# Practical Wide-Area Measurement-based Power Oscillation Damping Tool with Adaptability

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***Abstract*—With the increasing complexity of modern power systems, low-frequency oscillations pose a serious threat to system stability. While wide-area damping control has emerged as a promising solution—enabled by advances in Phasor Measurement Units (PMUs) and Wide Area Measurement Systems (WAMS)—conventional Power Oscillation Damping (POD) controllers suffer from limitations due to their reliance on offline tuning and accurate system models. To address these challenges, this paper builds upon a previously proposed measurement-based Wide-Area Power Oscillation Damping (WAPOD) method that identifies system dynamics directly from measurements without requiring prior model knowledge. Extending prior work, this study presents a production-ready WAPOD tool designed for deployment in the field. The proposed scheme incorporates several new functional modules—including an Oscillation Detector, Modal Analyzer, and Probing Controller—to enhance robustness under non-ideal and uncertain operating scenarios. The effectiveness of the tool is validated through hardware-in-the-loop (HIL) experiments, demonstrating its reliability and adaptability for field applications.**

***Index Terms*—power grid oscillation, wide-area measurement systems (WAMS), wide-area power oscillation damping, adaptive controller**

## I. Introduction

With the expansion of modern power grids, low-frequency oscillations (LFOs) are one of the significant threats to power system stability [1], [2]. Generally, LFO can be categorized into two types: local oscillations and inter-area oscillations [3]. In recent years, advances in Phasor Measurement Units (PMUs) and Wide Area Measurement Systems (WAMS) have greatly improved grid-wide observability [4]. By leveraging synchronized remote measurements, wide-area power oscillation damping (WAPOD) controllers have shown superior performances in mitigating inter-area oscillations compared to traditional local power system stabilizers (PSSs) [5].

Extensive research has been conducted on designing POD controllers using PSSs, governors (GOVs), Flexible Alternating Current Transmission Systems (FACTS), and High-Voltage Direct Current (HVDC) converters [6]. However, traditional POD controllers are typically tuned offline based on simulations under one or several standard operating conditions, which leads to two major drawbacks. First, the simulated scenarios are limited and may fail to capture the complex and variable operating conditions of modern power grids. Second, this approach relies on an accurate dynamic model of the system, which can be challenging to obtain due to the complexity of large-scale power grids.

In previous work, a measurement-based Wide-Area Power Oscillation Damping (WAPOD) method was proposed [7]. The key advantage of this method is that it identifies the system's transfer function using only measurements, eliminating the need for prior knowledge of the system model. This approach was further enhanced in [8] with adaptive capabilities, allowing the controller parameters to be adjusted according to the grid operating conditions.

This paper continues the aforementioned works, with the aim of developing a production-level WAPOD tool for field application. To ensure readiness for deployment in a real power system, the primary focus is on achieving reliable performance under complex, non-ideal conditions. Thus, several functional modules, such as Oscillation Detector and Modal Analyzer, have been introduced to the scheme, with tests conducted under various uncertainties. In addition, the proposed tool supports the coordinated operation of multiple actuators for coordinated damping. The developed tool has been deployed and operating in a real power grid for more than a year.

The structure of this paper is as follows: Section II presents the architecture of the proposed WAPOD and discusses implementation details to enhance reliability, Section III shows the HIL tests & results, and Section IV concludes the paper.

## II. The Proposed WAPOD Tool

### A. Architecture of the Proposed WAPOD Tool

Fig. 1 illustrates the overall architecture of the proposed WAPOD. The software mainly consists of two modules: the damping controller adaptor and the actuator interface adaptor.

The damping controller adaptor implements the control functionality. This adaptor contains a core damping control module, which processes the data collected from primary and backup PMU and generates streamed control commands (CMDs). Details of the adopted algorithm could be found in [7]. CMDs are subsequently forwarded to the actuator interface adaptor. The damping controller adaptor also includes multiple pluggable modules to meet various requirements in real-world power system operations, which will be introduced

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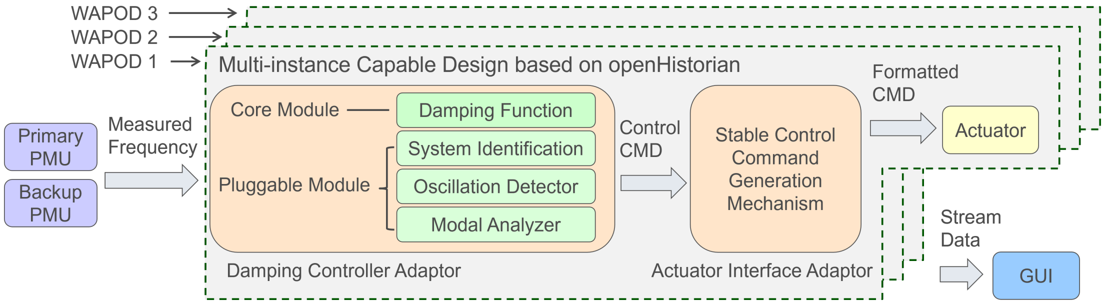


Fig. 1. The Architecture of WAPOD System

in the next subsections. The actuator interface adaptor ensures stable generation of control commands and is responsible for communicating with the actuators.

The proposed WAPOD is integrated into the open-source openHistorian platform [9], which provides interfaces for processing streaming time-series data and includes native support for the IEEE C37.118 synchrophasor communication protocol [10]. The framework also provides a GUI, which is implemented based on Grafana [11].

It should be noted that the tool adopts a multi-instance capable design that supports multiple WAPOD controllers and actuators operating simultaneously.

### B. Oscillation Detector

In grid operation, normal fluctuations and minor disturbances can cause small deviations in frequency or angle. If these variations were allowed to directly drive the damping controller, the controller could generate unnecessary or overly reactive outputs, potentially introducing control noise to the system. To prevent this, an oscillation detector acts as the triggering mechanism for the entire damping control system by evaluating whether a significant and sustained oscillation is present. Only when such an oscillation is reliably detected will the downstream damping controller be enabled.

The algorithm for oscillation detector is shown as follows.

**Algorithm 1** Oscillation Detection Algorithm

**Input:** Frequency data in both primary and backup PMUs
**for** each PMU **do**
  Set $counter \leftarrow 0$
  **while** data for a time window have all been received **do**
    Calculate the peak-to-peak frequency
    **if** peak-to-peak frequency $>$ threshold **then**
      $counter \leftarrow counter + 1$
    **else**
      $counter \leftarrow 0$
    **end if**
    **if** $counter >$ counter threshold **then**
      enable WADC
    **end if**
  **end while**
**end for**

### C. Modal Analyzer

The modal analyzer performs real-time identification of oscillation modes using ambient frequency data. It employs the ARMA-based estimation algorithm [12] to extract the modal parameters including oscillation magnitude, frequency, and damping ratio.

These modal characteristics are used to determine which oscillation mode is currently active in the grid. Based on this information, the WADC framework can implement mode-specific control logic, where a damping controller designed for a particular mode is enabled only when the modal analyzer indicates that the ongoing oscillation matches that mode. This function allows users to define more flexible control logic, for example, allowing multiple controllers to coexist while operating only under the conditions relevant to their designated modes.

### D. System Identification and Adaptive Parameter Update

The system identification module estimates the transfer function of the power system and updates the damping controller parameters accordingly. Since grid topology, operating conditions, and power flow patterns can change over time, fixed controller settings may become mismatched with the actual system behavior. To address this, the controller integrates system identification function based on measured system responses and is able to adjust its internal parameters so that the control action remains aligned with the current grid dynamics. The system identification could be performed either periodically or at user-defined times

The identification process is implemented through a probing mechanism. A sequence of small pulse-like signals is injected into the power grid through the actuator, with each pulse separated by a user-defined time interval as shown in Fig. 2. The amplitude of the probing signal is a critical parameter. The proposed tool allows the probing amplitude to be specified by the system operator based on grid conditions. A default probing amplitude of 0.04 p.u. is adopted, which has been verified to be sufficiently small to avoid noticeable impact on system operation while still providing adequate excitation for system identification. In practice, this value is usually determined by the allowable amount of energy (e.g., active or reactive power) that can be temporarily injected without

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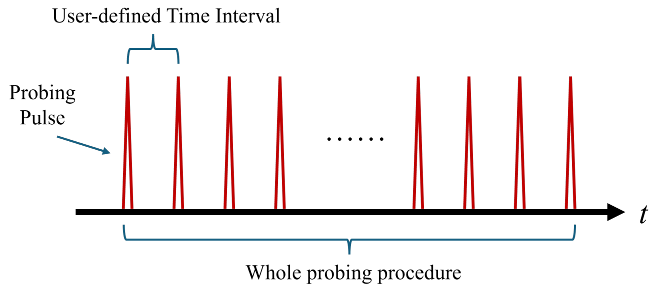


Fig. 2. Illustration of probing test procedure

violating operational limits. Besides, multiple relatively low-amplitude probing pulses instead of a single high-amplitude pulse are used and averaged for identification algorithm. This design also allows the amplitude of each pulse to be kept low. Probing is only permitted when no oscillation is present; if the oscillation detector indicates that an oscillation has occurred, the probing sequence is immediately terminated.

### *E. Multiple PMU Sources and Supervisory Control*

To address potential communication failures in the field, the system allows configuring multiple PMU data sources. A primary PMU is used during normal operation, and one or more backup PMUs are available for use if the primary source becomes unavailable.

The communication quality of each PMU is evaluated based on data delay. A PMU is considered to be in a valid communication state only when the delays of its incoming data points remain within a specified range for a predefined period of time.

A supervisory control module implements the source-selection logic. Based on the communication status of all configured PMUs, it determines when to continue using the primary PMU and when to switch to a backup source. If both primary and backup PMUs fail, it will perform re-initialization and send out warning messages.

### *F. Coordinator for Multiple Controllers & Actuators*

The coordinator module is introduced to address practical deployment challenges arising from the centralized wide-area control architecture. Since all measurements and control CMDs are processed at the control center, software-level coordination is required to ensure reliable and scalable operation when multiple controllers and actuators are configured. The design principle is as follows: for functions with low computational cost, they are kept independent to improve reliability; for functions with higher computational cost, users may choose between shared mode (to save resources) or independent mode (to enable differentiated control strategies). For probing, the module ensures that multiple actuators execute their probing sequences in an ordered manner. It should be noted that the coordinator does not modify the damping control logic. The coordination strategies are summarized in Table I.

TABLE I
COORDINATOR STRATEGY

| Function | Strategy |
|---|---|
| Oscillation Detector | Independent |
| Modal Analyzer | Shared or Independent |
| Probing | Coordinate actuators to perform probing sequentially. When one actuator is executing its probing sequence, all other actuators hold their outputs constant. |
| Supervisory Control | Independent |

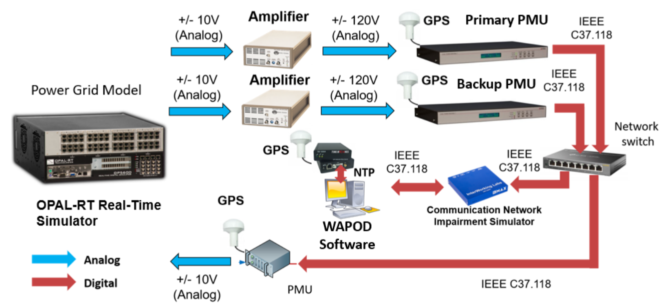


Fig. 3. HIL Test Setup

## III. HARDWARE-IN-THE-LOOP VERIFICATION

### *A. Testing System*

HIL experiments have been conducted to verify the performance of the developed WAPOD tool. The framework of the HIL test setup is shown in Fig. 3. A transmission network with approximately 4,000 buses is used as the test power grid. Two PMU measurements are configured as the primary and backup data sources, and two synchronous condensers in the system are selected as the actuators. The test power grid was emulated on the OPAL-RT's real-time digital simulator. An amplifier was used to step up the voltage from ±10V to ±120V to emulate the secondary side of a potential transformer and feed the analog voltage signal to PMU devices. A communication network simulator is used to introduce signal latency and data package loss to test the controller performance in non-ideal communication environment. Upon receiving PMU data, the WAPOD software generates control commands and sends them to an enhanced PMU with physical interfaces to actuators via the IEEE C37.118 protocol. Finally, the control commands were converted into ±10V analog signal and fed back to the Opal-RT simulator to control the actuator.

For the two WAPOD controllers, the target oscillation mode is set to 0.24–0.31 Hz. Since both controllers act on the same oscillation frequency range, the modal analyzer is configured in shared mode.

### *B. Basic Verification*

Two consecutive generation disconnections occurred at $t = 150s$ and $t = 350s$ were simulated to trigger an oscillation in the testing system. The measured frequency and behavior of the WAPOD tool are shown in Fig. 4.

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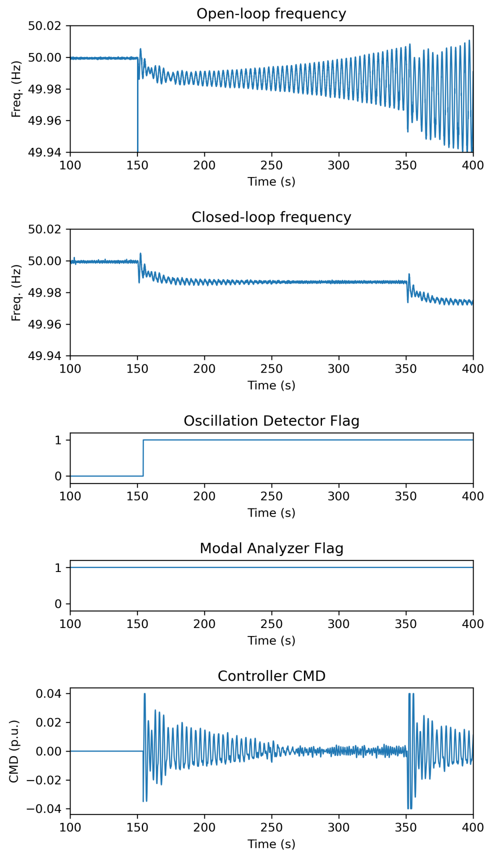


Fig. 4. Control Results of Typical Oscillation Event

It can be observed in Fig. 4 that under open-loop conditions, the event develops into a growing 0.27Hz oscillation; while with the WAPOD control enabled, the actuators effectively damped the oscillation, demonstrating the effectiveness of the proposed approach. The oscillation detector flag switched to 1 at about 4s after the event happened, and the controller started generating CMD outputs. Because the oscillation frequency fell within the configured target frequency range, the modal analyzer flag remained at 1.

Several other typical events were also used to validate the proposed method. For oscillations with small amplitude and high damping ratio, the conditions of the oscillation detector are not satisfied, and its flag remains 0. For oscillations whose frequency does not fall within the target frequency range, the modal analyzer conditions are not satisfied, and its flag also remains 0. In both cases, the WAPOD does not generate any CMD output.

### *C. Experiments under Degraded Communication Conditions*

To further evaluate the proposed approach, several degraded communication conditions were simulated and tested, as summarized in the Table II. The disturbance applied in the power grid remains the same as in the previous section, consisting of two generator trips.

TABLE II
TESTED DEGRADED COMMUNICATION CONDITIONS

| Idx | Scenario | Description |
|---|---|---|
| 1 | Constant Delay | Constant 200 ms delay<br>Constant 400 ms delay |
| 2 | Random Delay (Gaussian) | 200 ms mean, 50 ms std deviation<br>200 ms mean, 100 ms std deviation<br>200 ms mean, 150 ms std deviation |
| 3 | Data loss | 100 s chunk data loss<br>5% random data loss |

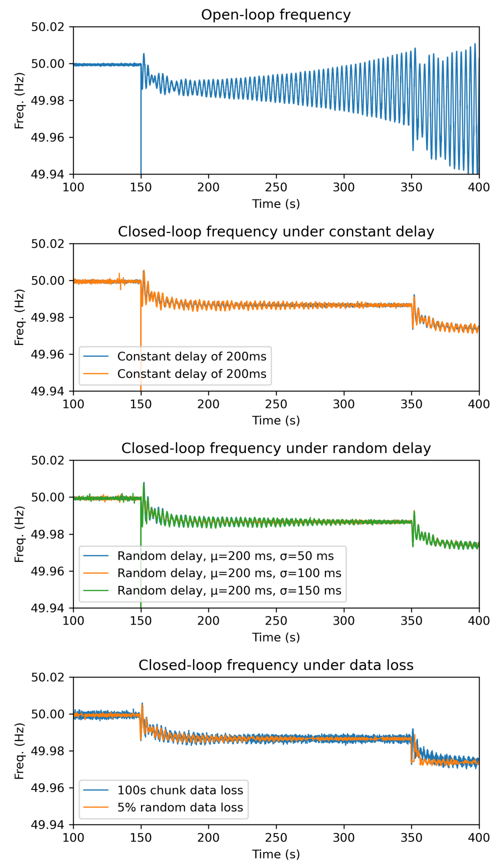


Fig. 5. Control Results under Degraded Communication Conditions

The results are shown in Fig. 5. It could be observed that in all scenarios listed in Table II, the proposed approach successfully damped the oscillation, demonstrating that the proposed method exhibits strong robustness under degraded communication conditions.

### *D. Experiments of Probing-based System Identification*

We also used the HIL platform to test the probing-based system identification. Fig. 6 shows the waveform in which the two actuators perform probing one after the other. Table III shows several WAPOD parameters and the corresponding control results after system identification under two different oscillation modes. It could be observed that the controller parameters can be updated adaptively and both oscillations can be effectively damped.

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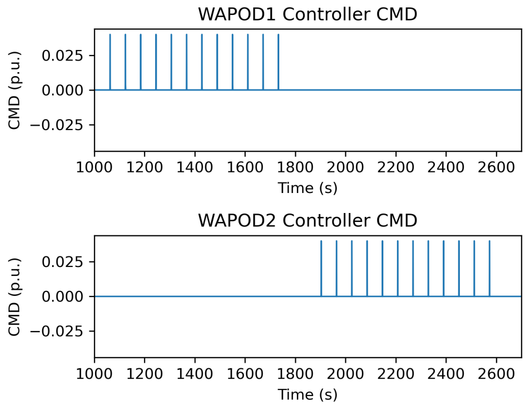



Fig. 6. Probing Signal

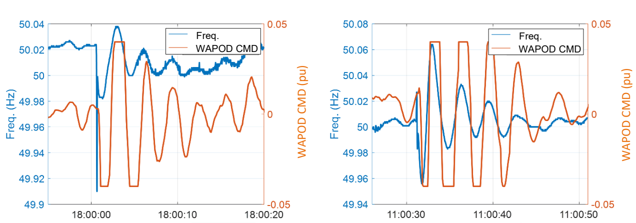
TABLE III
EXPERIMENT RESULTS OF PROBING-BASED SYSTEM IDENTIFICATION

| Idx | Oscillation Frequency (Hz) | Compensation Angle (degree) | Control Gain | Damping Ratio (%) | |
|---|---|---|---|---|---|
| | | | | Open-loop | Closed-loop |
| 1 | 0.62 | 28 | -24 | 2.0 | 10.3 |
| 2 | 0.49 | 87 | 82 | 3.3 | 13.1 |

## IV. FIELD TEST

To further evaluate the readiness of the proposed WAPOD, a long-term open-loop field test has been conducted in an operational power grid. During this testing period, the WAPOD system continuously processed real-time PMU measurements and generated controller CMDs, while no control action was applied to field actuators. During testing, the oscillation detector was intentionally bypassed so that the controller will continuously generate CMDs. Two representative disturbance events recorded during the field test are presented in Fig. 7.

As shown in Fig. 7, the generated controller CMD signals exhibit a clear in-phase relationship with the measured system frequency during both disturbance events, which is consistent with the expected damping control behavior. Althrough the recorded disturbances are relatively slight, the results confirms that the validity of the proposed control logic & system.




(a) Disturbance 1 (b) Disturbance 2

Fig. 7. Recorded Disturbances during Open-loop Testing

## V. CONCLUSION

This paper presented a practical measurement-based WAPOD tool designed for real-world deployment. Several functional modules, such as the oscillation detector, modal analyzer, probing-based system identification, multi-PMU supervisory logic, and actuator coordination, were integrated to ensure reliable operation under non-ideal and varying grid conditions. The tool was implemented on the openHistorian platform and validated through HIL experiments on a large-scale transmission grid. Results demonstrated effective oscillation damping, robustness to communication issues, and adaptive parameter updates, confirming the applicability of the proposed approach for wide-area damping control in practical settings. The developed tool has also been deployed in a real power grid, where it has operated reliably for more than a year.

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