

Review

A Comprehensive Review of Small-Signal Stability and Power Oscillation Damping through Photovoltaic Inverters

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Abstract: This paper focuses on the methods that ensure the rotor angle stability of electric power systems, which is most frequently analyzed with small-signal models. Over the past several decades, power system stabilizers (PSSs) for conventional excitation systems were the main tools for improving the small-signal stability of electromechanical oscillatory modes. In the last decade, power oscillation damping (POD) control implemented in photovoltaic (PV) inverters has been considered an alternative to PSSs. As PV generation undergoes massive rollout due to policy directions and renewable energy source integration activities, it could potentially be used as a source of damping, which is crucial for sustaining the rotor angle stability of the remaining in-service synchronous generators. Several studies have already been dedicated to the development of different damping strategies. This paper contributes to the existing research in power system stability by providing a comprehensive review of the effects of PV generation on small-signal stability, as well as the recent evolution of POD control through PV inverters. The features and impacts of the various ways to realize POD controllers are assessed and summarized in this paper. Currently, detailed information and discussions on the practical application of PV inverter PODs are not available. This paper is, thus, intended to initiate a relevant discussion and propose possible implementation approaches concerning the topic under study.

Keywords: power oscillation damping; small-signal stability; photovoltaic inverter; electromechanical oscillation; virtual synchronous generator; microgrid



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1. Introduction

Large interconnected power systems offer several advantages such as liberalized cross-border markets, shared power reserves, and reliable power supply. One of the major challenges encountered by such big power systems relates to the maintenance of the stability and reliability of their operation. Definitions and classifications of the phenomena of power system stability are available in [1,2]. These definitions suggest that, upon a disturbance, to ensure the stability of electric power systems, a transition to another steady state is required while maintaining a non-interruptible power delivery. The stability should be preserved in any possible operating conditions of the power system, including the constantly changing generation, demand, and weather conditions. According to [1], there are three main groups of power system stability: “rotor angle stability, frequency stability, and voltage stability”. This paper focuses primarily on the methods that ensure rotor angle stability, which is most frequently analyzed using small-signal models. For the past several decades, the power system stabilizers (PSSs) applied in the excitation systems of conventional generating units were the main tools used for influencing the electromechanical oscillatory modes of the power system, which also improved its small-signal stability. It is a well-known fact that these oscillations have low frequencies and can be classified into two main categories: local (typically 0.7–2 Hz) and interarea (0.1–0.7 Hz). The first recorded event of low-frequency oscillations happened in the 1960s [3]. Electromechanical

oscillations are inherent to the synchronous generators and their rotors can swing either with or against the rotors of the other machines in the system. The oscillations can also be classified as *single-mode power oscillations* when there is only one resonant frequency or as *multi-mode power oscillations* when many dominant frequencies are superimposed (for instance, both local and interarea).

Several cases have been documented in which interarea oscillations have led to black-outs of power systems due to degraded small-signal stability [4–9]. Several existing publications analyzed the nature of interarea oscillations and the possible measures to remedy their impact [9–15]. As an alternative to PSSs, some studies outlined the possibility of using the converters of FACTS and HVDC to mitigate stability issues [15–17]. Another large body of research studies, especially in the past 10 years, has focused on the application of power oscillation damping (POD) control implemented in photovoltaic (PV) inverters. This paper aims to provide a comprehensive review of the utilization of PV inverters for influencing the small-signal stability of power systems.

The nature of the electromechanical oscillations is strongly related to the rotating masses of the synchronous generators and the kinetic energy they store, i.e., their inertia. Recent changes observed in the generation portfolio of many power systems involve the gradual substitution of synchronous machines with the inertia-less inverter-based generation, which has a significant impact on the power system dynamics. Multiple instances have been recorded where, for short periods, the entire load of a country is covered by renewable generation [18]. Some transmission system operators (TSOs) deal with such situations by limiting the output of PV inverters [19]. Some suggestions posit [20] that such limitations will no longer be needed if better control solutions are designed for PV inverters. The issues concerning stability that arise from the increasing share of renewable generation and the corresponding uncertainties continue to be an important topic in the scientific and professional communities [21–23]. The authors of [22] stressed the need for additional research dedicated to the effects and proportions of grid-following and grid-forming inverters. Mathematical models for low-inertia power systems are being developed that afford special attention to the generation control [23]. The issue of decreasing inertia can be partly resolved by applying coordinated control of inverters [21] or by introducing synthetic inertial response [24]. The authors of [25] proposed that the global inertial concept be replaced by a local inertia concept, depending on the ratio between conventional and inverter-based generation at a given time instance. The inertia constants, on the other hand, can be considered as time functions. A comprehensive study of the distribution of inertia in continental Europe, the impact of neighboring areas, and the economic aspects related to the changing system dynamics was presented in [26]. The possible benefits of implementing an inertia monitoring system were also assessed.

Some scientists expressed with certainty that, with suitable control, inertia-less power systems can sustain a high degree of stability under various conditions and radically improve the response of the system to disturbances [27]. An underestimated source of inertia was considered in [28]: the electric motor as a part of complex loads. Its relevance, however, depends on the motor share of the total load.

The other types of stability phenomena are also affected by high penetration levels of PV generation. The voltage stability of a part of the Texas grid was studied in [29]. The analysis was carried out with up to 65% PV penetration. The study revealed that the voltage stability is threatened due to the insufficient volt/var control of PV inverters. An improved volt/var control was developed in [30]. In [31], it was demonstrated that the utilization of inverters' reactive power capability is important for maintaining the voltage stability of power systems.

The frequency stability is also expected to degrade due to the intermittent nature of solar power [32–34]. A good candidate solution for maintaining the power system frequency is the utilization of battery energy storage [35,36]. Operating the inverter as a virtual inertia device is also a viable solution, and a coordinated approach was developed

in [37]. It is later discussed in Section 4.3 of this review that the virtual inertia control of PV generation can also be effectively applied to POD.

The modeling of conventional synchronous generators is crucial for stability analysis. Relevant studies on the topic can be found in the literature [2,38,39].

The literature survey reveals that the transition of power systems to a form of generation that is dominantly inverter-based will likely not be flawless. Taking the conventional synchronous machines out of service compromises the inertial response and excludes the PSS as a main tool for damping electromechanical oscillations. Hence, there is an immediate need for an alternative source of damping control. In the past 15 years, a large number of PV systems were integrated into the power systems, and they could potentially be used as a source of damping, which is crucial to sustaining the rotor angle stability of the remaining in-service synchronous generators. Intensive research efforts have already been aimed at developing various damping strategies, which signals a need for reviewing the different alternatives for POD control from PV generation.

This paper contributes to the study of sustainable integration of renewables by providing a comprehensive review of the effects of PV generation on the small-signal stability, as well as the recent advances in POD control through PV inverters. POD controllers are very diverse. Their pros and cons, features, and properties are summarized and critically reviewed. The practical application of PV inverter PODs is not well established in the extant literature. Here, we initiate a discussion and propose possible approaches for its implementation.

Two very recent publications were brought to the authors' attention after the submission of this review [40,41]. These references are excellent surveys on the application of fractional order control for many different applications, including POD. They demonstrate and conclude that the fractional-order damping controller is more robust than its conventional counterpart, but the tuning methodologies are not yet well established. Hence, their practical application needs further development. While the two surveys focus solely on fractional-order controllers, our review attempts to present a wide range of POD topologies.

The paper is organized as follows: Section 2 briefly describes the basics of PV inverter control. Section 3 presents a review of the impact of PV inverters on the small-signal stability of electric power systems and outlines the main findings. Section 4 delineates the classification of the different POD strategies for PV generation into three groups. Section 5 reviews the application of POD in microgrids. Section 6 summarizes the features of the POD controllers. Section 7 discusses the practical application of damping control, and Section 8 presents the conclusions of the present comprehensive review.

2. Overview of PV Inverter System Control

Inverters are generally classified into single-stage and two-stage inverters. Single-stage inverters, where the PV array is directly fed to the DC/AC inverter, are more efficient than two-stage inverters, which have an additional DC/DC converter [42]. This was confirmed in [43], where a review of 45 different inverter topologies was presented. Some single-stage topologies have a lower number of switches operating with pulse width modulation (PWM). The PV plants in most power system applications are single-stage; hence, they are considered in this section.

The electronic power converters can be classified in terms of the main electrical variables. Two topologies are used in power conversion applications: voltage-source inverter (VSI) and current-source inverter (CSI). The CSI uses thyristors and a large series inductor connected at the DC side. The VSI uses IGBT or MOSFET transistors, and the DC voltage is supported by a parallel capacitor. Both these types have their respective advantages and disadvantages, which were summarized in [44,45]. The main advantage of the VSI is that its power control is very flexible, which provides good steady-state performance and excellent response during transient phenomena.

The typical control of a grid-connected VSI is shown in Figure 1 [46]. The inverter is controlled in a dq reference frame aligned to the voltage of the inverter's output. The dq

transformation reduces the three-phase alternating quantities into two static DC quantities. The DC quantities provide easier control and filtering and allow for decoupled active and reactive power control [46–48]. The inverters are connected to the grid via various topologies of passive filters such as L , LC , or LCL [49–51]. In Figure 1, an L filter is used to eliminate the higher-frequency current components from the inverter output. L_f denotes the output filter inductance and V^θ represents the voltage at the point of common coupling (PCC).

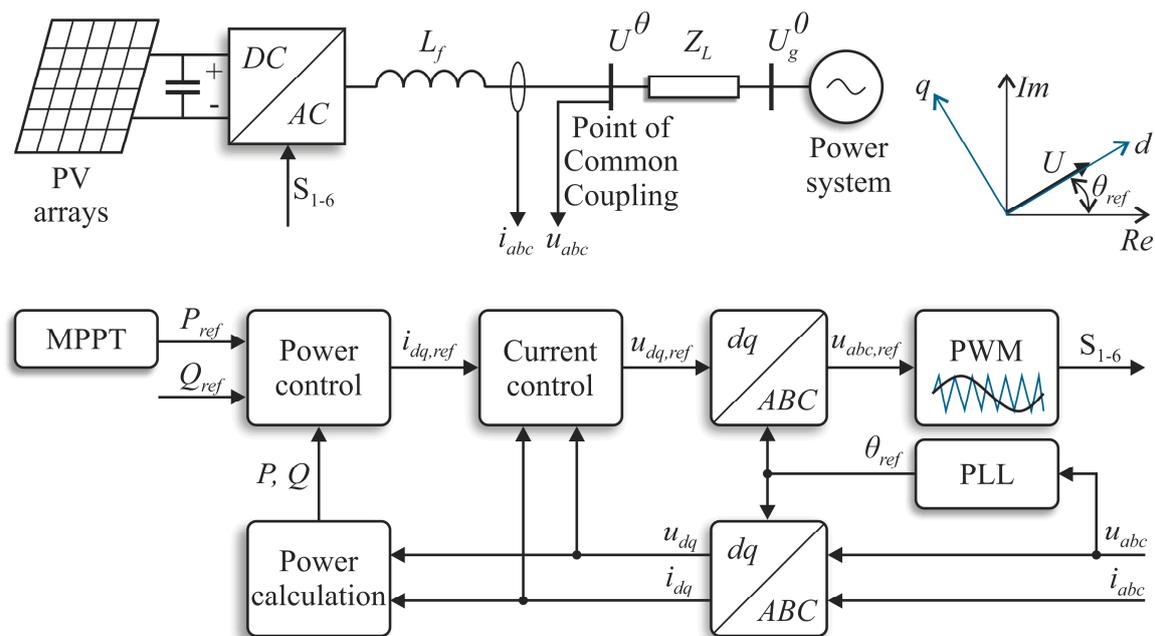


Figure 1. Control of grid-connected inverter.

This paper demonstrates that inverter control has a significant influence on small-signal stability analysis in power systems with prevailing generation from renewable energy sources and their inverter-based generators, especially on their current control and phase-locked loops (PLLs).

Key guidelines for modeling PV power plants for power system stability studies are available in [52,53]. The different modules that are part of the control of the grid-connected inverter are described below.

2.1. Current Control

Figure 2 illustrates the current control loop. It is the fast inner control loop of the inverter. It presents a dq cross-decoupling current control scheme, where both i_d and i_q are controlled using independent PI controllers [47,54–58]. The resulting output is the inverter's output voltage reference in the dq coordinate system.

2.2. Active and Reactive Power Control

To control the grid-injecting mode, additional blocks (power calculation block and power control block) are needed (see Figure 1). With two input signals, i_{dq} and u_{dq} , the power calculation block computes the active and reactive power (P and Q). These are compared to the references P_{ref} and Q_{ref} to form the control errors of the power control block. The real power value of the reference is supplied by the maximum power point tracking (MPPT). That power control acts as a slower outer loop, where two independent control blocks (for active and reactive power) generate the corresponding signals for the reference of the current controller [46]. The active and reactive power controllers are shown

in Figure 3. It should be noted that active power is controlled by varying the DC link voltage. Hence, the active power and DC voltage control are all the same modules.

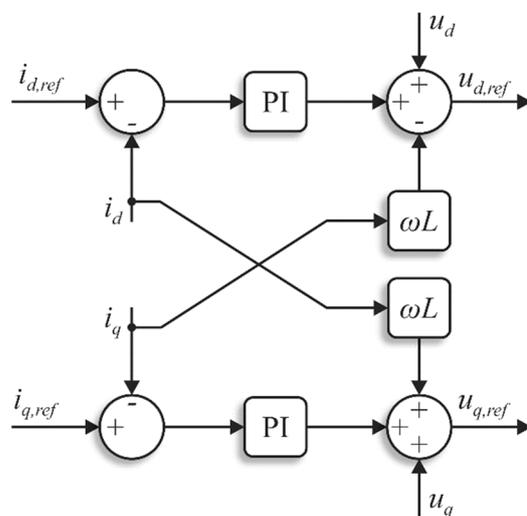


Figure 2. Current control block.

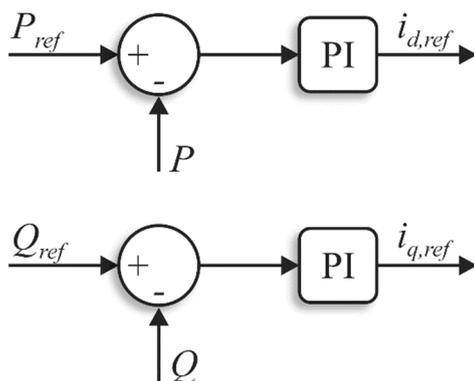


Figure 3. Power control block.

2.3. Pulse Width Modulation

The PWM technique is frequently applied in the design of inverters. It is the most common type of modulation for VSC [44]. There are different types of PWM such as single, multiple, sinusoidal, and modified sinusoidal. The dq voltage reference is reverse-transformed into the ABC reference frame. The obtained three-phase instantaneous reference voltages are used to produce the PWM signals using triangular waves. The reference transformation utilizes the phase angle provided by the PLL to ensure synchronization to the grid.

2.4. Phase-Locked Loop

The dq frame is aligned to the PCC voltage phasor so that the inverter can synchronize with the grid. This task is performed by a PLL [52,59], as depicted in Figure 4. The phase angle θ_{ref} is detected by synchronizing the reference frame with the vector of the three-phase voltage. The dq frame can be considered synchronized when u_q is equal to the desired value $u_{q,des}$ (zero) [46]. It is to be noted that, if $u_{q,des}$ is nonzero, the dq frame will be misaligned.

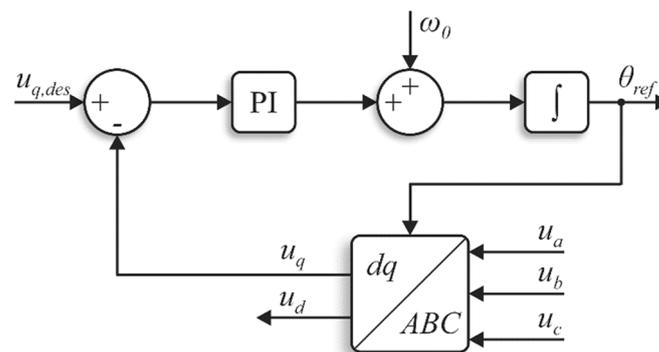


Figure 4. Phase-locked loop.

3. Small-Signal Stability of Power Systems with PV Generation

The effects of PV generation on the small-signal stability of power systems have been studied for more than a decade now. Initially, the research was conducted on simplified test models with up to a few machines. Mostly, either the single-machine infinite bus (SMIB) system whose transmission line is bisected to couple the PV inverter or the well-known Kundur's four-machine test model was used for the research. Then, large-scale studies were performed on models that represented real power systems. As detailed later in this paper, different methods were employed to analyze the oscillation modes and damping of the power systems under study. The results appear to be controversial and are not conclusive.

The stability of a SMIB model with PV generation placed in the middle of the transmission tie was studied in [60]. Using damping torque computations and dynamic simulation techniques, the authors demonstrated that the PV generation may have either a positive or a detrimental impact on the small-signal and dynamic stability of the system, depending on its operating conditions. The damping torque produced by the inverters changes its sign with the power system's varying operating points. The study presented in [61] arrived at the same conclusions. This shows that the closer the PV generation is to the synchronous machine, the greater is the damping it induces.

The authors of [62] presented small-signal stability results from Kundur's four-generator test system, where one of the generators was gradually replaced by PV generation. Contrary to the findings of the previous research, this study indicates an improvement of the damping when the PV share is increased and a slight degradation of the damping when the synchronous machine is fully disconnected. The authors did not comment upon this deviation or presented an analysis to explain why their results were different from those of preceding studies. Similar conclusions were drawn in [63] on the basis of both dynamic simulations and modal analysis.

The topology of the inverter also affects the damping ability provided by PV generation [64]. In most cases, voltage-source converters perform better than current-source converters in terms of small-signal stability. It was also found that the location and size of the PV injection influence the damping of the critical modes. The same authors demonstrated how PV installation equipped with either an ultra-capacitor or battery storage is capable of improving the oscillation damping in a multimachine infinite bus setup [65].

A bigger (14-bus) test system was studied in [66]. The setup comprised three synchronous machines and a PV generator. The impact of factors such as solar irradiation, cell temperature, and load on the electromechanical oscillation damping were assessed. The authors concluded that the damping is not sensitive to cell temperature, while a positive correlation was identified between the damping and the irradiance.

Shah et al. studied how the degree of PV generation dispersity affects the small-signal stability of bulk power systems [67]. PV penetration levels of up to 15% were analyzed in this study. The oscillation frequency was observed to increase slightly, while the damping reduced. This conclusion was based solely on analyzing one electromechanical mode, which may not be conclusive regarding the overall damping. It was demonstrated that the

trend of stability degradation persists, irrespective of the load model: constant Z, I, or P. They concluded that a more dispersed generation resulted in better damping. Furthermore, the power factor control performs better than the voltage control in terms of power system stability. Another review of wind power generation found that, while power factor control enhances the damping in some cases, it degrades the damping in other instances [68]. We did not find other papers dedicated to the impact of PV generation control mode on electromechanical damping. Therefore, the conclusion that the power factor control is beneficial shall be revised as new research becomes available.

In 2014, a comprehensive study of the small-signal stability of western North America's power system was published [69]. An increase of up to 15% of the share of renewables (both PV and wind) was studied. The publication concluded that, while the modal damping remained unchanged, the oscillation frequency increased slightly. The authors' explanation for the latter is that the overall moment of inertia in the system decreased with the increase in renewable generation. In [70], the stability of the Eastern Interconnected US grid was studied for PV penetration up to 65%. The analysis was based on time-domain simulations and the Matrix Pencil method. This study confirmed that the oscillation frequency increased; however, unlike [69], the results of [70] indicated that the damping degraded slightly as the PV share increased. It is likely that [69] did not detect changes in the damping since the considered inverter generation was just 15%.

Another large-scale study was presented in [71]. The Texas 2000-bus system was tested for PV penetration levels up to 50%. The small-signal analysis indicated that both the electromechanical oscillations frequency and the damping decreased slightly with higher PV injection. The damping trend corresponds with previous research. However, the decreasing oscillation frequency contradicts the evidence of previous studies and is counterintuitive to the reduced inertia in the system. The authors did not explain this observation, and one must consider this result with caution.

An interesting approach for analyzing the power system stability with increasing intermittency from renewables was developed in [72]. The authors proposed the use of a combination of offline- and online trained decision trees to classify and predict the electromechanical modes using the wide-area measurement system (WAMS). The decision tree output can be used to identify proper remedial actions. The offline training requires the simulation of multiple operating scenarios, accounting for the uncertainties of the grid, especially of the renewable generators. The simulations presented in this study suggested a very good identification of the electromechanical modes as compared to the full eigenvalue analysis.

In [73], in addition to the PV generation, the study of stability was extended using a battery energy storage system. It was demonstrated that the battery control can significantly improve the oscillation damping of both the local and the interarea modes. The battery control was equipped with a frequency feedback loop that allows a response to the electromechanical oscillations. The gain of this control induced a great mode shift and could be subject to optimization in terms of maximizing the damping. A slight improvement in damping was also confirmed in [71].

Jia et al. studied the small-signal stability of multiple parallel PV inverters coupled to a weak grid [74]. The authors demonstrated that the gain of the PLL has a significant impact on the system damping. The gain also affects the oscillation frequency. The results were confirmed in [75], where Jia et al. also proposed a virtual inductance control to improve the stability. It was established in [76] that the X/R ratio of the grid impedance significantly affects the stability of the inverter control. The stable operation can be maintained by increasing the LCL filter, controller time delay, and passive damping resistance or by decreasing the proportional controller parameters, i.e., by making it less responsive/sensitive.

Most of the available stability studies were based on deterministic methods. Gurung et al. applied a cumulant method to analyze the small-signal stability by considering the uncertainties of PV generation [77]. This method is based on the combination of sensitivity analysis and Gram–Charlier expansion to produce the probability density function and

cumulative density functions of the electromechanical damping. Such data are useful and fundamental for the risk-based reliability analysis of the power system. The study concluded that a higher PV penetration leads to a higher probability of instability. Another probabilistic approach, based on Monte Carlo simulation, was applied in [78] to evaluate the impact of both wind and PV generation. It was concluded that wind generation has a stronger influence on low-frequency oscillations.

The research findings concerning the impact of PV generation on the small-signal stability of power systems can be summarized as follows:

- The frequency of the electromechanical modes generally increases due to the reduced energy stored in the synchronously rotating masses throughout the power system, i.e., due to the reduced inertia. Only one study suggested a decrease in the modal frequency, but it was not supported by sufficient evidence, additional analysis, and explanation.
- A greater share of PV generation leads to a greater impact on the modal damping. At a relatively small percentage of PV generation, the effect on the damping is negligible. With shares above 15%, the damping either decreases or increases more significantly, depending on various factors, as presented in the subsequent bullet points.
- The damping torque induced by the PV inverters changes with the varying of the power system's operating point. This torque could be positive or negative.
- Locating the PV generation near synchronous units has a beneficial impact on the damping.
- Voltage-source converters perform better than current-source converters in terms of small-signal stability.
- The operational parameters of the PV installation have the following impact: The cell temperature does not affect the damping, while the solar irradiance improves it. The latter, however, should be treated with caution as the irradiance strongly correlates to the share of PV generation, and the statement that it improves the damping may not always be true.
- In terms of damping, dispersed PV plants are better than bulk concentrated plants.
- The mathematical model of the load characteristics (constant Z, I, or P) does not have a significant influence on the small-signal stability analysis aimed at studying the PV generation impact.
- The inverter's power factor control performs better than its voltage control in terms of damping. This conclusion is based on a single study, and further research is needed to either confirm or disprove it. It is also possible that a particular type of control cannot be conclusively declared to be superior to another because it may depend on various factors such as grid topology, PV share, power system and operating point.
- The parameters of the inverter's PLL have a strong effect on the damping, especially when coupled to high-impedance grids. This effect can be either positive or negative, depending on the selection of the control parameters.

The inverter-based PV generation changes both the frequency and the damping of the power system electromechanical modes. While the results of research studies regarding the change of modal frequency are more consistent with each other, the studies focused on modal damping indicate that it depends on numerous factors. This makes the analysis of small-signal stability particularly challenging, as factors such as the inverter topology, control scheme, and dispersity must be considered correctly and in a detailed manner to obtain reasonable results. Despite these difficulties, it has become obvious that PV inverters will play a central role in maintaining the power system stability, and dedicated damping control should be implemented.

4. POD in Bulk Power Systems through PV Inverters

4.1. PID, Lead Lag and Other Types of Damping Control

Similar to the studies on small-signal stability, the research approaches that designed and studied POD controllers typically applied the two-area four-generator test system

from Kundur [2] and a modified classical SMIB model, where the PV inverter is coupled to the middle of the transmission tie.

The study [79] from 1987 seems to be among the first to identify the need for utilizing the PV inverters for damping power system oscillations. The authors established an inverter control framework that consisted of a power flow model, a swing equation model, and PID controllers. The outputs were the angle and voltage magnitude corrections produced by the PID and D controls. The obtained signals modulated the reference of the inverter's voltage angle and amplitude controllers (Figure 5). The power system frequency and the voltage oscillations were stabilized. The simulations in this study demonstrated the importance of accurate tuning of the POD controller, as it can degrade stability. The authors of [80] adopted a similar approach.

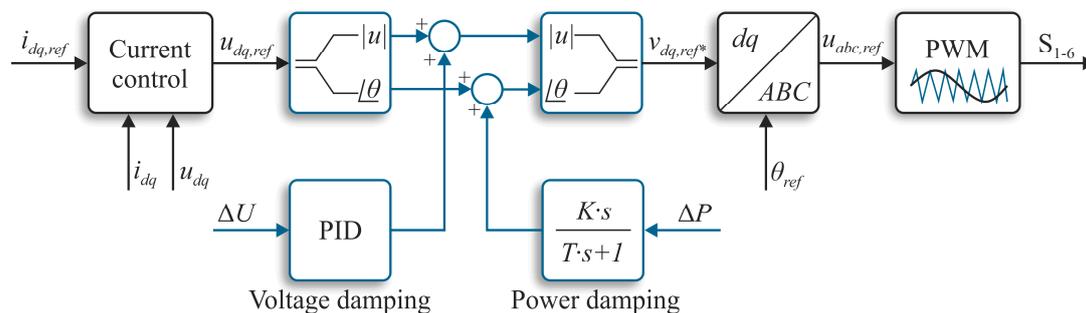


Figure 5. PID control modifying the inverter's voltage magnitude and angle reference.

Francisco de Leon et al. studied the possibility of using unidirectional power control for POD instead of bidirectional control [81]. They successfully demonstrated that this is possible and effective. Furthermore, unidirectional power control is more desirable as it allows the plant to operate at the maximum available power. A rather similar study was also conducted in [82], but the main difference was the use of bidirectional power control achieved by operating the PV system at 50% of the available solar power, thus leaving a range for significant participation in the damping process. The study presented in [83] indicated that slightly better damping is achieved by the bidirectional control as compared to the unidirectional control.

Through eigenvalue sensitivity computations, the authors of [84] proved that the critical mode is much more sensitive to reactive power control from PV than to active power. No previous study demonstrated the effectiveness of reactive overactive power for damping electromechanical oscillations (more recent research studies, however, suggested the contrary [48]). The most suitable stabilizing feedback signals were determined by computing the residues. The voltage magnitude and angle residues were studied. The inverter quadrature current was more sensitive to the voltage magnitude; therefore, it was the authors' choice for stabilizing feedback, although direct current could also be considered an option for other cases. The standard lead-lag structure was employed for the stabilizer. The tuning technique was analytical, but the authors did not elaborate sufficiently on the computation of the required compensation. Lead-lag structure was also adopted in [85–87]. An example of the incorporation of a lead-lag damping control in the inverter's current control loop is depicted in Figure 6, where the POD block consists of a lead-lag compensator and filters. The compensating time constants can be selected analytically, on the basis of the residue method, or using a numerical optimization procedure.

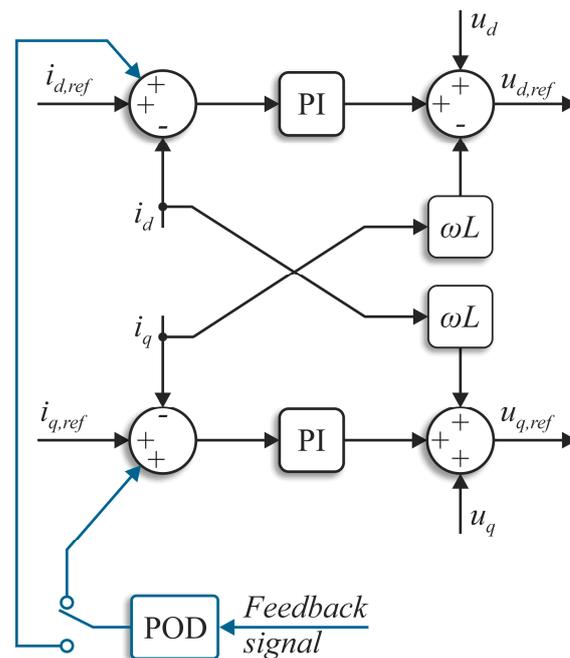


Figure 6. POD modulating the active or reactive current.

A damping controller for PV inverter was designed in [88]. The test system was a simple SMIB with the PV bisecting the transmission line. The feedback signal was the synchronous machine rotor angle deviation. The stabilizer was a simple integrator. Although the authors demonstrated the effectiveness of this approach, it is not very practical as the rotor speed deviation signal is not readily available. In addition, such a signal cannot be easily sent from the conventional power plant to the PV site. The authors extended their work by implementing particle swarm optimization for the POD controller [89].

The authors of [90] proposed the use of a structure-preserving energy function (SPEF) model to derive the POD control structure of PV inverters. Ultimately, the derived controller is a simple filtered derivative block, additionally equipped with low-pass and washout filters. This scheme takes the local voltage as an input signal, and the POD controller output is fed into the reactive current control of the inverter. The control diagram is depicted in Figure 6, and the switch is in a position to take over the control of $i_{q,ref}$. The goal of the implemented control is to increase the rate of power dissipation in the system, which is the fundamental requirement for the stability of any physical system. The usefulness of the idea was confirmed with simulations, as well as physical experiments.

Singh et al. developed a simple damping controller for both wind turbines and PV generators [91]. It consisted of wash-out and notch filters and a proportional gain. The notch was tuned for the interarea mode frequency. Since the output of the damping controller modulates the active power of the inverter, the gain must be low enough to comply with the equipment ratings. The input signal is the real power measured at the PCC to the power system. This is the first research study that we encountered in our review which examined the electromechanical damping in the frequency domain.

In [92], POD was simultaneously applied to both the active and reactive power control (Figure 7). The active power POD was connected to the battery control, and its feedback signal was the rotor speed deviation of the adjacent synchronous generator. The damped reactive power used the local voltage deviations as feedback. The classical lead-lag structure was used for both the PODs. Particle swarm optimization was used to minimize the transient response-based objective. It is difficult to evaluate whether two PODs significantly outperformed a single damper attached to either the active or the reactive power control, as the authors did not present such an analysis. Hence, the benefits of using two PODs remain unsupported by evidence.

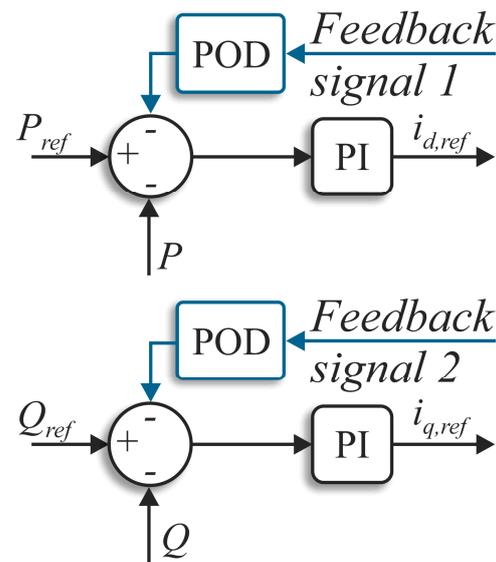


Figure 7. POD modulating the active and/or reactive power.

Li et al. recently published fundamental research on the mechanism of interaction between PV generation and synchronous machines [48]. The authors used a simple SMIB system including a PV generator to analytically derive the inverter current contribution to the damping and synchronizing coefficients acting on the synchronous machine's rotor. The study demonstrated that using rotor angle deviation as a feedback signal stacked with a PI damping controller can affect both the damping and the synchronizing coefficients. Using the frequency deviation as feedback with the PID damper affects both the damping and the synchronizing coefficients, as well as the resultant rotor inertia time constant. The computations indicated that the stabilization is more effective when applied to the inverter's P-control, but it requires the suboptimal operation of the MPPT to provide a sufficient range of active power modulation.

In another study, Silva-Saravia et al. proposed a method called step-down modulation (SDM) that does not require active power curtailment to enable the PV inverter to participate in the mode damping [93]. Upon the detection of electromechanical oscillations, the control method only temporarily shifts to the active power operating point to allow its bidirectional damping modulation. This approach is fairly similar to switching the inverter to STATCOM mode, as in [94]. After the mode is damped, the power is gradually restored to its maximum value. A single lead-lag block is used to compensate for the critical mode.

4.2. Damping Control Based on Wide-Area Measurement Signals

A more recent trend in POD research is to use feedback from WAMS. This section presents a chronological review of the advancements in this research field and examines the problems that demand solutions. The WAMS communication technology itself is a very broad area of study, and a comprehensive review is available in [95].

Shah et al. contributed to the robust design of POD synthesis for inverter-based generation. Their controller modulates the bus voltage reference signal, as shown in Figure 8. A minimax linear quadratic gaussian (LQG)-based power oscillation damper was used in [96] to improve the robust stability of the power system. The authors suggested that the features of minimax optimal controllers achieve an acceptable tradeoff between performance and robustness. The tuning procedure is complex and requires the estimation of an uncertainty matrix based on the probable operating conditions of the network. After the optimal stabilizer structure is synthesized, its order is reduced to make it effectively applicable. A similar study on minimax LQG was presented in [97]. In [98,99], Shah et al. demonstrated the possibility of using WAMS as an input to the inverter POD. In this case, the WAMS signal is the real power measured on a power line. The line to be measured is

determined on the basis of the mode observability technique. In [100], a more advanced study, Shah and Lee synthesized a low-order robust damping controller by defining a convex optimization problem, unlike similar contributions by others that rely on more complex nonconvex definitions [101]. Unlike Shah's previous works, this time, the most suitable feedback signal was selected according to the Hankel singular value. Ge et al. proposed a dominant mode ratio as a metric for the selection of the suitable feedback signal from WAMS [102]. Ge's dominant mode ratio identified the rotor speed deviation signal as the most potent in achieving higher damping, and it used a conventional PSS lead-lag structure. However, [102] did not take into account the WAMS time delay, which could be considered as the major drawback of this study.

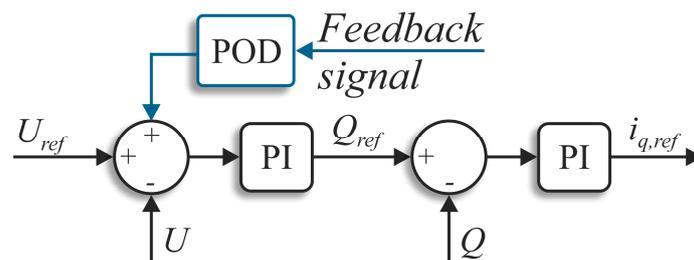


Figure 8. POD modulating the bus voltage reference.

Maleki and Varma developed a PV-STATCOM control scheme in [87,94]. At night, the inverter is operated purely as POD STATCOM, while, during the day, it operates in a PV mode and only briefly (for a dozen seconds) switches to the STATCOM mode upon detection of system power oscillations. The active power generation is entirely interrupted during the POD action, following which it is slowly restored to the pre-disturbance conditions. The feedback signal is the current measured on a line somewhere in the power system. In one of the test cases, the authors selected the current of a line that was not near the PCC. This would require the WAMS to provide the feedback signal. This aspect was not considered in these papers. The authors proposed an oscillation detection unit that activates the POD and the STATCOM mode. The POD is a first-order classic lead-lag with a washout filter. The first-order compensation is sufficient to damp a single interarea mode; however, in a real-life setting, there exist many modes. These studies do not provide clear observations concerning how the POD will react to electromechanical modes with frequencies differing from the tuned one, and they do not consider whether it would induce negative damping. The simplex method was used along with a master–slave technique to optimize the damping controller. In 2019, Verma et al. upgraded their PV-STATCOM concept with a fast frequency response to support the grid by reducing the frequency deviations through the inverter active power control [103].

Similar to the concepts already applied to wind power generators, Shen et al. applied goal representation heuristic dynamic programming (GrHDP) as an adaptive POD for PV generators, based on WAMS measurements [104]. The authors employed reactive power modulation for the damping control (see Figure 7). Adaptive dynamic programming was used to compensate for the feedback signal time delay. A time delay up to 750 ms was successfully tested. The latter was measured through the timestamps from the GPS system of the PMU. The GrHDP itself is a neural network (NN)-based controller. The three NNs work together: an Action NN performs the control, a Critic NN assesses the control quality and modifies the Action network accordingly, and a Goal NN modifies the Critic network by generating an internal reward signal. The authors proposed an offline training of the NNs, following which online training can be applied to adapt the POD to the varying operating conditions of the power system. Online training has a major advantage over classical POD control because the power system model details are usually not available to inverter manufacturers. However, extensive additional research is needed to address the issue related to the initial NN weights preset by the manufacturer before the

online training starts following the inverter grid coupling. The problem is that these preset weights can potentially degrade the power system stability, especially if the power plant has a high capacity.

Surinkaew et al. proposed a centralized damping controller based on WAMS [105,106]. The WAMS measures the real power flowing through the tie-lines between the areas. The centralized damping controller sends its stabilizing signals to the conventional generating units, wind generators, and PV inverters. The centralized POD is connected as depicted in Figure 8. The communication time delay is compensated for by a phase-lead block. However, this approach is less sophisticated as compared to others [104], and it is prone to performance degradation because, in real instances, the communication delay is subject to variations; hence, this fixed compensation is not expected to operate robustly. The authors proposed the implementation of a switch between the centralized and the local POD when the communication is interrupted. In a 2019 paper, Surinkaew and Ngamroo addressed the issue of the variable communication time delay of the WAMS by incorporating uncertainty into the POD parameter optimization [107]. In more recent studies, the authors applied a probabilistic selection of the WAMS signal on the basis of combined controllability and observability criteria [108,109]. It was demonstrated that, while a signal can be a good candidate for some operating points, for others, the same signal could be a bad choice. Therefore, the authors proposed the signal selection based on the power system state probability. Byrne et al. employed the vector Lyapunov technique to assess the effect of the structured uncertainties of communications in power systems with increased dispersed generation to improve the distributed control [110].

Multiple-model adaptive POD was developed in [111]. The authors proposed the use of the K-means clustering technique to reduce the number of operating conditions in terms of the observed electromechanical modes. The technique was used to develop a reduced number of damping control models. Each model was optimized for its cluster. During real-time operation, the different models are weighted dynamically, depending on the current operating mode to produce an optimal damping signal. A geometric approach was adopted to select the best feedback signal; the generator rotor angle was the best candidate in this case. This would require a WAMS. The authors tested the robust performance considering the feedback signal time delay but only for values up to 200 ms. No special means were utilized to compensate for the delay, and it seems that the multi-model approach inherently tolerates the latter.

Utilizing WAMS as a feedback signal for POD faces two main practical issues: communication delay and signal availability (reliability). Both of these issues are already being addressed in the literature. Different techniques for the selection of proper feedback measurement signals have also been developed. The analysis shows that the speed deviation of a synchronous machine and the real power flowing through a transmission line are the best stabilizing candidates, which are sometimes not even measured near the PV coupling point. It is even more complicated because it has been demonstrated that the efficiency of the feedback signals changes with the power flow conditions of the grid. Details regarding the practicalities of the general application of wide-area damping control in interconnected systems are available in [112].

4.3. Virtual Synchronous Generators

Zhong et al. proposed a novel static synchronous generator (SSG) control for power inverters [113]. Their idea is to use the well-established theory for synchronous machines and mimic that concerning the control of dispersed generation. This concept requires the presence of a small battery that will store/inject virtual kinetic energy, thus imitating an inertial response. A generalized diagram of SSG control is presented in Figure 9. The rotor mechanical equations block takes the reference active power P_{ref} , the nominal rotor speed ω_n (usually 1 p.u.), and the electromagnetic torque T_e as the inputs. The rotor speed ω_r and angle θ outputs are supplied to the electromagnetic equations block. The inputs of the latter are the measured inverter output currents i_{abc} and a field current component i_f , which is

proportional to the field winding mutual inductance M_f . Its outputs are the reactive power Q and the reference three-phase instantaneous voltage $u_{abc,ref}$ used to produce the PWM.

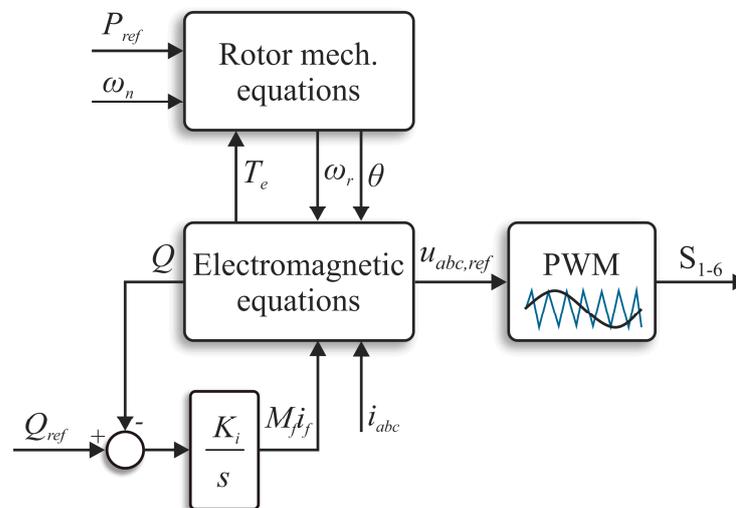


Figure 9. SSG/VSG inverter damping control.

This concept was applied by others for the control of storage systems with the capability of providing kinetic energy to the grid [114] or for hybrid solar power plants [83]. In [115,116], the same concept was named virtual synchronous generator (VSG) and was applied to a distributed generator with storage. Its main goal is to improve electromechanical damping. The PLL, together with the state-of-charge signals, is fed into the VSG control. The latter implements a linearized form of the electromechanical equations that are used to generate virtual inertia. The VSG control modulates the phase angle of the inverter control, i.e., its active power output. The presented simulation results look promising. Similar observations were also obtained from the laboratory experiments with real hardware. Further research by Miura and his team demonstrated an interesting approach by upgrading the VSG control with an alternating moment of inertia [117]. As the frequency tends to converge to the nominal value, the moment of inertia is decreased to speed up the recovery. When the frequency diverges from the nominal value, the moment of inertia is increased to limit the frequency excursion. In [118], the alternating moment of inertia was successfully demonstrated in a power system with multiple VSGs. Similar to the alternating moment of inertia, an alternating (adaptive) damping coefficient was proposed in [119]. The authors of [120] posited an alternative VSG control based on a state-space model using pole placement technique, which eliminates the need for PLL measurement. The results showed that this model provides the same damping characteristics as [116]. VSGs, being similar to actual synchronous machines, have an intrinsic oscillatory mode. Fixed-parameter damping methods using state feedback control were developed in [121] to damp the intrinsic mode. Four of the major VSG control schemes were incorporated in a unified modeling framework that can be used to study the inverter-based generation in different settings: grid-connected mode, islanded single inverter mode and islanded multi inverter mode [122]. A modification of the traditional VSG to improve the converter control under unbalanced voltage conditions was presented in [123].

The classical implementation of the VSG concept was verified for a bulk power system setting in [124]. The authors called the VSG a synchronous power controller. A more comprehensive study on the sensitivity of the power system stability to the VSG parameters was conducted in [125]. The small-signal model that was developed identified that three oscillation modes exist with poor damping induced by (i) the power control, (ii) the virtual impedance control, and (iii) the LC harmonic filter. High power droop gain or mechanical time constant can excite an unstable subsynchronous oscillation. The

value of the virtual resistance can also be a source of instability; low values will induce high-frequency synchronous oscillations (also studied in [126]), while high values will induce subsynchronous ones. The oscillation mode originating from the power control has relatively low damping for inverters connected to low-voltage grids. On the other hand, the LC filter mode dominates for high-voltage connections. Liu et al. also studied the impact of both virtual resistance and inductance in [127]. They concluded that reducing the inductance improves the interarea mode damping. The virtual resistance value depends on the damping strategy. Decreased values may improve the damping through the VSG active power control loop, while increased resistance could be favorable for damping from the VSG voltage control strategy.

The VSG small-signal model was extended in [54] to study the impact of the voltage closed-loop control (VCLC) on the observed oscillation modes. It was found that the VCLC could improve the damping induced by the LC filter, but this may degrade the virtual impedance mode. The VCLC also has a positive impact on the subsynchronous mode when applied to inverters connected to weak grids, such as the low-voltage ones. Another benefit of the VCLC is that it allows the accommodation of higher virtual inertia and droop, thus improving the inverter's inertial response.

In recent years, the VSG concept has been extensively developed, and this development continues to the present day. Although promising, such control has the inherent weaknesses of conventional synchronous machines. They introduce their oscillation modes that have to be dealt with. The main goal of VSG performance optimization is to select proper values for the virtual inertia and impedance, such that the POD control stays beneficial. This is not a straightforward task because the acceptable range or values strongly depend on the grid topology and the inverter's control scheme. General recommendations or a universal methodology for the proper selection of the virtual parameters are not available; hence, this must be done in a case-specific manner.

5. POD in Microgrids through PV Systems

In recent years, microgrids have become a much-promoted concept. A lot of research has been dedicated to developing their concept of operation and economics. Although microgrids are not attributed as much focus as bulk interconnected systems in terms of oscillation damping, some studies demonstrated the possible stability issues that arise from the interactions between power converters and loads and proposed remedial control solutions.

Kazemlou et al. considered an interconnected DC microgrid in [128]. Using only local measurements, the authors developed an adaptive nonlinear controller to mitigate the voltage and power oscillations, based on NN. As it is adaptive, the network learning is online, which omits the need for extensive offline learning with a big dataset. This is a major advantage as a dataset for such systems is not readily available.

Another significant study contributing to the POD control of DC microgrids was presented in [129]. Hamzeh et al. considered a composite generation setting that included a fuel cell, PV system, and supercapacitor. In this type of system, low-frequency oscillations originate from the power-sharing control unit. The control strategy presented in this study comprises a multi-loop voltage controller and a virtual impedance loop as an alternative to the conventional droop control. The virtual impedance loop implements a dynamic droop for efficient damping of the low-frequency oscillations. The authors applied the Guardian map theorem to guarantee a sufficiently robust stability margin. In addition to numerical studies, this paper presented hardware-in-the-loop (HIL) simulations to verify the efficacy of the proposed control. The results suggested that the HIL conveniently facilitates the development of microgrids in laboratory settings.

Jusoh et al. studied a DC microgrid setup consisting of PV arrays and constant power loads [130]. The authors explained the possible detrimental interaction between the power source and the load in terms of stability. The constant power load may present itself as a negative impedance, thus causing stability issues. The authors proposed stabilization of the DC grid using an active damping network that would introduce positive impedance,

which would compensate for the negative impedance of the loads. The damping network is a bidirectional DC–DC buck-boost converter, which draws a current proportional to the DC voltage, thus resulting in positive impedance.

Rafi et al. developed a modified VSI control that can operate and smoothly switch between the grid-tied mode and the island mode [131]. In the island mode, the inverter controls the voltage magnitude and frequency. The proposed modification of the typical control design presented robust operation under severe load conditions and improved oscillation damping. Small-signal analysis was used to set the virtual impedance gain to a suitable value.

A quasi-master–slave voltage/frequency control for microgrids was developed in [132]. The proposed control is capable of operating the microgrid both in the islanded mode and in the grid-tie mode. The small-signal stability of the grid was improved through the optimization of the DC capacitance, droop coefficients, and control parameters.

Satapathy et al. proposed the improvement of microgrid stability through an optimization of the converter's PLL and the diesel generator's governor gains, without implementing a dedicated POD [133]. The optimization was performed by developing a variation of the firefly algorithm. An improved firefly stabilization algorithm was developed in [134].

An interconnection between multiple microgrids was considered in [135], where load step changes in the microgrids were demonstrated to induce low-frequency inter-microgrid oscillations. The origin of these oscillations is the primary energy source of the PV installations and the DC voltage controllers. To dampen these oscillations, the authors proposed a POD that acts on both the real and the reactive power controllers. The inputs to the POD are the real and reactive power tie-line exchange errors, as well as the voltage and frequency deviations.

The effect of VSG control in microgrids was studied in [136]. Both the rate of change of frequency (RoCoF) and the frequency nadir were improved during large load disturbances. This study demonstrated that the VSG concept may be beneficial to power systems of any scale.

It is evident that, unlike large power systems, the possible configurations of microgrids are quite diverse, including DC and AC microgrids, independent or interconnected ones, and grids with or without synchronous machines. The nature of the stability issues also varies across the different configurations. The lack of a standard structure creates a major challenge for developing a universal control and damping management. This necessitates tailor-made solutions for every specific microgrid topology. This is the reason why the references cited above were only focused on particular configurations. While the application of firefly algorithms and NNs is a good scientific exercise, it is still far from being a practical reality for engineers. Hence, the development of a more general unified framework for the design and control of microgrids is imperative. The lack of such a framework is a major obstacle to the engineering and mass implementation of microgrids.

6. Summary of the Features of the POD Controllers

This section summarizes the features of the reviewed POD topologies concerning the type and origin of their inputs, destination of the output signals, control strategy, and optimization techniques.

Table 1 presents the types and the sources of the feedback signals utilized for damping control in the various research studies. In most cases, the POD relies on a single input signal, but there are instances where the damper topology requires two or even four signals (in a microgrid application). The signals can be categorized into two groups depending on their source: local and wide-area measurements. Among the local signals, the inverter's active power ΔP is the most used, followed by the frequency deviations Δf . In the studies dedicated to WAMS-based POD, the authors applied different techniques to determine the best signal. In most cases, ΔP was again revealed to be the best candidate, measured either on a tie-line or on a heavily loaded one.

Table 1. Feedback signals for POD.

Reference	Measured Signals
[79,80]	$\Delta P, \Delta U$: real power and voltage deviations
[83,85,91,96,97,100,120]	ΔP : real power deviations
[48,81,82,137]	Δf : frequency deviations
[84,90,92]	ΔU : voltage deviations
[77]	ΔI : current deviations
[48,88]	$\Delta \delta$: rotor angle deviations
[98,104–106]	P from WAMS on arbitrary line in the system
[94]	I from WAMS on arbitrary line in the system
[102]	$\Delta \omega$ from WAMS
[116,138]	$\Delta \omega$ from inverter's PLL
[86,92,139]	$\Delta \omega$ from nearby synchronous machine (WAMS use is not explicitly defined in the papers)
[135]	$\Delta \omega, \Delta U, \Delta P, \Delta Q$

Table 2 summarizes the applied POD control strategies. For several decades, the lead-lag phase compensation was widely used for the stabilization of synchronous generators. It is an extensively studied research area with several publications. This is probably the reason why the majority of the POD proposals are based on lead-lag control. Another conventional group of strategies relies on the well-known PID control or its P, I, D, and PI derivatives. In three of the references reviewed here, the POD structure was not fixed and was optimally synthesized. Our survey identified only two papers that studied the application of NNs. As of today, NNs have not been popularized for POD. The current trend, however, is the use of the VSG inverter control strategy. The highest number of research papers was dedicated to this type of damping control. This is probably because it simultaneously addresses two issues; it improves damping, and it provides an inertial response.

Table 2. POD controller structure.

Reference	POD Control Strategy
[48,79,80]	PID
[82,91,138,139]	P
[77,84–86,92,94,102,105,106,137]	Lead-lag
[88,89]	I
[48,135]	PI
[96,97,100]	Synthesized controller
[90]	D or filtered D
[54,83,113–127,140]	VSG/SSG
[104,128]	NN

The possible destinations (targets) of the damping controller outputs are summarized in Table 3. Some of the first and oldest studies modified the amplitude and the angle of the reference output voltage (see Figure 5). The more recent research studies targeted different parts of the decoupled control. Several studies applied POD to the active power control of the inverter. This approach has its drawbacks that derive from the power curtailment required to allow a margin for power modulation. More recent studies proposed strategies to detect stability-threatening events such that the power needs to be curtailed only in those short periods. Due to this complexity and reduced power efficiency, a more significant part

of the research is dedicated to modulating the reactive power or reactive current control loops. Only a few papers proposed the simultaneous application of POD to both the active and the reactive power loops (Figure 7). It remains unknown whether this strategy is advantageous, but it is certainly more complex.

Table 3. The POD signal destination.

Reference	Stabilizing Signal Is Fed into
[79–81,85]	Angle and amplitude controller
[48,82,92,135,139]	Both active power and reactive power controllers of the inverter
[77,84,90,94,96,97,100,102,104–106]	Power factor/reactive power/quadrature current controller
[83,86,88,89,91,116,120,137,138]	Active power controller

Table 4 summarizes whether the active power control is unidirectional or bidirectional. In the majority of cases, the modulation is bidirectional. Although the unidirectional approach is more favorable in terms of energy efficiency of the PV plant and, to a certain extent, is capable of coping with electromechanical oscillations, the bidirectional approach was proven to provide higher damping at the expense of real power output restrictions.

Table 4. Unidirectional/bidirectional POD through the active power control loop.

Reference	Unidirectional/Bidirectional Control
[81,88,89]	Unidirectional
[48,82,83,91]	Bidirectional
[86,92,116,120,139]	Bidirectional from an energy storage buffer
[79,80,85,135,137]	Authors did not comment or unclear from the paper

Optimizing the parameters of the POD controller is a crucial step as the wrong settings could significantly degrade the stability. Interestingly, a large number of research papers reviewed here did not comment on this important step (see Table 5). About half of these studies provided an analytical solution for the POD parameter computations, while the remainder defined objective functions and applied numerical optimization techniques to solve them.

Table 5. POD optimization techniques.

Reference	POD Controller Parameter Optimization
[77,79–81,86,90,91,97,106,139]	Authors did not comment
[48,82–84,88,102,116,120,138]	Analytic
[96]	Line search
[89,92]	Particle swarm optimization
[85,137]	Phase compensation
[100]	Solving Lyapunov functions and linear matrix inequalities
[94]	Simplex method
[105,133,134]	Firefly algorithm
[135]	Genetic algorithm
[104,128]	Offline and/or online NN training

7. Discussions on the Practical Application of POD Controllers

The POD of conventional generating units through PSS is based on well-studied, robust, and established techniques. Among them, the phase compensation approach [15,141–143] is the most widely recognized. It is widely used in practice, can be more or less easily verified on-site, and is based on well-defined theory. In contrast, this does not seem to be the case with POD for PV inverters. In most cases, the proposed tuning algorithms are very complex and can hardly be applied by utilities. While the PSS is typically tuned with either a SMIB model or a somewhat extended one, the tuning of the inverter's POD requires very detailed modeling of the power system. The latter is often not available to the plant owners, which makes the optimization of the POD controllers of PV plants hardly possible. On the other hand, the TSOs have full static and dynamic models of the grid. However, the PV plants, even the large ones, are several in number and distributed across the different locations of the grid. Having a large number of units makes it hard to tune and coordinate the PODs.

To overcome these issues, we propose two possible practical approaches:

Coordinated approach

- Standardize and adopt one or at most a few types of POD controllers for an inverter-based generation.
- Divide the transmission grid into a reasonable number of stability zones that are easier to manage in terms of stability analysis.
- Attach one or a few fictitious identical PV generators to each zone.
- Apply methods to find the optimal parameters for the PODs of the fictitious inverters for each zone.
- Utilities (e.g., TSOs) to request all plant owners in a given zone to set their inverters with the parameter values provided by the TSO.

Generalized approach

- Develop and standardize a universal POD structure and methodology that requires no retuning for the particular grid of application.
- Inverter manufacturers must follow the methodology to preset their PODs solely on the basis of the properties and sizes of their devices.
- This approach enables even the small-scale inverters connected to low-voltage grids to participate in the power system stabilization. The VSG is probably the best candidate among the reviewed concepts if its remaining issues are resolved and a practical methodology is established.

The second solution is more elegant, and it reduces the TSO's burden to tune and coordinate a countless number of PV plants. Fundamentally, it is a plug-and-play solution. However, extensive and complex research is required to develop and prototype this solution and prove that it works safely and consistently in practice. Although the first approach is not too easy to implement, it seems to be the more realistic choice, at least for the near future.

8. Conclusions

The impact of inverter-based PV generation on the small-signal stability of utility networks and microgrids has been widely studied, and, in many cases, this impact has been proven to be negative. One of the main reasons is the reduced inertial response in the power systems and control interactions with power converters. This situation calls for the development of dedicated POD control to mitigate the anticipated small-signal stability degradation.

The research efforts toward developing a POD for PV inverters date back to 1987 and continue to date. Many solutions have been proposed such as classical PID control, lead-lag compensation for stabilization based on WAMS and VSG, synthesized robust controllers, fractional-order controllers, and even artificial NNs. An extensive variety of algorithms have been applied to optimize the performance of these POD controls.

Although intensive research efforts have been dedicated to the development of POD control for PV inverters to date, the technology readiness level required for massive application to electric power systems has still not been achieved. The field offers ample opportunities for future research and standardization. The VSG concept is perhaps the best candidate for a future POD strategy as it is mostly based on the well-established theory of synchronously rotating masses. As found by our review, converters acting as VSGs may introduce undesired behavior and interactions between the current injecting devices in the power system, much like the conventional synchronous generators. Hence, more future research is needed to study the possible effects of massive deployment of VSG devices. Another barrier to be overcome in its application is the development of a more practical methodology that would help to robustly set its virtual parameters: inertia and impedance.

The other options for POD, such as PID, lead-lag, or fractional-order controllers, will require more research for the development of a well-established methodology for tuning their parameters. The main challenges are the need for coordinating the POD control of a huge number of converter-based generators and the need to know a detailed model of the hosting grid to be able to do the tuning.

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Abbreviations

CSI	Current-source inverter
FACTS	Flexible alternate current transmission systems
GrHDP	Goal representation heuristic dynamic programming
HIL	Hardware-in-the-loop
HVDC	High-voltage direct current
LQG	Linear quadratic gaussian
MPPT	Maximum power point tracking
NN	Neural network
PCC	Point of common coupling
PLL	Phase-locked loop
POD	Power oscillation damping
PSS	Power system stabilizer
PV	Photovoltaic
PWM	Pulse width modulation
RES	Renewable energy sources
RoCoF	Rate of change of frequency
SDM	Step-down modulation
SMIB	Single-machine infinite bus
SPEF	Structure-preserving energy function
SSG	Static synchronous generator
TSO	Transmission system operator
VCLC	Voltage closed-loop control
VSG	Virtual synchronous generator
VSI	Voltage-source inverter
WAMS	Wide-area measurement system

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