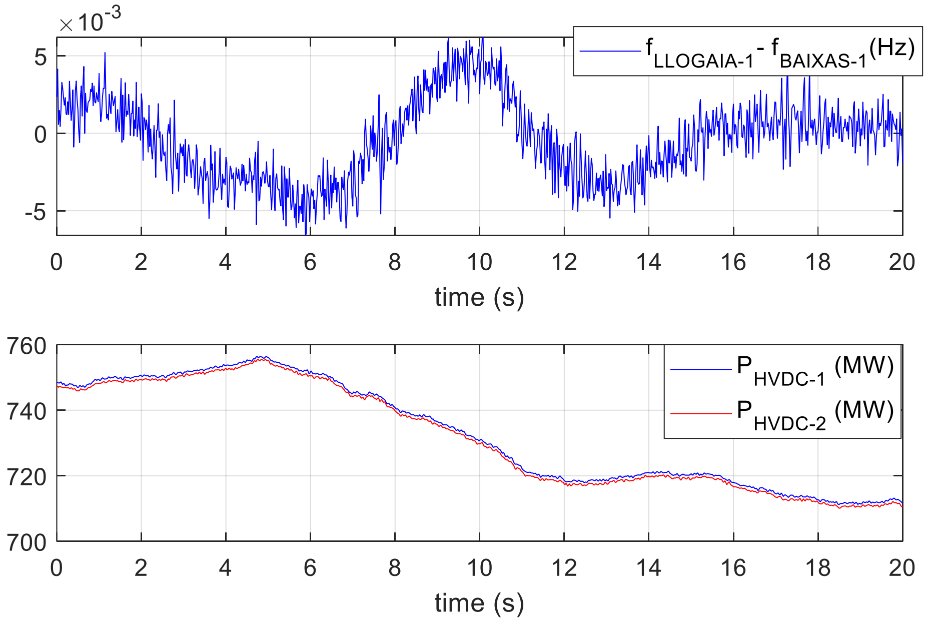
More information can be found in:
J. Renedo, A. Diaz-García, G. Torresan, E. Lorenzo Cabrera, A. Cordón, S. Sanz Verdugo, J. Peiró, J. Pérez Castro, G. Calvo, A. Hernández Sautua, A. Petit, H. Oukhayi, S. Akkari and H. Saad, "Tests on the POD-P controller of INELFE Spain-France VSC-HVDC interconnector," in Proc. CIGRE B4 International SC Meeting and Colloquium, paper B4-1145, Vienna, Austria, 11-15 Sep, 2023, pp. 1-15.

Test 1: POD-P in CPC/ADC modes

Test 1-a: CPC + POD-P



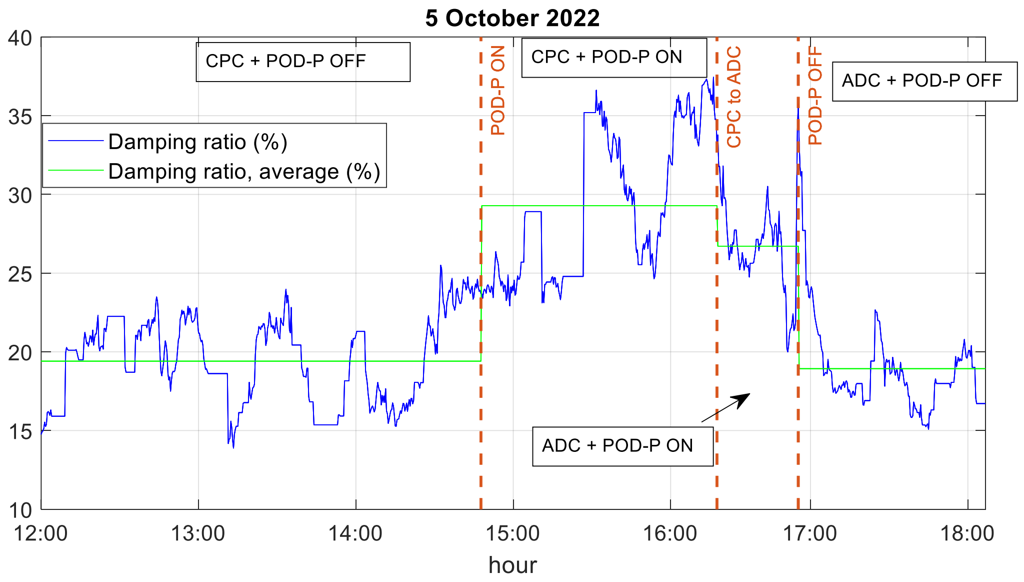
Test 1-b: ADC + POD-P



Correct behaviour of POD-P controller

Test 1: POD-P in CPC/ADC modes

Damping ratio of the inter-area mode (East-Centre-West mode, 0.15-0.25 Hz)



Damping ratio of the inter-area mode obtained from PMUs

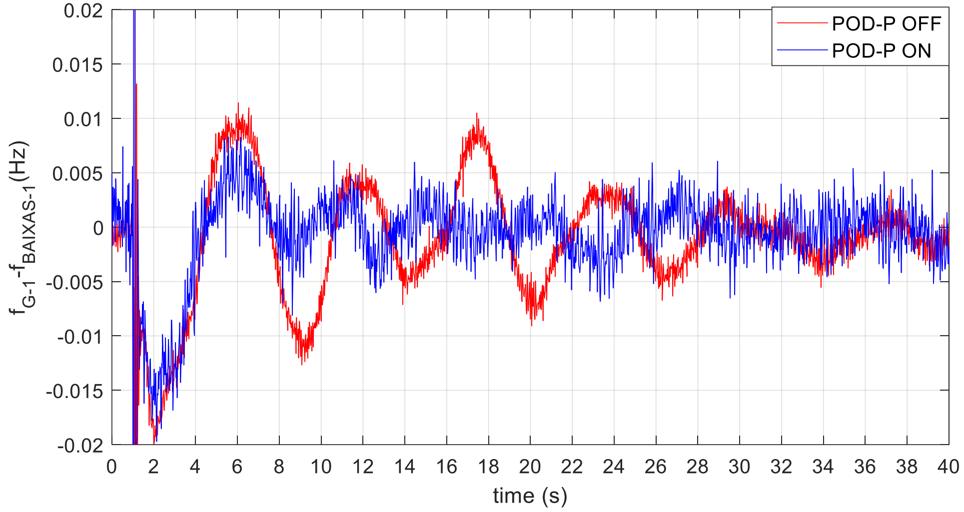
Test		Time	Average damping ratio (%)
CPC	POD-P OFF	12:00h – 14:47h	19.40
	POD-P ON	14:47h – 16:17h	29.28
ADC	POD-P ON	16:17h – 16:48h	26.71
	POD-P OFF	16:48h – 18:00h	18.93

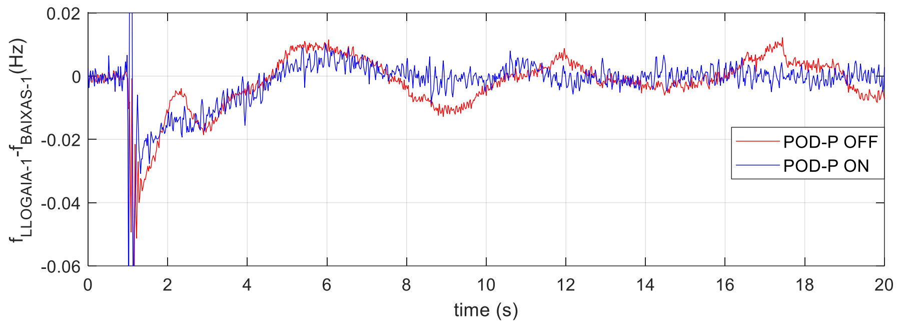
- Damping ratio of the inter-area mode is increased when using POD-P controller in both CPC and ADC
- It is difficult to identify the effect of the POD-P controller itself, because the power system conditions have impact on the damping ratio of the inter-area mode

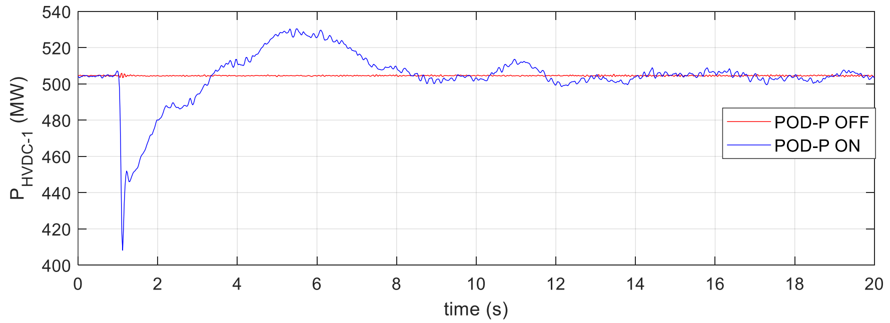
Test 2: Tests of POD-P control under the disconnection of line Vic-Baixas 400 kV

Test 2-a: CPC + POD-P

Difference between the frequency close to a generator in Spain and the frequency at Baixas 400 kV substation







Results show that the POD-P controller is effective to damp inter-area oscillations

Conclusions

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- Power oscillation damping (POD) controllers in power converters can contribute to damp electromechanical oscillations

- Key aspect: POD tuning

- Guidelines for the implementation of POD controllers:
  - Objective: To have a common and consensual understanding among the different stakeholders of the electrical energy sector on POD controllers.
  - Guidelines for the implementation of POD controllers in PPMs and ESM-PPMs.
  - Technical capabilities of POD controllers and compliance criteria of POD controllers.

- POD controllers can be implemented in facilities owned by the TSO or in facilities owned by other stakeholders
  - The philosophy of POD controllers is the same
  - Implementation aspects of POD controllers may may have different challenges

Contributors of this work

Thank you to all contributors of this work:

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Agustín Díaz García

Antonio Cordón

Davide Gotti

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[4] European Commission, “Network code on requirements for grid connection of generators – revision (draft),” (https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/14165-Network-code-on-requirements-for-grid-connection-of-generators-revision_en, last access 4-9-2024), Brussels, Belgium, July, 2026 (NC RfG2 – draft).

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[7] 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, pp. 1-6.

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[10] ICS Investigation Expert Panel, "Grid Incident in Spain and Portugal on 28 April 2025 – Factual Report," October 2025.

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[12] J. Renedo, M. Martín Almenta, S. Martínez Villanueva, A. Díaz-García, A. Cordón, D. Gotti, “Guidelines for the implementation of power oscillation damping controllers in power converters,” Proc. CIGRE Paris Session, C4-PS1, Paper ID 11445, Paris, France, 23-28 August 2026, pp. 1-15..

Questions?

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El valor de lo esencial

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