Navigating the Shift to Inverter-Based Generation: Selecting Effective Power Oscillation Damping Architectures

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***Abstract*—Electric power systems are susceptible to power oscillations arising from the interactions between generating assets and the electric grid. If not properly detected and damped, these oscillations limit the capability of transmitting maximum power and cause voltage and frequency disturbances. Power system stabilizers (PSSs) have been used in synchronous generators to control the power output via automatic voltage regulator (AVR) and damp low-frequency electromechanical oscillations, ensuring system stability. However, with synchronous generators being retired from operation and replaced with inverter-based resources (IBRs), there is a decline of synchronous machines with PSS capabilities to damp these power oscillations. To address this trend, the electric power industry has shown increased interest in deploying power oscillation damping (POD) techniques within inverter-based power plants. Two primary strategies to implement POD in IBR power plants are IBR- and power plant controller (PPC)-based POD. This paper investigates the application of POD in inverter-based power plants to support low-frequency (0.1 to 2 Hz) power oscillations damping and presents a direct comparison between inverter-based and PPC-based POD schemes. As PPC-based POD for IBRs represents a relatively new deployment application within the industry, it is important to review centralized vs. distributed POD characteristics and understand the benefits and challenges of each deployment.**

***Keywords*—Inverter-Based Resources, Low-Frequency Oscillations, Power Oscillation Damping, Power Plant Controller.**

I. Introduction

Electric power systems are susceptible to power oscillations arising from the interactions between generating assets and the electric grid, which may manifest as local or interarea modes. If not properly detected and damped, these oscillations limit the capability of transmitting maximum power and cause voltage and frequency disturbances. The growing integration of inverter-based resources (IBRs) has increased the risk of oscillations because inverters are dynamic assets that rely on firmware and settings to dictate their electrical response under various system conditions. Power system stabilizers (PSSs) have been traditionally used in synchronous generators to damp electromechanical oscillations by regulating output power through automatic voltage regulator (AVR) control, thereby ensuring system stability. Synchronous generators are being retired from operation and replaced with IBRs, leading to a decline of synchronous inertia and an insufficient capability to damp electromechanical oscillations. To address this trend, the electric power industry has shown increased interest in deploying an equivalent control mechanism to PSS in inverter-based power plants, called power oscillation damping (POD).

There are two primary strategies to implement POD in IBR-based power plants. The first strategy is at the IBR level. Individual inverters detect oscillations at either local or remote buses and independently modulate active and reactive power to provide damping. Local control requires minimal design and tuning, and each individual inverter can provide a fast and precise POD response since all computation occurs locally. However, the lack of coordination among IBRs can result in conflicting control actions, which may worsen the oscillation. IBR-based POD also introduces operational challenges, as settings and firmware must be managed individually at the inverter.

The second strategy is at the power plant controller (PPC) level. A single controller coordinates individual set points across many inverters. This strategy focuses on creating a response to damp oscillation at the point of interconnection (POI), typically on the high side of the transformer. Depending upon the site topology, the PPC-based POD response can differ significantly from IBR-based response characteristics. By coordinating the response at the POI, the PPC approach may provide more effective damping. However, this method requires careful handling of communications delays and other interactions between the PPC and the inverters to ensure a stable and effective response.

This paper examines the application of POD in inverter-based generation and presents a comparison of inverter-level and PPC-level POD architectures. The discussion begins with a review of power system low-frequency electromechanical oscillations and traditional damping methods, followed by an overview of inverter-based POD techniques. The paper then evaluates the benefits, challenges, and implementation considerations associated with distributed inverter-level POD and centralized PPC-based POD approaches, providing points for consideration and discussion regarding selecting effective oscillation damping architectures in inverter-based generation sites as electric power systems continue to add more of this type of asset.

II. Electric Power Oscillations

The electric power system is made up of many loads and generating sources, which must remain balanced to maintain stable voltage and frequency in the grid. Since the electric grid is composed of many independent loads and generation sources that do not necessarily coordinate when added or removed from the grid, there are cases where generation needs to balance

changes in demand. Events in the grid, such as transmission line and bus tripping, large load connection and disconnection, fault occurrences, etc., lead to transients, while the assets try to achieve new balancing. As these generation assets attempt to regulate their output to target levels, the generation assets may overshoot or undershoot because their responses are not instantaneous [1]. These generation assets may be electrically distant from each other, increasing the amount of time it takes for the generation assets to see the implemented changes. These fluctuations and responses of generation assets appear as oscillations in the power system. Oscillations are undesirable in the electric power system for various reasons, as oscillations may reduce the amount of power across transmission corridors [1] and cause additional mechanical stress on generators as the equipment physically responds to power oscillations, potentially depreciating their operating life [1]. Control and protection techniques are commonly used to minimize the impact of such events. As further discussed, the control of generating assets can support damping of low-frequency oscillations, but for larger oscillations and events, out-of-step tripping and remedial action schemes [2] can support system stability by isolating electrical areas. Power system disturbances may persist or increase if oscillations are not damped, leading to instability in the electric power system and requiring loads and generating units to be taken offline to ensure stability [3].

Typically, these oscillations are monitored in active power, frequency, or voltage angle, but other less common measurements, like rotor speed deviation of rotating generation, voltage, or reactive power flow, can be used [4]. Because electrical oscillations can arise from different physical and control interactions, they are generally classified according to the dominant interaction. Specifically, PSS and POD techniques focus on low-frequency electromechanical oscillations, which involve an exchange of energy between the rotating masses of synchronous generators and the electrical network. Following a disturbance, an unbalance between mechanical input power and electrical output power causes generator rotors to accelerate and decelerate relative to the rest of the system. This produces oscillations in rotor angle, speed, and electrical power until the exchanged energy is dissipated through system damping or the oscillation becomes unstable. Electromechanical oscillations typically occur in the approximate range of 0.1 to 2 Hz and may be divided into the following subcategories:

- Local-area oscillations: These oscillations typically range from 1 to 2 Hz and are categorized by a single generator or multiple generators that oscillate against each other in a close geographical region.
- Interarea oscillations: These oscillations typically range from 0.1 to 1 Hz and often involve groups of generators in a large geographic area oscillating against generators in another large geographical area.

This paper focuses only on low-frequency power oscillations and the possible solutions that can be facilitated by coordination and automation schemes of IBRs. As this paper discusses in detail in subsequent sections, the speed at which many inverters can be coordinated by communications, measurement, and centralized processing algorithms limits the effectiveness of POD mitigating oscillations above approximately 2 Hz.

III. Power Oscillation Damping

A. Concept

Historically, power system oscillations were primarily damped by synchronous generators. One of the primary mechanisms was the use of PSS through AVR in these synchronous machines (SMs). Because the synchronous generators were large, they would oppose any sudden change in generator speed. The primary technique for damping oscillations for the last half century has been the deployment of PSSs.

PSSs primarily damp power oscillations by modulating the synchronous generator excitation angle to create supplementary damping torque [1]. The PSS control is based on a gain block, a washout filter, and lead-lag phase compensation blocks to adjust the excitation with the correct phase relationship, creating additional electrical torque that opposes the swings generated by the oscillations. This acts as a shock absorber, damping the oscillations. The additional information from phasor measurement units allows for real-time coordination of data from multiple geographical areas to coordinate responses to further enhance damping methods [3].

As many synchronous generators are retired from power system operation due to age or changing fuel sources, these generation sources are not always replaced with new SMs. There has been a substantial increase in the use of IBRs with a variety of primary sources [5]. While these new generating assets replace the active and reactive power produced by SMs, they do not carry the same physical characteristics, requiring the reconsideration of how oscillations are handled in the electric power system.

The decline of synchronous inertia due to the retirement of SMs and the increased interconnection of IBR-based power plants has led to industry investigations into alternative strategies for ensuring sufficient damping oscillation capability. The concept of IBRs performing PSS functionality has been around since the 1980s [6], but only in the last decade have stabilizing controls implemented in photovoltaic inverters, commonly referred to as POD applications, been considered a feasible alternative to PSSs.

B. Comparison of PSS and POD

Fundamentally, PSS and POD applications attempt to damp low-frequency power oscillations in the electric power system; however, they achieve this through different mechanisms. As previously discussed, a PSS regulates output active power control by controlling the excitation phase of generators through AVR while an inverter modulates active and reactive power output. Table I provides a high-level comparison of these solutions.

TABLE I
PSS AND POD COMPARISON

Category	PSS	POD
Maturity	Established/Mature	Evolving
Communications Required	No	Yes, If Using PPC-Based POD
Benefits From Communications Data	Sometimes	Yes
Asset Response Speed	Fast	Faster
Control Options	Excitation Only	Active, Reactive, Both
Wide-Area Control Capability	Local	Local or Wide-Area

While PSSs are a time-proven solution for oscillation damping, POD may offer a practical path forward with the reduction in the number of synchronous generators in the electric power system, where POD is a control system capable of managing power oscillation responses of IBRs. Initial studies and experiments show that, though not a replacement, POD can be applied as a complementary technique to a PSS to support the damping of power oscillations in power systems with a declining presence of SMs [3].

C. Benefits

Inverters have the capability to react faster than SMs in adjusting inverter active and reactive power, potentially allowing for a faster response to the oscillation. Although dependent upon the target frequency of the oscillation, this benefit may not be a significant advantage of IBR.

IBR has the potential to adjust both its active and reactive power to mitigate oscillations, depending on the capability of the inverter, its available margin capacity, and the POD control algorithm. This allows for increased design flexibility when targeting various oscillatory modes.

While POD is still a relatively new concept compared to PSS solutions for oscillation damping, some studies and implementations have shown it to have similar effectiveness levels [4].

D. Challenges

IBRs are typically operated at or close to maximum output. When active and reactive power are used to control the modulation signal, the assets must have the necessary headroom capacity to meet the gain requirements of the POD algorithm for damping. If IBRs operate at or near maximum output, then the inverters will have limited capability to participate. IBRs reducing their current output to allow for modulation may unnecessarily reduce revenue, increase oscillations, or create further system instability.

IBR sites connected at transmission levels commonly have site nameplates of double-digit megavolt-amperes to multiple gigavolt-amperes, which require many inverters ranging from 0.5 MW to 5 MW or greater. All these inverters must respond in unison to create an effective damping response. PSS units tend to be larger units that require less coordination between generation assets.

For POD to be effective in damping oscillations, certain frequency ranges must be tuned with specific input parameters to the POD algorithm. System designers must know what is typical for oscillatory frequency modes. Knowing what frequencies will appear on the system may require a reactive approach rather than the proactive approach that PSS can provide. One potential proactive approach for POD is the use of system studies, which help identify frequency modes that may appear in the system.

E. Control Architecture

The PSS and POD control loops follow a similar architecture of washout low- and high-pass filters, lead-lag phase compensation filters, and gain, as shown in Fig. 1.

The low- and high-pass washout filters are responsible for cleaning the input signal based on the monitored frequency range. The lead-lag filters provide the needed phase shift to create a phase relationship between the input reference and output compensation signals that can support the oscillation damping. The gain defines the relationship between the input signal and the control signal amplitude.

The tuning of the filter coefficients requires careful study and design. Common approaches to support tuning include eigenvalue sensitivity analysis, frequency response methods, and time-domain validation using benchmark test systems. Usually, the target oscillatory mode and required phase shift are used as starting points. From there, the impact of the low- and high-pass filters to the signal phase input must be accounted for in the lead-lag phase shift design. Similarly, the attenuation or amplification introduced by each filter stage must be accounted for in the gain design. The output signal of POD is usually used as a compensation signal to manage either active power or reactive power. When a POD control loop is assigned to manage active power, it is commonly referred to as POD-P and frequency or active power are used as reference signal. On the other hand, when POD control loop is assigned to manage reactive power, it is referred to as POD-Q and voltage or reactive power flow are used as reference signals. When both control loops are enabled, this can also be referred to POD-PQ, even though POD-P and POD-Q are independent control loops managing active and reactive power, respectively.

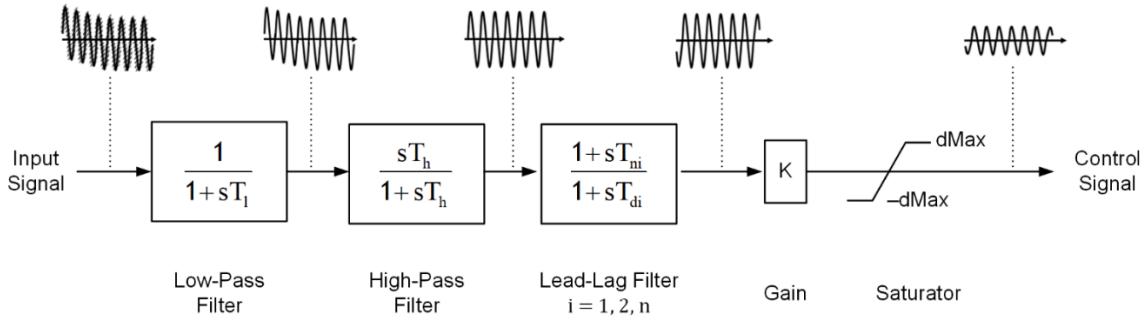


Fig. 1 Oscillation Damping Control Loop Architecture

F. Performance Metrics

The performance of a damping control is commonly validated by analyzing the improvement it provides to the oscillation damping, σ, and damping ratio, ξ. Considering (t_1, A_1) and (t_2, A_2) are the points of the first two peaks of an oscillation, the damping and damping ratio can be calculated based on (1) and (2), respectively.

$$\sigma = \frac{1}{t_2 - t_1} \bullet \ln\left(\frac{A_1}{A_2}\right) \quad (1)$$

$$\xi = \frac{1}{2 \bullet \pi} \bullet \ln\left(\frac{A_1}{A_2}\right) \quad (2)$$

The damping of a signal represents how fast the oscillation fades out per second, while the damping ratio is a dimensionless quantity that represents how the signal damping is relative to critical. The following list covers the different damping categories a system can present:

- Undamped ($|\xi| = 0$)
- Underdamped ($0 < |\xi| < 1$)
- Critically damped ($|\xi| = 1$)
- Overdamped ($|\xi| > 1$)

When analyzing the efficiency of a damping control, the system response when the control is enabled is compared to when it is disabled. Considering the two generic signals shown in Fig. 2 with normalized magnitudes based on their units, the damping and damping ratio of each signal can be calculated by (1) and (2), respectively, based on the first two peaks when the control is disabled, $P_1^d = (t_1^d, A_1^d)$ and $P_2^d = (t_2^d, A_2^d)$, and when the control is enabled, $P_1^e = (t_1^e, A_1^e)$ and $P_2^e = (t_2^e, A_2^e)$.

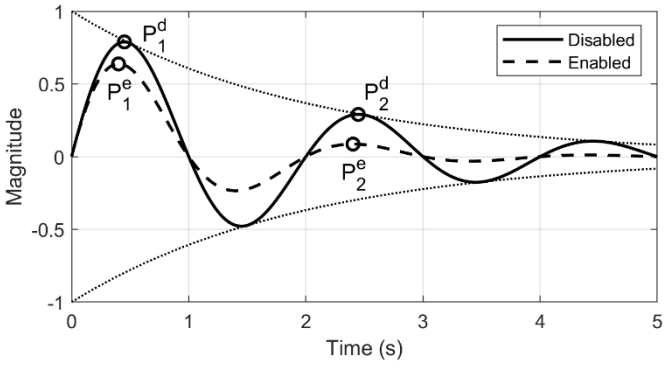


Fig. 2 Oscillation Damping Performance Analysis

The percent change in damping ($\Delta\sigma$) and damping ratio ($\Delta\xi$) can then be obtained based on (3) and (4), respectively, considering the response is not undamped ($|\sigma^d| \neq 0$ and $|\xi^d| \neq 0$).

$$\Delta\sigma = \frac{\sigma^e - \sigma^d}{|\sigma^d|} \bullet 100\ [\%] \quad (3)$$

$$\Delta\xi = \frac{\xi^e - \xi^d}{|\xi^d|} \bullet 100\ [\%] \quad (4)$$

where:

σ^d and ξ^d are the damping and damping ratio, respectively, for when the control is disabled.

σ^e and ξ^e are the damping and damping ratio, respectively, for when the control is enabled.

Such a relationship is essential when evaluating the performance of control, as enabling the control should not degrade the damping and, for POD applications, it is commonly required that the POD-P and POD-Q, when enabled exclusively or together, provide a damping ratio improvement, usually from 5 to 10 percent.

G. Economic Considerations

In addition to technical aspects, there are economic considerations when implementing POD in inverter-based power plants. Depending on the regulator code, the power plant POD functionality may be categorized as a requirement or an optional ancillary service. Based on the agreement, the plant may be compensated for this service during an event; otherwise, the reduction in exports can lead to a loss of revenue. In many markets, PSSs are not considered a market product, so IBR sites may need to operate below their rated nameplate capacity or approved export limits for a sufficient margin to operate POD. This may have implications for the profitability of IBR sites.

Additionally, deploying POD in inverter-based power plants requires specialized infrastructure and equipment. The communications network must be optimized and robust enough to enable fast monitoring of electrical quantity, as well as control of assets. It is then expected that the assets provide a superior response. The additional engineering and materials needed to obtain a reliable infrastructure to perform POD may significantly increase the design, deployment, commissioning, operation, and maintenance costs.

IV. Inverter-Based POD

A. Concept

An inverter-based POD control strategy is when the local inverter control is responsible for performing IBR POD functions. Such capability can be present in either grid-following (GFL) or grid-forming (GFM) inverters.

In GFL inverters, POD is typically implemented as additional control loops acting as POD-P and as POD-Q references. The structure of the POD controller is similar to a conventional PSS, consisting of low-pass and high-pass filters followed by lead-lag compensators, gain and saturator, as shown in Fig. 1. The input signal can be based on local or remote bus or branch measurements, such as frequency or active power for POD-P and voltage or reactive power for POD-Q.

GFM inverters regulate system voltage and frequency, typically using droop control or virtual inertia. Such capabilities inherently support system stability by regulating voltage and frequency. However, additional damping control may be implemented by using POD as a supplementary loop that modifies the frequency or voltage reference.

Fig. 3 illustrates the integration of POD into a generic inverter control architecture. The compensation signal created by POD modifies the outer loop of the inverter without interfering with the inner control loops. In the case of a GFL inverter, the outer loop is responsible for the active and reactive power references, while for GFM inverters, the outer loop is responsible for the frequency or voltage references.

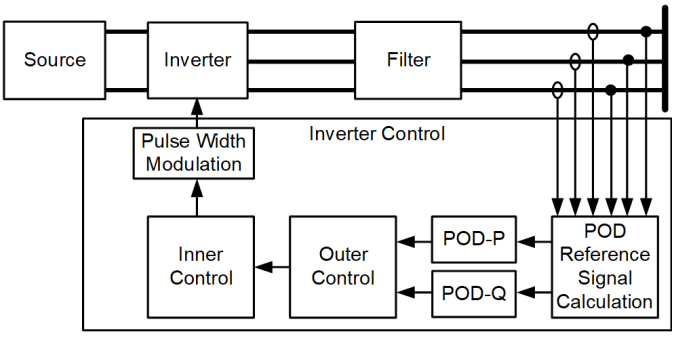


Fig. 3 Inverter-Based POD Architecture

B. Benefits and Challenges

The use of POD in either GFL or GFM inverters provides several advantages, but also presents challenges. As inverter-based POD does not depend on any type of communications delay, it allows for a fast dynamic response due to its local measurement, implementation, and modulation of active and reactive power, providing a more successful replication of PSS-like behaviors. However, the characteristic of local response also creates visibility and coordination challenges. Due to the local measurement, interarea modes may be missed and, especially for GFM inverters, there is a potential for the oscillation to interact with the inner control loops. In addition, for large power plants with multiple inverters, the independent operation results in a lack of coordination among inverters, which can lead to conflicting control actions that may worsen the oscillation rather than support its damping. Inverter-based POD also introduces maintenance challenges, as settings and firmware must be managed individually at each inverter.

V. Power Plant Controller-Based POD

A. Concept

In a PPC strategy, the damping algorithm and set point generation are removed from the generation asset and placed inside a controller. The controller sends coordinated set points to inverters to generate the appropriate response to damp an oscillation. By obtaining electrical measurements from the power plant POI, the PPC can perform oscillation detection and POD on various types of electrical quantities. Similar to the PSS, the PPC-based POD consists of low-pass and high-pass filters with lead-lag compensators and gain to adjust the phase and magnitude of the response, as shown in Fig. 1. The compensation signal is then integrated into the PPC core functionalities, responsible for managing operational active and reactive power set points to the plant assets.

Fig. 4 illustrates the PPC-based POD integration into an IBR power plant.

Several common processes in the control loop introduce delays, such as metering, processing, inverter response, and communications. Fig. 5 illustrates the control delays present in PPC-based POD architecture.

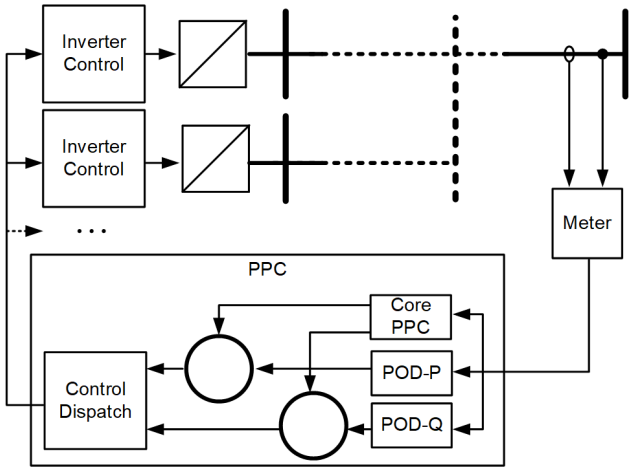


Fig. 4 PPC-Based POD Architecture in an IBR Power Plant

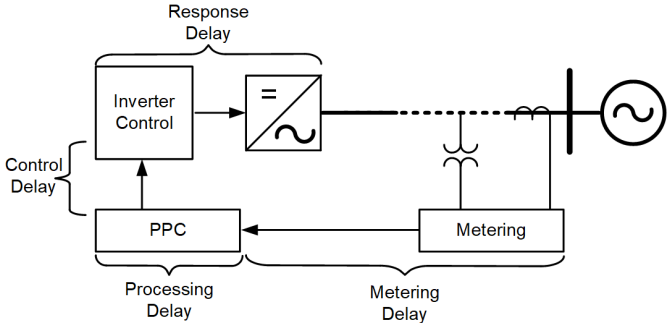


Fig. 5 PPC-Based POD Architecture Control Loop Delays

For most of the applications, POD creates a 180-degree phase shift to compensate for the oscillation and support its damping. However, with the delays, an additional phase shift must be introduced to properly compensate for the closed-loop

time delay. Fig. 6 illustrates the difference between ideal and realistic PPC-based POD control. The ideal control would provide a 180-degree phase shift, while the realistic control would provide a φ phase shift that accounts for the closed-loop delays in addition to the desired 180 degrees.

If the effective phase shift is not the designed one, this would reduce the effectiveness of the POD control, and it may take longer or may not reduce the oscillation at all. The calculations for identifying the acceptable margins to provide damping are beyond the scope of this paper.

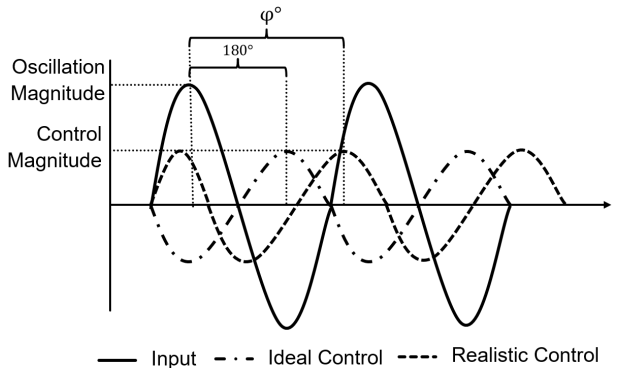


Fig. 6 POD Phase Shift Compensation

B. Benefits

Because PPC typically uses data transmitted over communications networks rather than physical metering connections, PPC-based POD offers flexibility in choosing where to monitor for oscillations. The PPC can take a reference signal from different metering points to perform POD, such as from an internal bus within the generation facility, from the POI with the transmission system, or from another metering point that is determined by the system implementers. The POD signal does not need to be the same feedback signal used for active and reactive power objectives at that generation facility.

PPC-based POD can be implemented with existing GFL inverters, which are not capable of POD algorithms, provided the inverters are capable of responding to the necessary speed of the set points generated by the PPC for damping. This allows for existing sites to potentially be upgraded at a significantly reduced cost compared to inverter-based POD.

A PPC has a complete understanding of the capabilities of all the inverters it manages. Some inverters may be limited by irradiance, out-of-service modules, or reduced capacity. The PPC can adjust set points across all inverters within a generation site, allowing for a nonproportional distribution while still meeting the overall site gain expectations of the POD algorithm—provided sufficient capacity is available in inverters across the generation site.

A PPC, in addition to its communications capabilities, offers significant flexibility in its algorithm inputs and tuning parameters during runtime—a flexibility that does not exist in many inverter implementations. Because oscillations may have dynamic characteristics over time, multiple oscillations may exist at the same time and common oscillation frequencies may change as system topology and load characteristics change. The PPC offers opportunities for more flexibility in the tuning and prioritization of different oscillation frequencies that may occur in the power system [3].

Unlike IBR-based POD, the PPC-based POD operates on a centralized architecture in which a single device is responsible for damping compensation rather than multiple individual inverters. As a result, this approach reduces the operational challenges associated with managing settings and firmware.

C. Challenges

While communications enable flexible design in the oscillation-detection signal and correction calculation of PPC-based POD, they also introduce challenges.

Depending upon the communications network, the data transmission delays may or may not be constant, leading to uncertainty and variability, which can be challenging for PPC-based POD tuning and performance. In a serial RS232 or R485 with dedicated communications channels, communications delays are likely to maintain a deterministic value. However, communications networks that share multiple devices on an RS485 network or an Ethernet-based network may experience dynamic transmission times in set points from the PPC to the inverters. In order for the POD implementation in a PPC to work effectively, it relies on stable and deterministic transmission times. While there are several engineering processes to stabilize and create deterministic transmission times in Ethernet-based networks, this generates additional complexities in the deployment of PPC-based POD. One technology, software-defined networking, offers a networking solution that creates deterministic networks in a predictable design pattern [7]. The cost of developing a suitable communications network for PPC-based POD may exceed that for regular power plant control. This is due to potentially increased costs in equipment and engineering when compared to IBR-based POD.

While the flexibility in the feedback signal for a PPC-based POD deployment is a unique benefit, it also introduces risk—the wrong feedback signal for oscillation detection and damping correction could be used for the area. Depending upon the characteristics of the oscillation, it may be more or less advantageous to use active power feedback, frequency, or voltage angle. Careful design and consideration of the oscillatory modes are needed in the selection of the feedback signal [3]. In addition, if the closed-loop time delays are not properly accounted for in the lead-lag phase shift design, or the as-designed and as-operated time delays differ beyond phase and magnitude margins, the POD control action may lead to unstable conditions rather than support the oscillation damping.

VI. Conclusion

The need for IBR generation facilities to contribute to power system stability will continue to increase. While POD may not be as straightforward as PSS design, it offers several opportunities for unique design and flexibility of local-area and interarea oscillation damping. As IBRs continue to become a larger percentage of generation connected to the bulk electric system, oscillation damping capabilities will increasingly transition from being a function of SMs to a function of

advanced control systems. The ability to effectively deploy, coordinate, and validate POD functions within inverter-based generation facilities will play an important role in maintaining reliable system operation and supporting future renewable integration targets. Continued research, field validation, and industry experience will further refine both IBR- and PPC-based POD approaches and help establish best practices for implementing oscillation damping in future power systems.

The question is no longer whether IBRs should contribute to oscillation damping but rather which control architecture in the correct circumstance can most effectively deliver that capability while maintaining reliability, scalability, and operational simplicity.

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VIII. Biographies

Konrad Schmitt received the PhD degree in electrical engineering from Texas Tech University, USA, in 2023, and the BSc degree in electrical engineering from the Federal University of Santa Maria, Brazil, in 2019. Konrad is a power engineer at Schweitzer Engineering Laboratories, Inc. (SEL), in Pullman, USA, where he supports the design, development, and validation of Distribution Management System (DMS) and advanced power system applications that improve reliability, continuity, quality, and safety of power delivery. Konrad's technical expertise is in the field of power distribution systems, where he has various technical publications and a book chapter related to network reconfiguration, self-healing, outage restoration and management, voltage control, and hardware-in-the-loop simulation. Since 2017, Konrad has been an active IEEE Power & Energy Society (PES) member and volunteer, where he has held local and global leadership positions, besides contributing to IEEE Technical Committees. He is a certified Project Management Professional (PMP) and member of IEEE Eta Kappa Nu (HKN), Tau Beta Pi (TBP), and Phi Kappa Phi (PKP) Honor Societies.

Brian Waldron is a senior automation engineer with Schweitzer Engineering Laboratories, Inc. (SEL). He has over a decade of experience in designing and troubleshooting automation systems, communications networks, and distributed energy resource (DER) control systems. He has authored several technical papers, application guides, and teaching presentations focusing on integrating automation products. Brian graduated from Gonzaga University with a BS degree in electrical engineering.

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