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Performance of IBR Power Oscillations Damper according to power system operating conditions

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Abstract—This paper analyses the performance of a Power Oscillations Damping (POD) controller through small-signal stability analysis. The POD is installed in a photovoltaic (PV) power plant controlled in conventional grid-following (GFL) mode. During frequency transients, the POD modifies the reactive power reference of the GFL control, in order to damp electromechanical power system oscillations. The transmission power grid IEEE 9-bus benchmark has been analysed in DigSILENT PowerFactory software. The PV plant capacity, its location in the network, and the power system operating conditions are considered. Particularly, the analysis of a few specific consumption and generation conditions shows that the electromechanical oscillatory modes of the system are more critical in case of peak load, as it happens for 100 % synchronous generation. The main results are twofold: (i) the significant contribution of the POD to damping electromechanical modes in the scenario of winter evening peak consumption, when the PV plant does not inject active power to the grid, which coincides with the most poorly damped electromechanical modes; and (ii) the lack of negative interaction between PSS and POD controllers.

Index Terms—rotor angle small-signal stability, power system electromechanical oscillations, power oscillations damping, inverter-based resources

I. INTRODUCTION

The dynamics of power system are undergoing a change of paradigm due to energy transition, in particular massive integration of Renewable Energy Sources (RES). Power grid operators are concerned about the related arising challenges, in particular concerning power grid stability, in all its categories [1]. Indeed, conventional stability phenomena are impacted, and in addition new stability categories are appearing with the observation (thanks to powerful measurement units) of new stability phenomena [2].

This article focuses on the small-signal, rotor angle stability. This belongs to the broader term, recently used often in research: oscillatory stability. Conventionally, it concerns the damping torque necessary to diminish and extinguish electromechanical oscillations of synchronous generators (SGs). Power System Stabilizers (PSSs) are the specific controls of synchronous generators that tackle this stability issue. A few decades ago, the negative impact on damping torque

of High Voltage Direct Current (HVDC) and Flexible AC Transmission Systems (FACTS) devices was observed, and similar controllers to PSSs were designed for such devices [3]. This type of active damping controller is usually called Power Oscillation Damper (POD), Power Oscillation Damping controller or simply damping controller; and it is a mature technology nowadays.

With the massive integration of RES, there are periods of preponderance of converter interfaced generation over synchronous generation. In such periods, the remaining PSS (together with the FACTS and HVDC POD) may not provide sufficient damping torque so that the electromechanical oscillatory modes of remaining synchronous generators are well-damped. Indeed, research shows that both photovoltaic power plants and wind power plants can negatively impact power system electromechanical oscillation modes ([4], [5], respectively). On the other hand, any Inverter-Based Resource (IBR) can technically provide damping to electromechanical modes, provided that appropriate outer control loops are designed. Such control has recently become the focus of ongoing research, being often called POD (as for HVDC and FACTS devices) or, more generally, active damping control and stabilizer control.

Conventionally, PSSs were proved to be robust against changing power system operating conditions [6]. It may not be the case for IBR-PODs; from that perspective two approaches are identified in bibliography: (a) online adaptive tuning of PODs (accounting for different operating conditions, faults, network configurations, etc.) [7], [8]; and/or (b) consideration of numerous operating conditions [9] (often obtained from randomization [8]), in order to validate the tuning methods (often based on AI techniques [8]).

However, to the authors knowledge, there is no expert knowledge of the impact of operating conditions on the performance of IBR-PODs. Such insight from the system point of view would guide towards specific operating conditions to be considered when tuning POD controllers, as well as towards conditions in which it may be necessary to update their tuning. This would reduce the computational burden involved in testing numerous operating conditions.

The second research gap that this article addresses is the combined action of PSS and POD controllers. Some studies

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validate the proposed IBR-POD on a system without any synchronous generator including a PSS [7]–[9]. Therefore the electromechanical modes they tackle with PODs are more poorly damped than in reality. They compare the oscillatory modes with only SG-PSSs versus only IBR-PODs. Other studies focus on coordination and/or tuning optimization of PSS and POD simultaneously [10]. Instead, our approach keeps the PSSs as they were tuned for a 100 % synchronous generation system, and we add a POD in order to assess possible interactions.

The rest of the article is organised as follows: section II presents the test case including the tuning of PSSs for 100 % synchronous generation. Section III assesses the evolution of system electromechanical modes, with part of the synchronous generation being replaced by a large-scale PV plant; considering load conditions as well as PV plant size and output. The results are shown in section IV, mainly built on the worst case scenario (presented in Section III-C).

II. TEST CASE

A. Overview

The IEEE 9-bus benchmark represents a transmission network with three synchronous generators, being the biggest one (the south synchronous generator or S-SG in Fig. 1) connected to the slack bus. As shown in Fig. 1, in this article we replace in turn the medium and the small synchronous generators (west and east, W-SG and E-SG, respectively) by PV power plants (W-PV and E-PV, respectively).

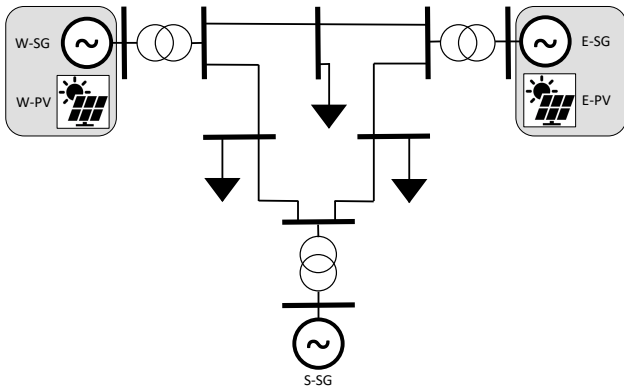


Fig. 1: Overview of the benchmark IEEE 9-bus, with the addition of PV power plants on the west and east generation nodes

The default configuration of the benchmark model in DIgSILENT PowerFactory is considered the base case for the study. The only modifications carried out concern (a) synchronous generators models: detailed models (10th in PowerFactory) with the parameters by default instead of the standard ones (4th order); and (b) PSSs, as detailed next.

B. Power System Stabilizers (PSSs)

Without any PSS, the benchmark has two electromechanical modes (also called swing modes) with oscillation frequencies

of around 1.2 Hz (with more participation of the medium synchronous generator or W-SG), and 2.1 Hz (with more participation of the small synchronous generator or E-SG).

Instead of adding a single PSS on the west synchronous generator (as proposed in the PowerFactory model of the benchmark), we add a PSS on both the west and the east synchronous generators. This will allow to assess the combined contribution of PV-POD and SG-PSS to damping swing modes, as well as any possible interaction between the two controls.

The chosen PSS topology is shown in Fig. 2, and it corresponds to the IEEE STAB1 with the modification of the lead block order being a free parameter (n). It is composed of:

- the rotation speed of the synchronous generator as stabilizing signal (input signal of the control)
- the washout filter: high-pass filter with a time constant (T_W) of 10 s, which is a common value to capture the oscillations in the typical electromechanical frequency range
- the phase compensation of as many first order lead filters as necessary (usually 2), which are tuned identically
- the gain allowing to achieve the desired damping (we choose $\sigma_{max} = -1$ and $\zeta_{min} = 10\%$ for both oscillatory modes in the base configuration)

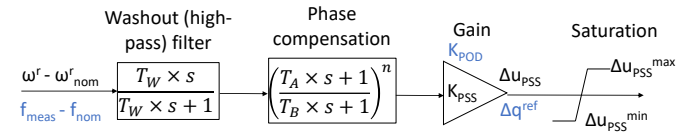


Fig. 2: PSS topology (signals in black)

The two PSSs are tuned following the modified root-locus design technique [11]. Table I shows the parameters for the PSSs of the west and east synchronous generators.

TABLE I: PSSs parameters obtained from modified root-locus tuning technique

Generator	T_A (s)	T_B (s)	n	K_{PSS} (pu)	Δu_{PSS} (pu)
West	0.3664	0.0485	2	0.7	0.05
East	0.2087	0.0266	3	0.5	

The oscillatory modes without and with the two PSSs appear in the following page in Fig. 3 (middle figure for base load condition), with the symbols “×” and “+”, respectively.

III. ELECTROMECHANICAL MODES ACCORDING TO OPERATING CONDITIONS

The objective of this section is to conclude about the impact on the electromechanical oscillation modes of: (a) the load condition (for base generation type: 100 % synchronous) and (b) the generation mix including capacity and set points (for base load condition).

According to a preliminary sensitivity analysis, the electromechanical modes are very little sensitive to reactive power

variations of both generation and consumption. Therefore the focus of the remaining is on active power variations.

A. 100 % synchronous generation: impact of load condition

1) “Normal load conditions”: In the base configuration, the total active power consumption of the network (315 MW) is around 56 % of the installed synchronous generation capacity (567.5 MVA). In order to characterize the actual load condition, we compare this ratio with that corresponding to five “normal steady-state operating conditions” [12] for the simplified 14-generator, 50 Hz system (see Table II).

TABLE II: Ratio of total active power consumption to total synchronous generation capacity of a transmission network according to load condition [12]

Case	1	2	3	4	5
Load condition	Heavy	Medium-heavy	Peak	Light	Medium
Ratio P/S (%)	67	63	75	44	56

Accordingly, the base configuration is identified as medium load condition (case 5 in Table II). Peak load condition can then be defined based on the ratio of the Case 3, and light load condition based on Case 4. To achieve this, the active power consumption of the three loads is multiplied by the corresponding ratios (1.3 and 0.8, respectively). It results in a total peak load of around 420 MW, and a total light load of around 250 MW.

2) *Adaptation of SGs active power output*: Next, the active power output set point of the three SGs is adapted, according to their nominal apparent power, to the two new load conditions.

In peak load, it is considered that the medium and small synchronous generators (west and east, respectively) saturate their output set point at 90 % of their rated apparent power.

3) *Impact of load condition on electromechanical oscillation modes*: Fig. 3 shows the eigenvalues of the system for the three load conditions, without any PSS and with the PSSs previously tuned for both the west and east SG.

One observes that:

- tuning of PSSs is perfectly adapted (i.e. robust) to different load conditions: the eigenvalues are shifted horizontally left in all cases, meaning that pure damping torque is provided, and therefore small-signal stability is improved.
- swing modes are poorly damped in peak load condition without PSSs (around 5 % of damping ratio), but none of the modes is critical with PSSs
- PSSs add slightly more damping torque for peak load condition (i.e. the most critical situation in terms of damping), in particular for the east swing mode (around 2 Hz)
- the oscillation frequency slightly increases with the increase of load

This analysis gives a basis for comparison of the performance of POD compared to that of the PSS.

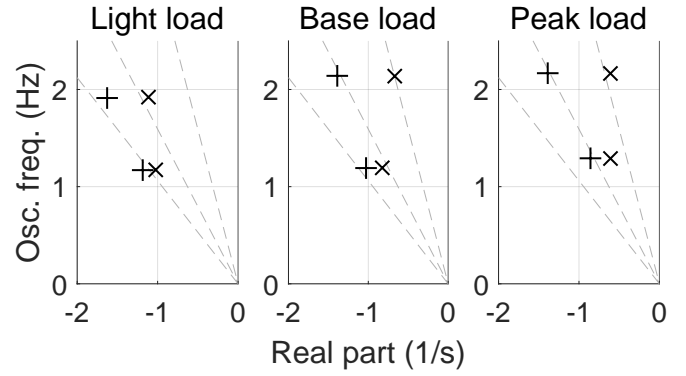


Fig. 3: Impact of PSSs action on the swing oscillatory modes according to the load condition. “x” and “+” correspond to the electromechanical modes of the system before and after the addition of the two PSSs. The grey dashed lines correspond to damping ratios of 5 %, 10 % and 15 %, as indicated in the next Fig. 4 (they have not been included here for clarity reasons).

B. Impact of PV power plant

In this section, the PV power plant capacity and its active power output are assessed. For brevity reasons, the figure and discussion correspond to the replacement of the west synchronous by a PV plant. The same trends are observed for the replacement of the east synchronous generator, although the remaining electromechanical mode is in such case significantly less sensitive to the variations, in comparison.

The load condition is the base case of the previous section, and the PSSs are disabled (that is, the operating condition by default of the benchmark).

1) *PV power plant capacity*: The PV power plant replacing the west synchronous generator has the same rated apparent power (192 MVA). The same active power output of the base configuration (163 MW) is chosen as well. This corresponds to the eigenvalue at the origin of the arrows in Fig. 4. From this point, the rated power of the PV power plant is increased, keeping the same active power output, in order not to alter the power transfer throughout the system. Fig. 4 shows the evolution of the remaining swing mode as we increase S_r^{PV} 25 % and 50 % (to 240 MVA and 288 MVA, respectively) from the initial rating.

One observes that the swing mode is very sensitive to the PV plant capacity. It is note the case for the rest of the system modes, which have not been included for clarity reasons, but which are not or very little sensitive to this variation. The mode is shifted horizontally left as the capacity increases, therefore the small-signal stability is improved.

With this insight, in the rest of the article, the PV power plant capacity is fixed to the same rated power as the replaced synchronous generator (either west or east), adhering in this manner to the worst case in terms of swing mode damping.

2) *PV power output*: Similarly to the previous section, the sensitivity of the swing oscillatory mode according to the PV

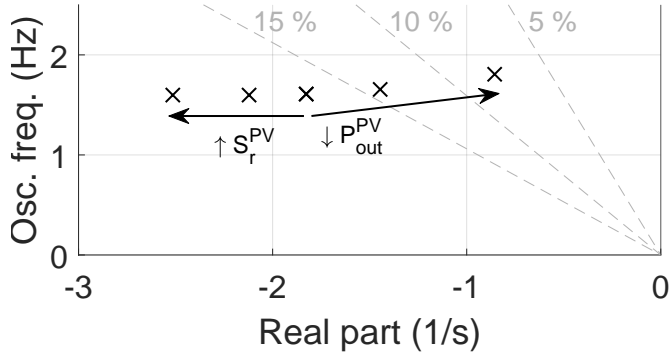


Fig. 4: Impact of the PV power plant capacity (S_r^{PV}) and the generated active power (P_{out}^{PV}) on the remaining system swing mode

active power output is assessed this time. This will provide some more insights to characterize the worst case scenario in terms of damping.

Starting from the same configuration as in the previous section (base load condition with west PV power plant, i.e. the eigenvalue at the origin of the arrows in Fig. 4), the output power of the PV plant (P_{out}^{PV}) is reduced from 85 % to 50 % and 15 % of its rated power (96 MW and 29 MW, respectively). As previously done for defining the different load conditions, the active power output of the two other synchronous generators are increased in order to balance out the difference, proportionally to their capacities.

Fig. 4 shows, once again, the strong sensitivity of the swing mode to the active power variation: it becomes more poorly damped as the PV plant injects less active power to the grid. The oscillation frequency slightly increases. In contrast to the PV power plant capacity, on this occasion the power transfer of the network is obviously modified.

We conclude at this point that the periods with low or null PV generation may be delicate in terms of damping of electromechanical modes, i.e. in terms of small-signal stability.

C. Worst case scenario

Given the insights from the previous sections, it looks appropriate to test the POD performance in peak load condition, together with null PV generation, as the worst case scenario in terms of swing modes damping. This could correspond to a weekday evening in winter.

However, when the medium-size synchronous generator is replaced by a PV plant, the remaining two synchronous generators are not capable of supplying the whole load, so the total load is limited to 364 MW, according to the generators capacity (which corresponds to 87 % of the previously defined peak load, for the case of only synchronous generation).

IV. RESULTS AND DISCUSSION

The impact of the following parameters are assessed in this article:

- 1) Load condition (and adapted output of generation, as detailed above): light, base and peak load conditions

- 2) POD tuning : according to W-SG PSS (Table I, 2nd line) or E-SG PSS (Table I, 3rd line), discussed next
- 3) PV plant location (or replaced synchronous generator): west or east (as illustrated in Fig. 1)
- 4) remaining PSS: active or disabled; in order to assess the contribution of each stabilizing control, their combined action, and possible interactions

A. POD tuning

Intuitively, it was expected that tuning the POD as each of the PSSs would perform better for replacing each of the synchronous generators (west and east) by a PV power plant with POD controller. Instead, the tuning of the east PSS does not provide a good performance in any of the two PV-POD locations. In the first place, there is a significant overcompensation of the phase (so instead of adding pure damping torque, it also reduces the synchronising torque of the remaining synchronous generators). Removing one of the three single order lead filters, the phase compensated is as desired, but the mode is little sensible to the gain of the POD.

On the other hand, the tuning of the PSS west is well performing in both cases, therefore this tuning (see Table I, first row) is retained in the remaining of the article. The gain is rounded up to $K_{POD} = 1$.

B. Impact of POD and remaining PSS: comparison and combination

Fig. 5 shows the impact of the POD controller on the remaining swing mode after replacing either the west (blue eigenvalues) or the east (pink eigenvalues) synchronous generator by a PV power plant of the same rated power as the replaced synchronous generator. \times and \square symbols correspond to the remaining PSS disabled, while $+$ and $*$ correspond to the remaining PSS active. Black eigenvalues correspond to the case of 100 % synchronous generation (as in Fig. 3), and are included here as a reference for comparison.

Regarding peak load conditions (Fig. 5 top), one observes that:

- The POD performs well in the four cases: two locations of the PV plant (blue or pink colours), remaining PSS disabled or active (\square and $*$). Its contribution is slightly more significant for the poorly damped modes (i.e. for the remaining PSS disabled), as it happened with the 100% synchronous generation according to the load condition.
- The damping effect of the PSS ($+$ vs. \times) is more significant than that of the POD (\square vs. \times). This can straightforwardly be counteracted by slightly increasing the gain of the POD, as the phase compensation (i.e. the shift direction of the poles) is the appropriate.
- The combined action of the remaining PSS and the POD is added ($*$ symbols), showing that there is no adverse interaction between them.
- The oscillation frequency of the remaining swing mode is within the initial (100 % synchronous generation) electromechanical modes frequency range.

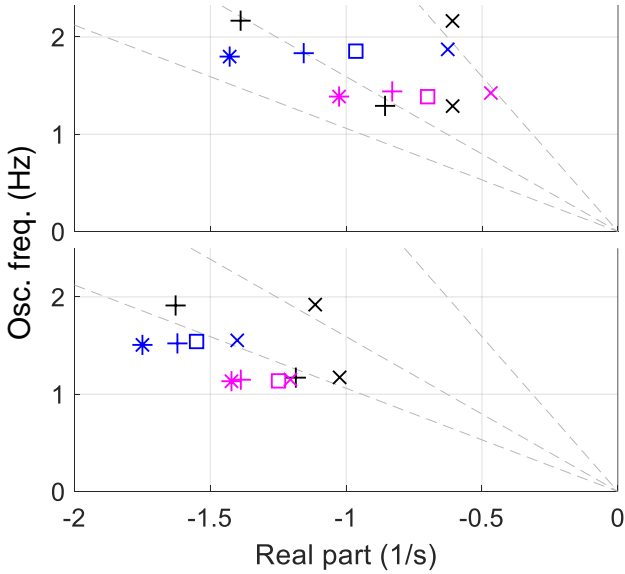


Fig. 5: Comparison of PSS and POD performance: impact on electromechanical modes (individually and combined) for peak (top) and light (bottom) load conditions.

The eigenvalues corresponding to the light load condition (Fig. 5 bottom) are significantly less sensitive to both PSS and POD controllers. This is especially true for POD controller and west PV configuration (pink * and □ compared to pink + and ×). This is not considered a problem, since the poles are quite well damped even before the action of the controllers ($\sigma_{max} < -1$ and $\zeta_{min} > 10\%$).

Fig. 6 shows, for the case of the west PV network configuration, and peak load condition, the active power injected by the east synchronous generator, after an increase of its mechanical torque of 0.05 pu. The impact of PSS and POD controllers is illustrated, and it has good agreement with the corresponding blue eigenvalues in Fig. 5 (top).

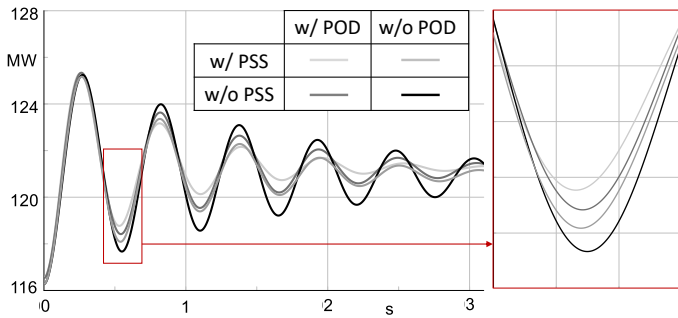


Fig. 6: Active power injected by the east synchronous generator after a 0.05 pu increase in its mechanical torque

CONCLUSION

This article presents a systematic assessment of the behaviour of electromechanical oscillation modes according to load conditions, generation mix in terms of installed capacity and active power output. This eigenvalue analysis leads to the

definition of σ_{min} , the worst case scenario in terms of swing modes damping. The individual and combined contribution of PSS and POD controllers to damping electromechanical system modes is then compared for such worst case, considering in addition two different locations for the PV power plant. The same results corresponding to non-critical conditions are provided for comparison. Time-domain simulations illustrate the modal analysis results.

The main results are (i) the damping capacity of the PV-POD even when there is no PV generation, and (ii) the combined damping contribution of PSS and POD without presenting any adverse interaction.

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