



HAL
open science

A new benchmarking method for the study of dynamic interactions in island power systems with hybrid conventional and inverter-based resources controlled in grid-forming mode

Pamela Zoghby, Bogdan Marinescu, Antoine Rossé

► To cite this version:

Pamela Zoghby, Bogdan Marinescu, Antoine Rossé. A new benchmarking method for the study of dynamic interactions in island power systems with hybrid conventional and inverter-based resources controlled in grid-forming mode. 2nd International Conference on Renewable Energies and Smart Technologies (REST 2024), Jun 2024, Prishtina, Kosovo. hal-04670312

HAL Id: hal-04670312

<https://hal.science/hal-04670312>

Submitted on 12 Aug 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

A new benchmarking method for the study of dynamic interactions in island power systems with hybrid conventional and inverter-based resources controlled in grid-forming mode

Pamela Zoghby
Electricité de France (EDF R&D)
Palaiseau, France
Ecole Centrale Nantes
CNRS, LS2N UMR 6004, Nantes
pamela.zoghby@edf.fr

Bogdan Marinescu
Nantes université
Ecole Centrale Nantes
CNRS, LS2N UMR 6004
Nantes, France
bogdan.marinescu@ec-nantes.fr

Antoine Rossé
Electricité de France (EDF R&D)
Palaiseau, France
antoine.rosse@edf.fr

Abstract—This paper presents a novel methodology for detecting and analyzing oscillation modes resulting from interactions between synchronous machines (SMs) and inverter-based resources (IBRs). The methodology utilizes a conceptual benchmark specifically designed to identify various oscillation modes, particularly those involving SMs and IBRs in a minimal order model for any power system. These phenomena can be studied by adapting the benchmark to represent any power system - in this paper a French island power system - where the IBR is controlled in grid-forming mode. In this system, oscillations among its generation sources raise concerns for the grid operator, necessitating comprehensive studies to understand potential stability and safety risks. The benchmark is linearised around an operating point and the type of each detected mode is identified through calculation of participation factors. The impact of key parameters on the damping of the modes is studied through sensitivity analyses. Nonlinear time-domain simulations, based on electromagnetic transient (EMT) modeling using EMTP-RV software are employed to validate the linearised model of the benchmark. Finally, a power oscillation damping (POD) controller installed on the inverter is proposed to mitigate critical oscillation modes.

Index Terms—Grid-forming control, Modal Analysis, Synchronous Machine, Conceptual Benchmark, Inverter Based Resources, Interactions

I. INTRODUCTION

As power systems transition towards cleaner energy sources, integrating both synchronous machines (SMs) and inverter-based resources (IBRs) like photovoltaics (PV), battery energy storage systems (BESS), and wind turbines, the dynamics of SMs may interact with the inverter controls, introducing new modes of oscillation and potentially threatening system stability.

Inverters can operate in either current control mode, commonly referred to as grid-following mode, or in voltage control mode, known as grid-forming mode. Grid-following sources use a phase-locked loop (PLL) to measure the grid voltage angle, enabling synchronisation and the injection of active and reactive power into the ac grid [1]. Nevertheless, this control

mode lacks the inertia contribution provided by conventional SM [2] and may encounter stability challenges in weak grids. To address these concerns, grid-forming controls in which both the magnitude and phase at the point of common coupling (PCC) are imposed, have been explored in the literature [3]. Numerous grid-forming strategies exist in the literature, among which droop control stands out as a well established and robust approach, essentially replicating the droop behavior seen in traditional power plants [4]. Additionally, various methods have been developed to not only replicate damping but also emulate the inertial effect of SMs. These include virtual synchronous machine control (VSIMA) [5], virtual synchronous generator (VSG) [6], synchronverter [7], and matching control [8]. The distinction between these strategies lies in their ability to capture the dynamics of SMs with varying levels of detail. In previous works, many studies have been conducted to examine the stability limits of power systems comprising SMs and IBRs controlled in grid-forming mode [9]–[13]. Coupling modes due to the interaction between SMs and IBRs have been highlighted in low inertia power systems, as well as the impact of key parameters such as short circuit ratio and IBR penetration level on small-signal stability [14] [15].

All these studies were conducted on a simplified academic representation consisting of an inverter vs SM model that does not capture the influence or dynamics of the rest of the system. Having a model for the rest of the system is essential as the dynamics of the ac system can significantly impact the stability of the power system, as demonstrated later in this paper. This paper proposes a methodology to comprehensively investigate novel coupling modes resulting from interactions between SMs and IBRs, as well as the influence of IBR control parameters on existing modes. This methodology, based on a conceptual benchmark introduced in [16] originally proposed for the synthesis of new IBR controls, represents a multi-source system comprising a SM, an IBR,

B. Equivalent grid model

In the island power system under examination, primary frequency control is performed by a combination of BESS and conventional power plants equipped with SM including hydroelectric and thermal technologies. To accommodate this, and better represent the overall aggregate dynamics of the system, enhancements have been made to the equivalent grid model proposed in [17] by incorporating a lead-lag filter in the feedback loop of the swing equation as proposed in [20] and illustrated in Fig. 3.

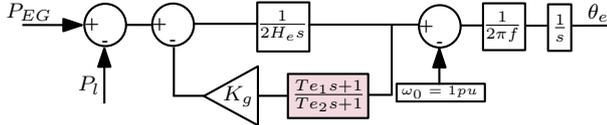


Fig. 3: Equivalent grid block diagram.

P_{EG} denotes the active power generated within the grid, while P_l represents the power consumed by the system's loads. The equivalent grid parameters have been tuned using the island system's measured frequency response to a 3 MW load step. As shown in Fig. 4, this response has been approximated by a second-order response, whose transfer function was used to identify the parameters of the equivalent grid model shown in Fig. 3. The identification results in: $H_e = 3.78$ s, $K_g = 10.24$, $T_{e1} = -0.5056$ s, and $T_{e2} = 1.21$ s.

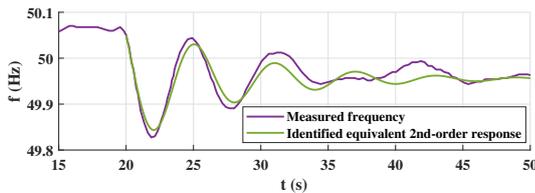


Fig. 4: Frequency response of the island power system after a sudden load variation of 3 MW.

III. MODAL ANALYSIS RESULTS

To explore oscillation modes resulting from the interactions between SMs and IBRs in grid-forming mode, both nonlinear time-domain simulations and modal analysis are employed. The latter enables the capture of highly damped modes and provides insights into all the different mode types. The modal analysis approach involves developing and linearising the differential-algebraic equations of the system as explained in [17] around an operating point and expressing the system equations in state-space representation as in (2). Subsequently, the eigenvalues of matrix A , representing the modes of oscillation, are analysed. Additionally, from matrix A , participation factors can be computed to gain insights into the states involved in each mode. Consequently, this provides an understanding of the nature of each mode.

$$\dot{x} = Ax \quad (2)$$

The critical modes of oscillation detected are presented in Table I. The droop value R_p is set at 4% in this case, and the inertia H_{VSM} of the VSM is equal to 2.5 s.

TABLE I:
Relevant modes of oscillation

Mode	$\lambda = \sigma \pm j\omega$	Frequency (Hz)	Damping (%)
Inter-area Mode	$-0.68 \pm 8.8j$	1.4	7.71
Frequency Mode	$-0.27 \pm 1.12j$	0.18	23
VSM Mode	$-1.78 \pm 14j$	2.23	12.6

The main participation factors of the first mode identified in Table I are $\Delta\omega_{SM}$ and $\Delta\theta_e$, the rotor speed of the SM and equivalent grid angle respectively, with little participation of the grid-forming control angle $\Delta\theta_m$. As the states are related to the swing equation of both SM and equivalent grid, the detected mode is identified as the well-known inter-area mode [21] between the equivalent grid and the SM.

The frequency mode is the one at very low frequency, representing the global frequency dynamics of the system. The states involved in this mode are the SM's speed deviation $\Delta\omega_{SM}$, the SM's governor-related state ΔP_{gov} , the equivalent grid's dynamics ($\Delta\omega_e, \Delta T_e$) and the grid-forming control's speed $\Delta\omega_m$.

The VSM mode is the one introduced by the VSM control strategy of the grid-forming inverter. The main participation factors in this mode are the dynamics related to the VSM control strategy ($\Delta\omega_m, \Delta\theta_m$), the angle of the equivalent grid swing equation $\Delta\theta_e$ and a minor involvement of the SM's rotor speed $\Delta\omega_{SM}$. This mode is eliminated when τ_ω equals zero, indicating that it is introduced by the VSM control strategy. This particular situation corresponds to the unfiltered droop strategy as explained in Section II.A.

IV. SENSITIVITY ANALYSIS

To evaluate the influence of key parameters such as the droop value R_p , the VSM's inertia H_{VSM} and the equivalent grid parameters (H_e and K_g), a sensitivity analysis has been performed to observe the behavior of the identified modes.

A. Sensitivity to the VSM inertia

Given that the inertia constant of the VSM is purely a control parameter with no physical constraints, unlike actual SM-based generators, any inertia value can be chosen for the VSM. In the sensitivity analysis performed here, it has been varied across a wide range, spanning from 1 to 30 s. As shown in Fig. 5, the damping of the inter-area and VSM modes decreases drastically when increasing the VSM inertia, and the inter-area mode even becomes unstable for values greater than 10 s. In contrast, there is a slight increase in the damping of the frequency mode with the increase in H_{VSM} .

B. Sensitivity to the VSM droop control gain

To evaluate the influence of the primary frequency control gain on the system stability, R_p has been varied from 1% to 10%. As illustrated in Fig. 6, a reduction in R_p from 10% to 1% improves the overall system stability as the damping of the three modes increases.

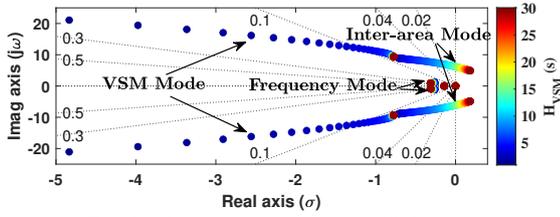


Fig. 5: Modes sensitivity to the VSM inertia.

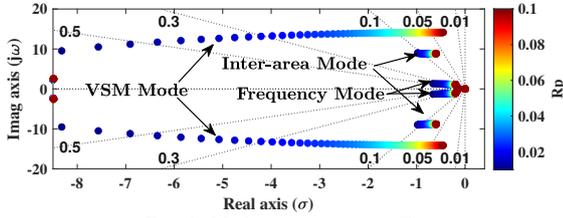


Fig. 6: Modes sensitivity to R_p

C. Sensitivity to the equivalent grid parameters

As depicted in Fig. 7, increasing the inertia of the equivalent grid H_e results in increasing the damping of the frequency mode. This effect is consistent with increasing the inertia of the VSM as shown in Fig. 5, as both contribute to the overall inertia of the grid, thus influencing the in-phase oscillation of all states in the system's global dynamic response which the frequency mode represents. In contrast, the inter-area and VSM modes involve oscillations between elements in the grid, depending on the inertia ratio of different sources. Here, the damping is primarily influenced by the inertia ratio (H_{VSM}/H_e), not the total grid inertia. Thus, increasing H_e enhances damping by reducing this ratio, while increasing H_{VSM} diminishes damping by raising the ratio. This aligns with Fig. 5 and Fig. 7, where lower H_{VSM}/H_e ratios correspond to improved damping in these modes.

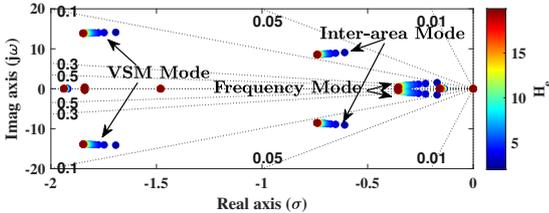


Fig. 7: Modes sensitivity to the equivalent grid inertia.

V. POWER OSCILLATION DAMPING CONTROL

As indicated by the sensitivity analyses conducted in the preceding section, it has been observed that under certain critical conditions, the three low-frequency oscillation modes identified in this study may exhibit insufficient damping characteristics. To ensure enhanced stability of the power system, a POD controller, depicted in Fig. 8, is proposed and added to the IBR control.

This controller takes the frequency ω_m of the VSM as an input and its output P^* is subtracted from P_0 of the external power loop in Fig. 2. A washout filter with a time constant T_{POD} set to 5 s is used to eliminate the steady-state value,

TABLE II:
Modes of oscillation with and without POD

Mode	1	2	3
Without POD	f = 1.4 Hz D = 6.5 %	f = 0.236 Hz D = -2.99 %	f = 2.25 Hz D = 3.15 %
With POD	f = 1.4 Hz D = 8.37 %	f = 0.38 Hz D = 14.5 %	f = 3.11 Hz D = 9 %

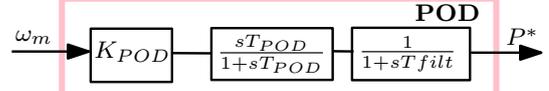


Fig. 8: POD used to stabilise modes of oscillation.

and a low-pass filter with a time constant of $T_{filt} = 0.2$ s is used to suppress the high frequencies. The gain K_{POD} is set to 200 pu. To test the effectiveness of the proposed controller, R_p is set at 10%. Furthermore, adjusting K_g to 20 enables to intentionally destabilize the initial condition. In this case the frequency mode is unstable as indicated by a negative damping value and the two other modes have a very low damping as shown in Table II where 1, 2 and 3 are the inter-area, frequency and VSM modes respectively. The

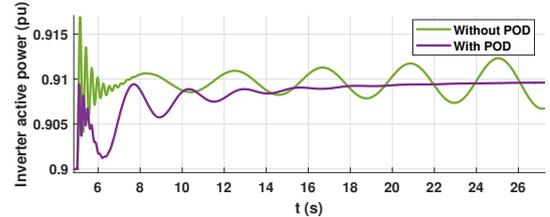


Fig. 9: Active power measured after the inverters filter after a step of 0.05 pu at P_0

nonlinear time-domain simulations depicted in Fig. 9 validate the conclusions drawn from the modal analysis outlined in Table II. Specifically, the VSM mode is observed immediately following the step change, while the frequency mode emerges as the diverging oscillation that can be observed toward the end of the simulation result. While the inter-area mode oscillation is also present, it is not visible on the active power curves shown in Fig. 9 as its amplitude is insignificant compared to the other two depicted modes. Moreover, in instances where additional damping for the inter-area mode is needed, the installation of a Power System Stabilizer (PSS) on the SM can also be considered [21].

VI. CONCLUSION

This paper primarily proposes a new methodology to examine the dynamic stability of any real power system. This methodology is based on a conceptual benchmark designed to analyze various modes of oscillation between targeted dynamic elements of a power system, achieved by associating IBR and SM with a dynamic equivalent grid model. The structure of the benchmark allows for the representation of any real power system in a minimal order model as illustrated by the French island power system studied in this paper.

The analysis of participation factors has revealed that the VSM control of IBR introduces a low-frequency mode, in addition to the well-known inter-area mode between SM and the equivalent grid, and the frequency mode governing system-wide frequency behavior.

Sensitivity analyses reveal that higher VSM inertia reduces damping of certain critical modes, while a lower droop value (corresponding to a greater primary frequency regulation contribution) enhances it, consistent with prior research. However this study goes further by investigating the impact of equivalent grid model parameters on system dynamics, finding that increasing its inertia increases damping of critical modes, contrary to VSM inertia. Additionally, this methodology enables the identification of the frequency mode and its effect on the system stability and provides a reduced order model for the power system of interest.

A POD installed on the external loop of the grid-forming control has been proposed and proven to be effective in increasing the damping of all three detected low-frequency modes.

REFERENCES

- [1] D. Wei, T. Francis, *et al.*, "Modeling of Grid-Forming and Grid-Following Inverters for Transient Stability Simulation of Large-Scale Distribution Systems," *IEEE Transactions on Power Delivery*, vol. 36, no. 4, pp. 2035–2045, 2021.
- [2] T. Qoria, F. Colas, *et al.*, "Inertia Effect and Load Sharing Capability of Grid-Forming Converters Connected to a Transmission Grid," in *IET Conference Publications*, 2019.
- [3] R. Rosso, W. Xiongfei, and L. Marco, "Grid-Forming Converters: Control Approaches, Grid-Synchronization, and Future Trends - A Review," *IEEE Open Journal of Industry Applications*, vol. 2, pp. 93–109, 2021.
- [4] P. Unruh, M. Nuschke, *et al.*, "Overview on Grid-Forming Inverter Control Methods," *Energies*, vol. 13, pp. 1–21, 2020.
- [5] H.-P. Beck and R. Hesse, "Virtual Synchronous Machine," in *9th international Conference on Electrical Power Quality and Utilisation*, 2007.
- [6] P. Unruh, M. Nuschke, *et al.*, "A Generalized Droop Control for Grid-Supporting Inverter Based on Comparison Between Traditional Droop Control and Virtual Synchronous Generator Control," *IEEE Transactions on Power Electronics*, vol. 34, pp. 5416–5438, 2019.
- [7] Q.-C. Zhong and G. Weiss, "Synchronverters: Inverters that Mimic Synchronous Generators," *IEEE Transactions on Industrial Electronics*, vol. 58, pp. 1259–1267, 2011.
- [8] Q.-C. Zhong and G. Weiss, "Grid-forming control for power converters based on matching of synchronous machines," *IEEE Transactions on Industrial Electronics*, vol. 58, pp. 1259–1267, 2018.
- [9] G. S. Pereira, V. Costan, A. Bruyère, and X. Guillaud, "Impact of synchronous machine dynamics on the stability of a power grid with high penetration of variable renewable energies," in *15th IET International Conference on AC and DC Power Transmission (ACDC)*, 2019.
- [10] D. Pattabiraman, R. H. Lasseter, and T. M. Jahns, "Comparison of grid following and grid forming control for a high inverter penetration power system," in *IEEE Power and Energy Society General Meeting*, 2018.
- [11] Y. Lin, B. Johnson, V. Purba, S. Dhople, and W. Virginia, "Stability assessment of a system comprising a single machine and inverter with scalable ratings," in *IEEE North American Power Symposium*, Morgantown, West Virginia, 2017.
- [12] L. Benedetti, P. Papadopoulos, *et al.*, "Small Signal Interactions Involving a Synchronous Machine and a Grid Forming Converter," in *IEEE PowerTech*, Madrid, 2021.
- [13] Z. Xinyi, C. Shu, W. Xun, and X. Rao, "Influence of Photovoltaic Power Plants Based on VSG Technology on Low Frequency Oscillation of Multi-Machine Power Systems," *IEEE Transactions on Power Delivery*, vol. 37, pp. 5376–5384, 2022.
- [14] L. Ding, X. Lu, and J. Tan, "Comparative small-signal stability analysis of grid-forming and grid-following inverters in low-inertia power systems," in *IEEE Industrial Electronics Society (IECON)*, 2021.
- [15] R. Mourouvin *et al.*, "Understanding the role of VSC control strategies in the limits of power electronics integration in AC grids using modal analysis," *Electric Power Systems Research*, vol. 192, 2021.
- [16] B. Marinescu, E. Kamal, and H.-T. Ngo, "A system model-based approach for the control of power park modules for grid voltage and frequency services," 2021. [Online]. Available: <http://arxiv.org/abs/2107.02000>.
- [17] P. Zoghby, B. Marinescu, and A. Rossé, "A Conceptual Benchmark for the Study of Interactions and Inter-area Oscillations in Power Systems with High Power Electronics Penetration," in *IEEE ISGT Europe*, 2023.
- [18] P. Zoghby, B. Marinescu, A. Rossé, and G. Prime, "Exhaustive Classification and Quantification of Coupling Modes in Power Systems with Power Electronics," *arXiv: 2402.04701*, 2023.
- [19] D. Salvatore and A. S. John, "Equivalence of Virtual Synchronous Machines and Frequency-Droops for Converter-Based Microgrids," *IEEE Transactions on Smart Grid*, vol. 5, pp. 394–395, 2014.
- [20] M. Georges, M.-G. Jeanne, *et al.*, "Grid Supporting VSCs in Power Systems with Varying Inertia and Short-Circuit Capacity," in *IEEE Milan PowerTech*, 2019.
- [21] P. Kundur, *Power system stability and control*. McGraw-Hill, Inc, 1994.