Field Implementation and Hardware-In-the-Loop Testing of Wide-Area Damping Controller as OpenPDC Adapter

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***Abstract*—In our previous research, a measurement-driven wide-area damping controller (WADC) design method for suppressing inter-area oscillations has been proposed and a hardware prototype was developed and validated through Opal-RT real-time simulator. As a continuation of the work, this paper introduced the implementation of WADC software prototype, which is developed and operated as an openPDC adapter. A graphical user interface (GUI) is also developed to monitor the input frequency signals, communication delays from the primary and backup PMUs, the status of WADC, and the output WADC command. The WADC software prototype was fully tested in an enhanced hardware-in-the-loop (HIL) test setup. Its performance is verified by using different communication protocols (TCP and UDP) under various communication uncertainties, such as random time delays, random and chunks of data loss. The results of the experiment indicate that the designed WADC can deliver sufficient damping to suppress the targeted oscillation mode, and it has the capability of future field deployment.**

***Keywords*— wide-area damping controller (WADC), hardware-in-loop (HIL), inter-area oscillation, openPDC adapter**

I. INTRODUCTION

In modern interconnected power grids, various types of oscillations, such as inter-plant mode oscillations, local mode oscillations, control mode oscillations and inter-area mode oscillations, have posted major threats on power system stability. Furthermore, poorly damped inter-area oscillations are proven to have the most severe impacts on interconnected power systems since unstable oscillations can result in possible system collapse [1], [2]. The development in synchrophasor measurement devices and the wide-area measurement system (WAMS) contributed greatly in the monitoring and suppression of inter-area oscillations. The massive deployment of phasor measurement units (PMU s) in the last decades enabled the real-time identification of inter-area oscillation. By utilizing these remote synchronized measurements, significant improvements also have been made in the damping control of inter-area oscillations when comparing to using the traditional local power system stabilizer [3], [4].

Several wide-area oscillations damping controller (WADC) algorithms have been designed based on measurement driven approaches recently and proven to have effective damping performance by tests and simulations. A novel wide-area control strategy by modulating active power injection on the power system has been proposed in [4] to damp critical frequency oscillations such as inter-area oscillations and the transient frequency swings. An adaptive control scheme based WADC control techniques, that was capable of damping both forced oscillations and inter-area oscillations simultaneously, was designed and validated with various uncertainties and disturbances in [5]. A WADC control algorithm was developed by using system transfer functions identified from synchronized measurements collected during system disturbances, and its performance was validated by an actual undamped oscillation event in [6]. Another study on adaptive WADC technique was conducted in [7], and it has shown better ring-down performance by adaptively updating the controller parameters based on corresponding operating condition.

The WADC from work [6] - [7] was implemented and tested with hardware-in-the-loop (HIL) setup thoroughly in [8], and the test results have ensured the proposed WADC can reach satisfactory performance under realistic operating conditions. In this paper, as a continuation work of [8], the implementation of WADC software prototype was introduced. The software prototype was implemented and operated as an openPDC [9] adapter. A GUI is developed along with the WADC software for monitoring the input signals from PMUs and the output command and status of WADC software. The prototype is fully tested in an enhanced HIL test setup with various communication protocols and uncertainties involved. The experiment results indicated WADC software prototype can deliver satisfactory level damping performance.

The structure of this paper is organized as follow. In Section II, the implementation of WADC software and GUI is discussed. Section III introduces the HIL test setup. The test results verifying WADC damping performance under different communication uncertainties using both TCP/IP and UDP/IP communication protocol are presented in Section IV. Lastly, Section V concludes the WADC software prototype and its potential developments in the future.

II. WADC Software and GUI Implementation as OpenPDC Adaptor

The openPDC is a complete Phasor Data Concentrator software tool designed to process time-series data steam in real-time. The PMUs used as WADC inputs are configured to streaming GPS-synchronized measurements to openPDC using IEEE C37.118 [10] communication protocol. This section will present how WADC software is integrated into openPDC as an adaptor and the GUI that is specifically designed for user-friendly monitoring purpose. Both WADC and GUI are implemented using C# programming language.

A. *WADC software and its integration into openPDC*

The WADC software's overall structure is shown in Fig. 1 below. The WADC software are required to be installed in the root folder of openPDC in order to run as its adaptor. The WADC algorithm reads control parameters from a parameter configuration file, then calculates the control command based on the PMU measurements.

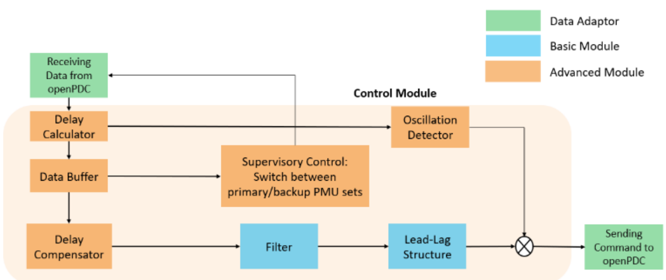

Fig. 1. Overall structure of WADC

The data adaptor modules are capable of converting the PMU measurement data from IEEE C37.118 format into the format required by the WADC algorithm. Once the openPDC is running as a Windows service, these modules will continually be forwarding the data to WADC, receiving the WADC output commands, and sending these commands to user-defined destination IP addresses.

The WADC function modules includes both basic modules and advanced modules. The basic modules include filters and lead-lag structure blocks that are implemented from transfer function. The parameters of these transfer functions are configurable through the configuration file. The advanced modules include the following blocks:

- Delay Calculator: Used to determine each PMU data point's time delay. The delay is computed by subtracting the PMU measurement timestamp from the computer timestamp.
- Data Buffer: Used for selecting specific data point from the most recent 3 seconds PMU measurements for the command calculation.
- Supervisory Control: Used to control the switch between the primary and backup PMUs in situations of communication failure. The switching between PMU channels are determined by 2 parameters, the buffer size and supervisory control threshold. If the delay of the most recent 3s PMU measurements is in the range of (buffer – threshold) ms <= PMU delays <= (buffer + threshold) ms, the PMU channel will be evaluated as good communication. If bad communication is detected only for primary PMU channel, the WADC will switch to backup channel for command calculation immediately. Once the primary channel resume good communication for continues 5s, the WADC will switch back to use primary channel for command calculation. This is for preventing the switch between PMU channels happens to often. In case both PMU channels are marked as bad communication, the WADC will output 0 until communication is resumed for over 5s.
- Oscillation Detector: This module monitors the oscillation in the system and decides when to activate or deactivate the damping controller.
- Delay Compensator: Implemented with several transfer functions that have configurable parameters.

B. *WADC monitoring GUI implementation*

Since openPDC operates as a Windows service without a Graphical User Interface (GUI), a separate GUI is developed to display the bus frequency, time delay, control command, etc. The screenshot of the GUI is shown is Fig. 2 below.

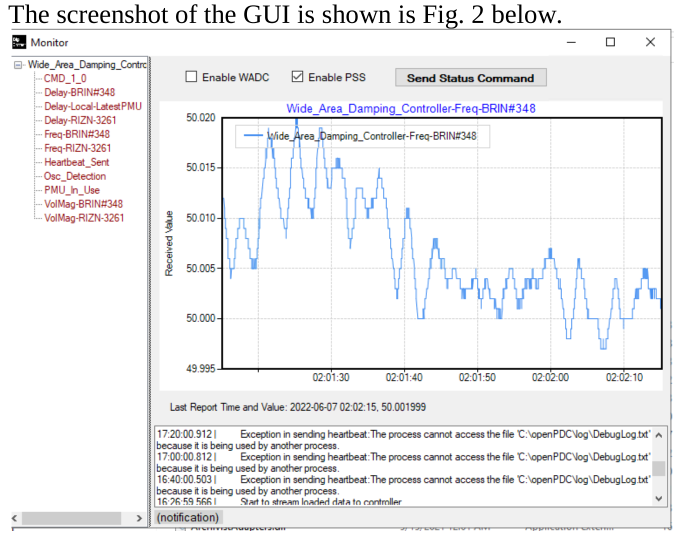

Fig. 2. WADC monitoring GUI interface

III. Hardware-In-Loop Test Setup

The damping performance of the WADC software prototype is tested on a HIL platform [8]. Most major components are similar as the HIL setup in [8] with few upgrades included in order to compatible with the software WADC. The complete HIL test setup are shown in Fig. 3.

The Continental Europe Synchronous Area system with detailed Italy power grid models emulated on the OPAL-RT's real-time digital simulator OP5600. Two condensers at South Italy is used as the actuator of WADC to damp the inter-area oscillation between Italy and France. The bus frequency PMU measurements are collected by openPDC and then send to WADC for real-time control command calculation. The network simulator (KMAX) [11] is used to mimic various network uncertainties such as random time delay, random data drop, etc. to test the software WADC's delay compensator performance, random data lose tolerance and the functionality of supervisory control. The LogicLab enhanced PMU device is an executor that receives the WADC control commands in a specified data frame. Then, the LogicLab PMU can convert the digital control command into 4-20 mA analog signal.

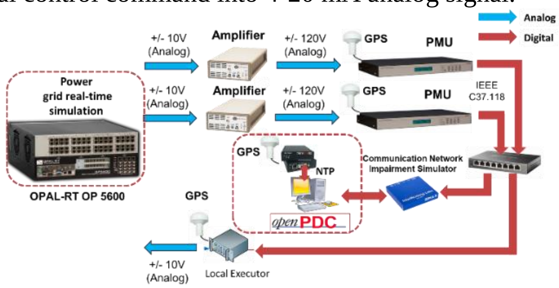

Fig. 3. HIL test setup for WADC

IV. Hardware-In-Loop Test Results

In this section, the WADC HIL experiment findings will be presented. The conducted experiments cover inherit delay plus constant delay, inherit delay plus constant delay with random variation, random data drop tolerance, and supervisory control performance. The WADC HIL experiment performance were compared using both TCP/IP and UDP/IP communication protocols. The effect of utilizing different buffer sizes are also included in this section.

A. Constant delay compensation

Various constant delays are added by the network simulator to simulate scenarios that total delay equals to 600ms, 800ms, 1000ms, and 1200ms for both TCP and UDP protocols. The test results are shown in Fig 4 and 5 below. The WADC with delay compensator module has good damping performance for both communication protocols in various constant delay scenarios. The WADC can tolerate up to 1200ms time delay.

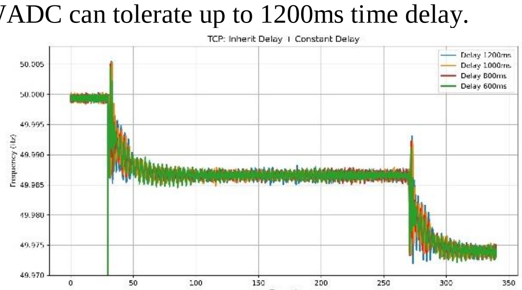

Fig. 4. WADC performance for constant delay compensation under TCP/IP

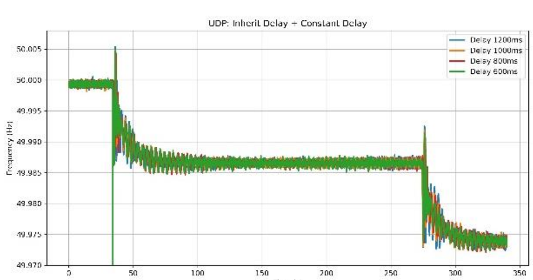

Fig. 5. WADC performance for constant delay compensation under UDP/IP

B. Random delay compensation

In this experiment, random variations have been added on top of constant delay by the network simulator. The 4 random delay variations and WADC performance are listed below:

- Buffer size 300 ms: Gaussian mean value 200ms constant delay plus 50ms variation
- Buffer size 300 ms: Gaussian mean value 200ms constant delay plus 150ms variation
- Buffer size 700 ms: Gaussian mean value 400ms constant delay plus 50ms variation
- Buffer size 700 ms: Gaussian mean value 400ms constant delay plus 150ms variation

The results are shown in Fig. 6 and 7 below. The WADC using the proper buffer size can handle random delay scenarios with acceptable damping performance for both communication protocols.

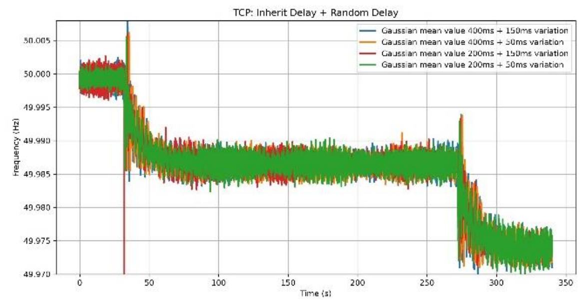

Fig. 6. WADC performance for random delay compensation in TCP/IP

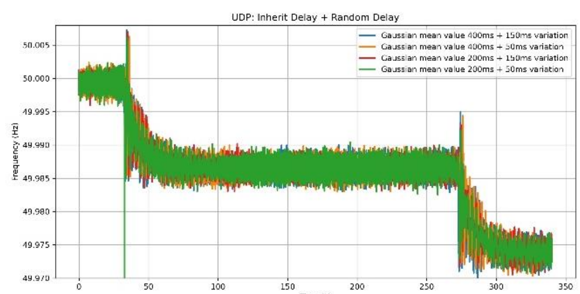

Fig. 7. WADC performance for random delay compensation in UDP/IP

C. Random data drop tolerance

The network simulator is used to control the input PMU measurements and randomly drop certain percentage of the data points. The results of both TCP and UDP protocols is shown in Fig. 8 and 9 below.

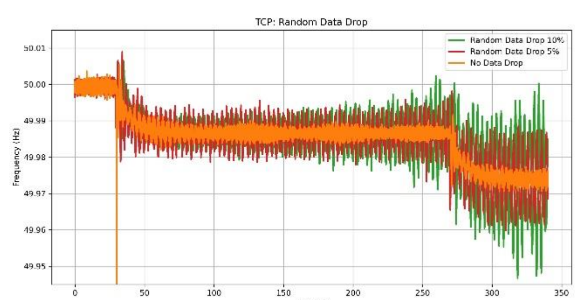

Fig. 8. WADC random data drop tolerance for TCP/IP

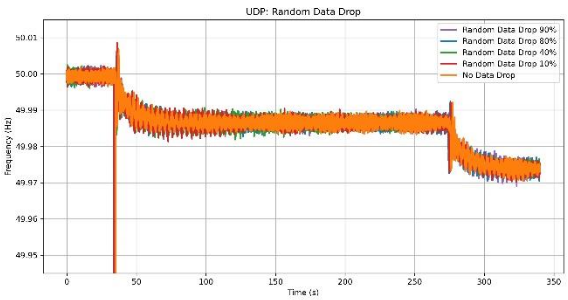

Fig. 9. WADC random data drop tolerance for UDP/IP

The random data drop for TCP/IP is around 5% while UDP can tolerate up to 90% random data drop. These opposite results are cased by the communication protocols' different methods on handling data loss.

D. *Chunk data loss with supervisory control performance*

The chunk data loss and supervisory control functionality is tested by using the network simulator to induce a 100s chunk data loss at primary PMU channel after the 1st generation trip event. The performance of WADC with and without supervisory control is compared for both protocols in the figures below. For TCP protocol, the system will become unstable without supervisory control due to the long recovery time of data (~150s). On the contrary, the UDP protocol can have stable damping control performance due to the rapid data recovery time (~5s).

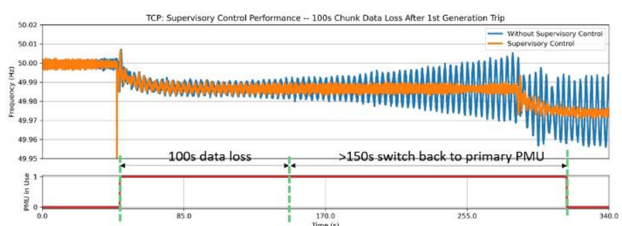

Fig. 10. WADC supervisory control performance for TCP/IP

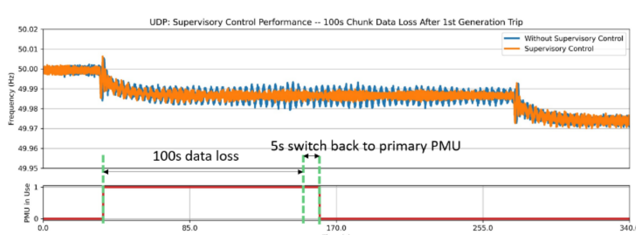

Fig. 11. WADC supervisory control performance for UDP/IP

E. *HIL test results summary*

The WADC software prototype's HIL tests performance is summarized in Table 1. As for performance comparison, TCP and UDP protocols have very similar damping performance when handling the constant and random delay compensation. However, due to the data recovery time difference between the two protocols, the UDP/IP performs obvious better for random data drop tolerance and chunk data loss tolerance.

TABLE I. HIL TEST SUMMARY

Protocols	***Constant Delay Compensation***	***Random Delay Compensation***	***Random Data Drop***	***Chunk Data Loss with Supervisory Control***
TCP	Tolerate up to 600ms inherit delay + 600ms constant delay	Tolerate up to 600ms inherit delay + 400ms constant delay with 150ms random variation delay	Tolerate around 5% random data drop	Start receiving data with additional waiting time (~150s) after chunk data loss
UDP	Tolerate up to 600ms inherit delay + 600ms constant delay	tolerate up to 600ms inherit delay + 400ms constant delay with 150ms random variation delay	Tolerate up to 90% random data drop	Start receiving data immediately (~5s) after chunk data loss

V. CONCLUSIONS

In this paper, the WADC software controller is implemented as an openPDC adaptor along with a GUI for user-friendly monitoring of the WADC communication status. In order to validate the software prototype's control performance, various HIL tests have been conducted for both TCP/IP and UDP/IP. During the HIL testing, a wide range of communication uncertainties have been simulation including constant delay, random delay, random data drop and chunk of data loss. These HIL testing results show that the WADC software can have effective damping performance under large constant and random delays for both communication protocols with the proper buffer size selection. However, UDP/IP would be recommended for the future field deployment of WADC with consideration of regular random data drop and chunk of data loss situations. The HIL experiments have provided valuable support for future field deployment of wide-area damping controller in the Italy power grid. Future work should focus on the upgradation of WADC software functions such as adding the system identification module for online adjustment of controller parameter.

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