

Mitigating Inter-Area Oscillations Using Adaptive Wide-Area Damping Controller Based on Measurement-Driven Model: Case Studies on Realistic Grid Models and Actual Events

L. ZHU¹, C. ZHANG¹, Y. ZHAO¹, H. XIAO¹, I. ALTARJAMI¹, Y. LIU^{1,2}, E. FARANTATOS³, M. PATEL³, C. PISANI⁴, G. GIANNUZZI⁴, R. ZAOTTINI⁴, L. MICH⁴, E. CARLINI⁴

**1. The University of Tennessee at Knoxville, 2. Oak Ridge National Laboratory,
3. Electric Power Research Institute, 4. Terna
1-3: USA 4: Italy**

SUMMARY

Low frequency oscillations have been a significant threat to the secure and economic operation of large interconnected power systems. Several severe oscillation events with low damping ratio have occurred in the interconnected power grid of Continental Europe. For instance, on December 3rd 2017, a sustained low frequency oscillation interested especially the southern part of the power system.

Wide-Area Damping Controllers (WADC) using remote signals as feedback can suppress low frequency oscillations in a more efficient way than conventional Power System Stabilizers (PSSs) which use local signals as feedback. However, these WADCs are usually designed and tuned based on offline simulations using system planning models for several assumed system operating conditions. Therefore, they are not adaptive to the varying system operating conditions, which could cause inadequate damping ratio in some extreme cases. Equally important, the ever-increasing integration of intermittent renewables and intense competition of electricity markets, make the variations in operating conditions more and more dramatic and frequent. Therefore, adaptive design of WADCs is highly desirable to ensure that the WADCs will always provide optimal damping control under varying operating conditions.

With widely deployed PMUs and advancements in system identification techniques, the measurement-driven approach becomes a practical and low-cost solution to adaptive WADCs. A simple linear measurement-driven model can be built to depict oscillatory behavior for WADC design, which could be more accurate and representative of the online operating condition than the system planning models. More importantly, the measurement-driven model can be updated

Email: lzhu12@utk.edu (Lin Zhu)

online to accurately track variations in operating conditions and adjust WADC's parameters adaptively.

In this paper, the Continental Europe Synchronous Area system was utilized for a case study to demonstrate the design and application of an adaptive WADC based on a measurement-driven model. Two WADCs were designed using the measurement-driven approach. The bus frequency in south Italy was selected as the optimal feedback signal of the WADCs, and two synchronous condensers were selected as the actuators. Computer simulations demonstrated that the two WADCs can suppress the oscillations in the December 3rd 2017 event. The WADC was also implemented on a generic hardware platform (National Instrument's CompactRIO), and tested in a controller hardware-in-the-loop (CHIL) test environment using a realistic grid model and actual events. The Continental Europe Synchronous Area system was emulated on OPAL-RT's real-time simulator OP5600, and the December 3rd 2017 oscillation event was replicated. The basic functions, like PMU data receiver, lead-lag structure, and D/A converter of the WADC were implemented. The closed-loop test results demonstrate the effectiveness of the developed WADC. Future work will continue the implementation and test of WADC in the CHIL environment, with focus on realistic operating environment of the WADC, including variable signal latency, data package loss, measurement error/noise, and varying power grid operating condition. More test results will be presented in the near future.

KEYWORDS

Continental Europe synchronous area system, controller hardware-in-the-loop, low-frequency oscillation, measurement-driven model, PMU, wide-area damping control.

1. Introduction

In large-scale interconnected power grids, low-frequency oscillations is a common phenomenon in which one group of generators is oscillating against another group of generators [1]. Thanks to the widely deployed power system stabilizers (PSSs), those low-frequency oscillations usually can be suppressed quickly after they are excited by generator trip, line trip, load shedding or other disturbances. However, due to increasing penetration of renewables, significant changes have been made to conventional power grids, e.g., modified power flow paths, reduced system inertia, large angular spread along the system, and more dramatic variations of operating condition. When the system is operating in an unusual condition, the damping ratio of the dominant oscillation mode may decrease to an inadequate level. Therefore, a common disturbance could trigger undamped oscillations, which could limit the power transfer capability of tie lines, and even lead to system separation and wide-spread outage [2]. Recently, some oscillation events with low damping ratio have occurred in the interconnected power grid of Continental Europe [3]-[5]. The most recent one occurred on December 3rd 2017, the interconnected power grid of Continental Europe was operating under a light-load condition, and two consecutive generation disconnections excited a sustained 0.29Hz oscillation, which lasted for 10 minutes [5].

Compared with local PSSs, the usage of wide-area damping controller (WADC) is a more effective way to suppress these low-frequency oscillations, since WADC utilizes a remote signal with better observability of the target oscillation mode as the feedback signal. If the WADCs are adaptive to the varying operating conditions, they will always provide optimal damping control. Robust control [6],[7], adaptive control [8],[9], machine learning techniques [10]-[12], and measurement-driven approach [13],[14] have been proposed by researchers to improve adaptive capability of WADCs. However, robust control-based WADCs may only guarantee their stability under the predefined boundary, but not the optimal control performance under different conditions. The conventional self-tuning based adaptive control and model predictive control usually rely on a linear transfer function model or state-space model, which has a fixed structure with fixed order, and may not be able to capture required oscillatory dynamics. Machine learning-based approach is a promising solution, but a large number of training cases are needed, and extreme cases may not be fully covered. In industry practice, U.S. Sandia National Lab developed a WADC using HVDC links as the actuator, and conducted field testing on a real HVDC link in the U.S. western interconnection [15],[16]. The testing results demonstrated that it can provide better damping control to suppress oscillations. Nevertheless, it is not adaptive yet.

With widely deployed PMUs and advancements in system identification techniques, the measurement-driven approach becomes a practical and low-cost solution to adaptive WADCs. In our previous study, two WADCs were designed based on the ring-down measurement-driven approach, which does not rely on system planning model. According to observability and controllability study, as well as practical considerations in the realistic system, the bus frequency in south Italy was selected as the feedback signal and two synchronous condensers in south Italy were selected as the actuators. The simulations in the Continental Europe Synchronous Area system demonstrated that the two WADCs can quickly suppress the undamped oscillation occurred on December 3rd 2017 [17].

Aiming at eventual field deployment and demonstration, the developed WADC is implemented on a generic purpose hardware platform, and tested in a controller hardware-in-the-loop (CHIL) test environment. Compared with computer simulations, CHIL test can emulate a real-time operating environment to verify the performance of the developed WADC under more realistic scenarios, including varying signal latency, data package loss, measurement error/noise and cyber attack. In this paper, the built CHIL test environment is introduced. The Continental

Europe Synchronous Area system is emulated on the real-time simulator, and the actual oscillation event occurred on December 3rd 2017 is used for test. Since the controller implementation and the associated tests are still ongoing, only preliminary test results are presented in this paper. More test results will be disseminated in the near future.

2. Continental Europe Synchronous Area system model

There are three dominant oscillation modes in the Continental Europe Synchronous Area system. One is the ‘North-South mode’ between Northern Europe (Germany/Denmark, etc.) and Italy with approximately 0.3 Hz in oscillation frequency. Second is the ‘former Western-Eastern mode’ between Western Europe (Spain/Portugal) and Eastern Europe (Greece/Balkan), with about 0.18 Hz in oscillation frequency. While the third mode is the ‘Western-Eastern mode’ between Western Europe (Spain/Portugal) and Eastern Europe (Turkey), with about 0.15 Hz in oscillation frequency [18],[19].

The Continental Europe Synchronous Area system model utilized in this study was developed by Terna (the sole Transmission System Operator in Italy) for the purpose. As shown in Fig. 1, the model has 16 zones, comprising most of continental Europe. The generators in Italy (Zone 10 to Zone 16) are represented by detailed models, while the generators in other zones are represented by equivalent models. This model is a snapshot model to represent the operating condition very close to the 2017 December 3rd event scenario. The ‘North-South mode’ is established between Germany/Denmark (Zone 8) and south Italy (Zone 13 & 14): under the unusual condition with light load and huge import in the southern part of the European system can be characterized by low damping ratio. On December 3rd 2017, a 0.293Hz undamped oscillation event occurred in the Continental Europe Synchronous Area system. Fig. 2 shows the bus frequency measurements in Zone 11 and Zone 14 captured by two PMUs during the event. The undamped oscillations were triggered by two consecutive generation disconnections, and persisted for more than ten minutes. The bus frequency in Zone 14 exhibits approximately 300 mHz oscillation magnitude (peak-to-peak), which is much higher than the magnitude of bus frequency in Zone 11.

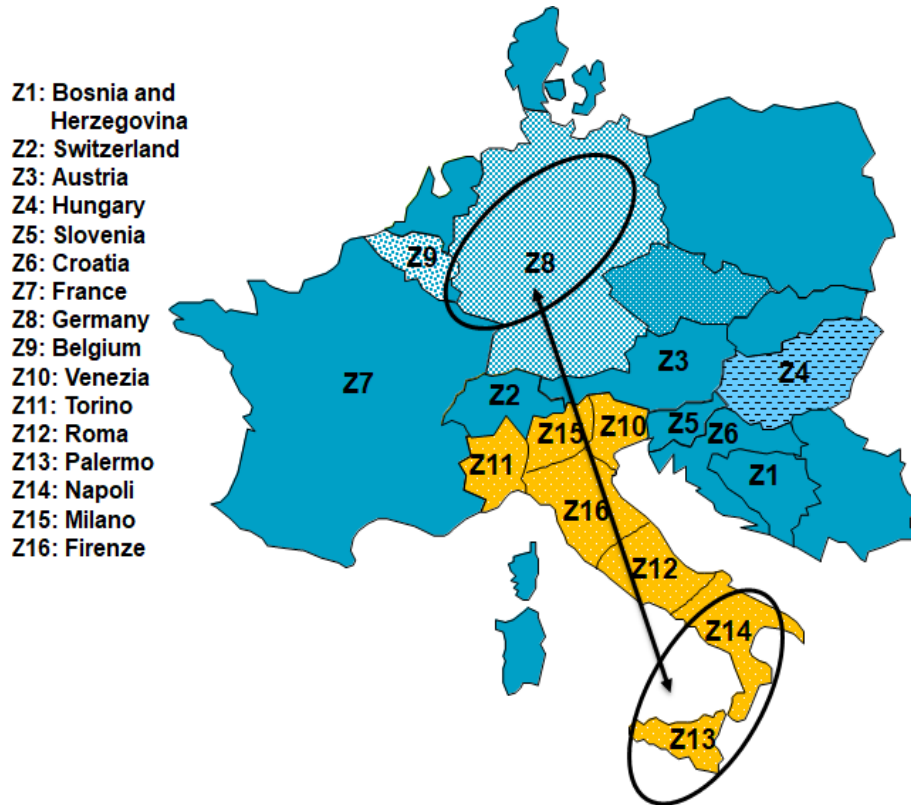


Fig. 1 Continental Europe Synchronous Area system.

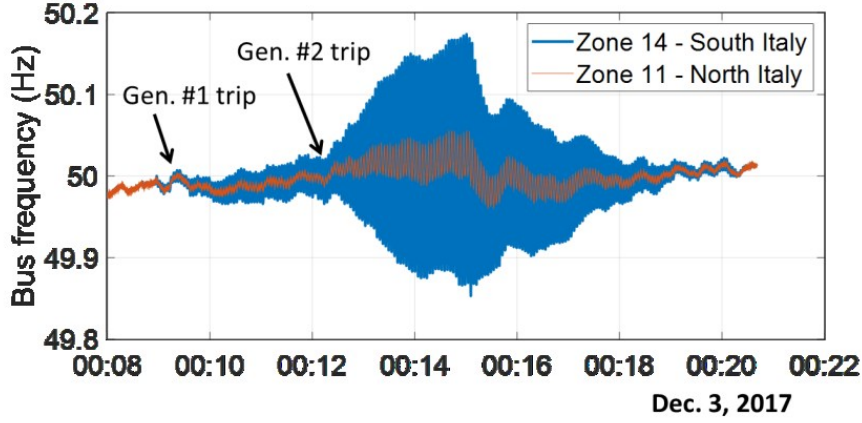


Fig. 2 PMU measurements during December 3rd 2017.

3. WADC based on measurement-driven model

Fig. 3 shows the overall architecture of the adaptive WADC based on a measurement-driven model. The measurement-driven model is identified using ring-down measurements collected during large disturbances to capture the current operating condition and tune WADC's parameters adaptively. The open-loop system model between V_{ref} (voltage reference of exciter) and Δf (selected observation/feedback signal) need to be identified. This model can be divided into two parts: $G_{V_{ref}-V_t}(s)$ and $G_{V_t-\Delta f}(s)$. Considering that $G_{V_{ref}-V_t}(s)$ depends only on the generator and the exciter structure, it stays the same under different system operating conditions and can be identified off-line by injecting step, pulse or other probing signals. The transfer function model $G_{V_t-\Delta f}(s)$ between V_t (generator terminal voltage) and Δf can be identified using collected ring-down measurements. The online model identification is triggered by system events including generation trip, load shedding, and topology changes due to line trip, etc. More detailed information can be found in [17].

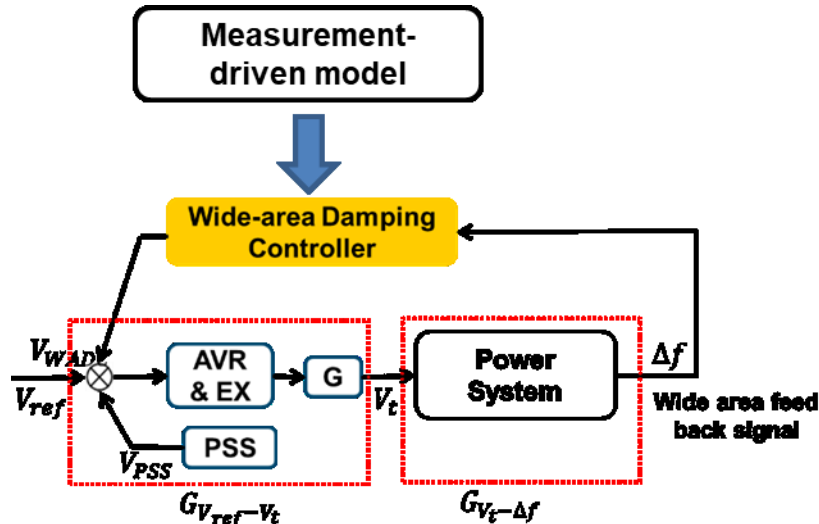


Fig. 3. Ring-down measurement-drive model based adaptive WADC.

4. Controller Hardware-in-the-Loop (CHIL) test

4.1 CHIL Test environment

The diagram of the built CHIL test environment is given in Fig. 4. The Continental Europe Synchronous Area system model is emulated on the OPAL-RT's real-time simulator OP5600 [20]. Based on the phasor domain simulation results, e.g., voltage magnitude, phase angle, and frequency, the real-time simulator can generate the associated analog voltage waveform. An

amplifier is used to step up the voltage from $\pm 10\text{V}$ to $\pm 120\text{V}$ to emulate the secondary side of a potential transformer and feed the analog voltage signal to a PMU device. The WADC receives PMU streaming measurements complying with the standard IEEE C37.118. A communication network impairment simulator can introduce signal latency and data package loss to test the controller performance in non-ideal communication environment. Nevertheless, the communication network impairment simulator is bypassed for the preliminary tests shown in this paper. The WADC generates control command, converts it into $\pm 10\text{V}$ analog signal, and feeds it to the real-time simulator.

4.2 Grid model emulation on real-time simulator

To emulate the model on the real-time simulator, the Continental Europe Synchronous Area system is converted to ePhasorSim model in OpenModelica. Fig. 5 shows a unit model for instance, which consists of a salient pole generator model (GENSAL), a simplified excitation system model (SEXS), a dual-input signal stabilizer model (IEE2ST), and a steam turbine-governor model (TGOV1).

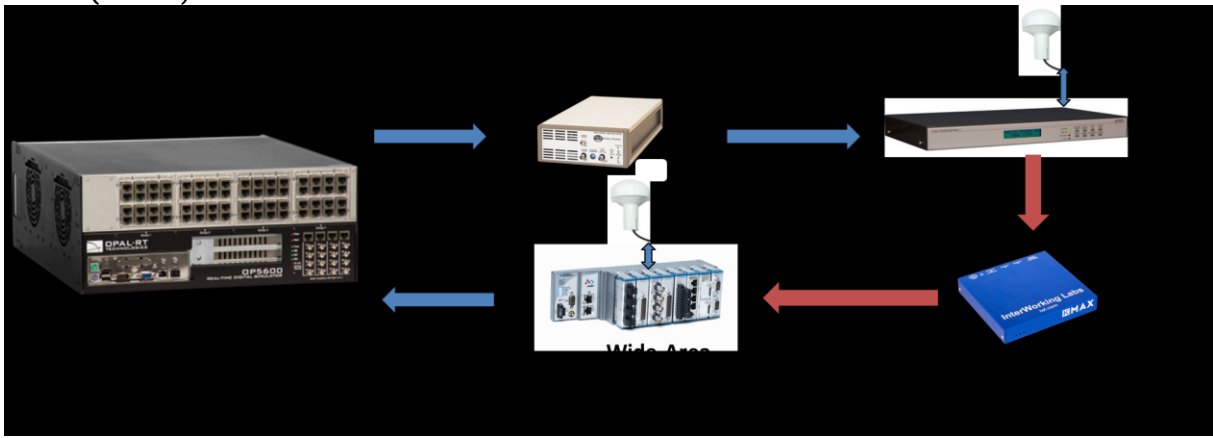


Fig. 4 Controller hardware-in-the-loop test environment.

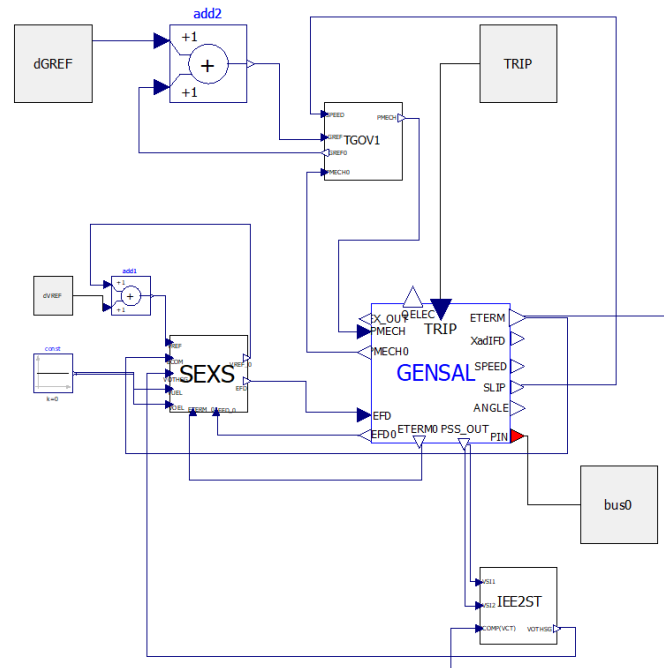


Fig. 5 ePhasorSim model in OpenModelica: Example.

The model replicates the 0.293Hz undamped oscillation occurred on December 3rd 2017. Fig. 6 shows the simulations in PSS/e and OPAL-RT under the two generation disconnections, which are consistent with each other. Fig. 6(a) and Fig. 6(b) show the bus frequency in south Italy and active power of one tie line between France and Italy, respectively. The Prony analysis of the simulation results and real PMU measurements are given in Table I. Both simulations in PSS/e and OPAL-RT can replicate the 0.293 Hz oscillation event occurred on December 3rd 2017. It is noted that bus frequency magnitude in simulations is slightly lower than that of PMU measurements, but the growing 0.293 Hz oscillation is duplicated.

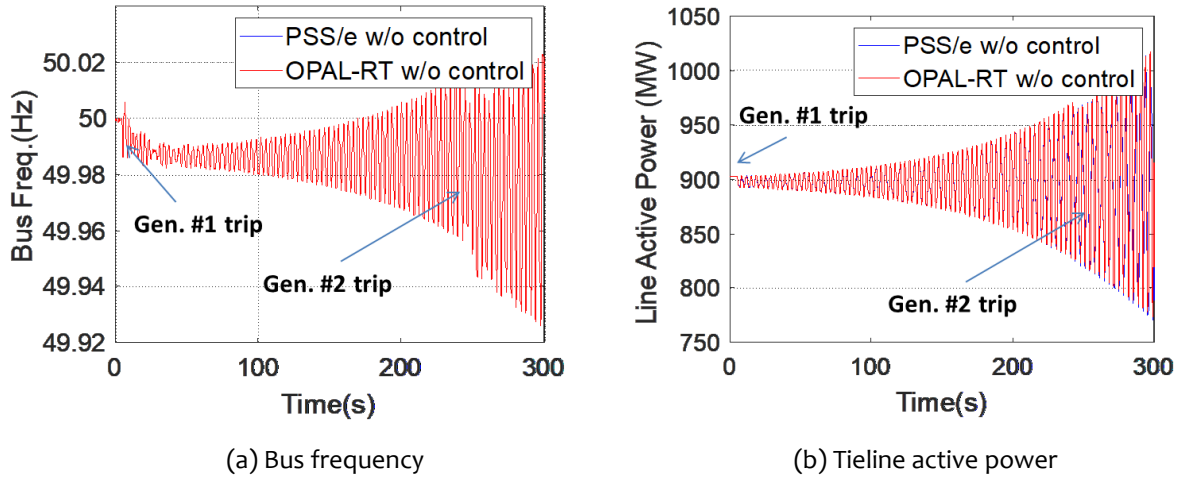


Fig. 6. Comparison of simulation results in PSS/e and OPAL-RT.

Table I. Comparison of oscillation frequency and damping ratio

Data window	PSS/e		OPAL-RT		PMU measurements	
	Freq. (Hz)	Damp. (%)	Freq. (Hz)	Damp. (%)	Freq. (Hz)	Damp. (%)
[5 seconds, 45 seconds] after trip of first generator	0.293	-0.410	0.293	-0.410	0.293	-1.062
[250 seconds, 290 seconds] after trip of second generator	0.292	-0.628	0.292	-0.628	0.292	-0.614

4.3 WADC implementation

In this paper, the WADC is implemented on a generic purpose hardware platform – National Instrument's CompactRIO, using LabVIEW [21]. As shown in Fig. 7, the controller consists of six function blocks: PMU data receiver, missing data estimator, signal latency compensator, lead-lag structure, data quality monitor, and D/A converter. The PMU data receiver is able to receive the PMU package complying with IEEE C37.118, and unpack the data package to retrieve the measurements [22]. The PMU reporting rate could be 10 frames/second to 60 frames/second. The signal latency compensator is used to eliminate the impact of signal latency, while the missing data estimator is to restore the missing data using interpolation algorithms. The control command is generated by a classical lead-lag structure, and then is converted into analog signal to be fed to the real-time simulator. Moreover, the data quality monitor function block is used to monitor the data quality of multiple PMUs. If measurements from one PMU are not good, e.g., longer signal latency, or higher rate of data package loss, the data quality monitor function block can switch to another PMU for control and adjust the parameters of lead-lag structure if needed. Currently, only the PMU data receiver, lead-lag structure and D/A converter have been implemented, as shown in Fig. 8. Other function blocks will be implemented and tested in the near future.

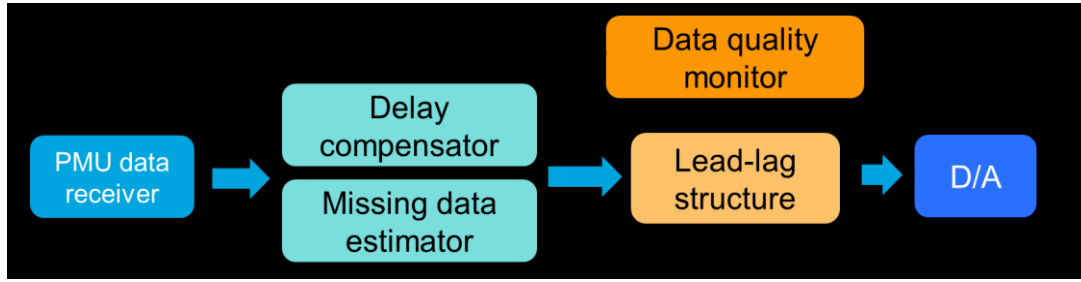
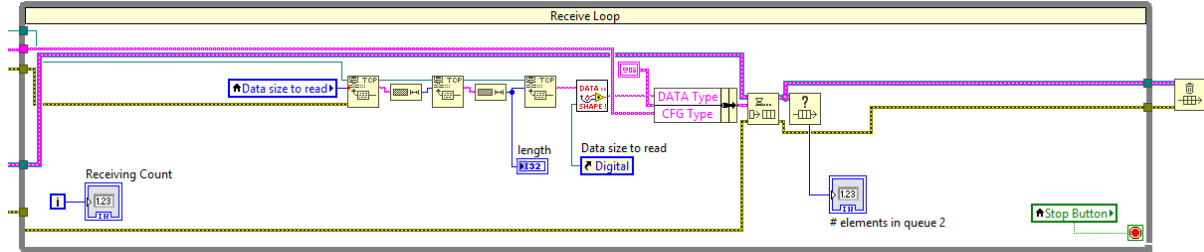
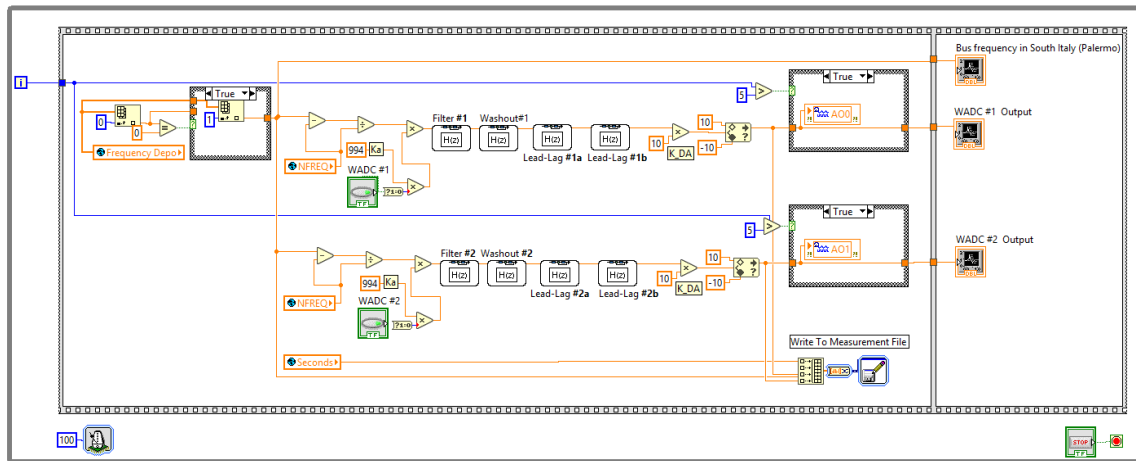


Fig. 7 Main function blocks in WADC.



(a) PMU data Receiver



(b) Lead-lag structure and D/A converter

Fig. 8 WADC implementation on CompactRIO 9035.

4.4 Closed-loop test results

Based on the previous offline simulation study [17], two synchronous condensers are selected as the actuators, and the bus frequency in south Italy is selected as the feedback signal in the CHIL closed-loop test. The two WADCs are implemented on the same CompactRIO, configured with the same parameters in [17]. The two consecutive generator trip disturbances are applied at 5 second and 245 second, respectively. Four scenarios are tested and compared: 1) no control, 2) WADC #1 is activated, 3) WADC #2 is activated, and 4) both WADCs are activated. The test results are given in Fig. 9. Fig. 9(a) and Fig. 9(b) show the bus frequency in south Italy and WADC output, respectively. When there is no WADC, the system exhibits the growing oscillation. However, if at least one WADC is activated, the oscillation can be suppressed quickly. It is also noted that when two WADCs are activated, the control effect is a bit better than only one WADC is activated, as shown in Fig. 9(c) and Fig. 9(d). These two WADCs can backup each other.

5. Conclusions and future work

In this paper, the developed WADC with basic functions is implemented on a generic purpose hardware platform, and a CHIL test platform is built to test the WADC in a realistic power grid model under actual events. The Continental Europe Synchronous Area system model is emulated

on a real-time simulator, and the 2017 December 3rd oscillation event is replicated to test the developed WADC. Test results show that the WADCs can suppress the oscillation quickly.

Future work will continue with the implementation and test of WADC in the CHIL environment, including: 1) implementation of remaining function blocks, 2) test under variable signal latency and data loss pattern, 3) test with backup PMUs and actuators, and 4) adaptive WADC under varying operating condition.

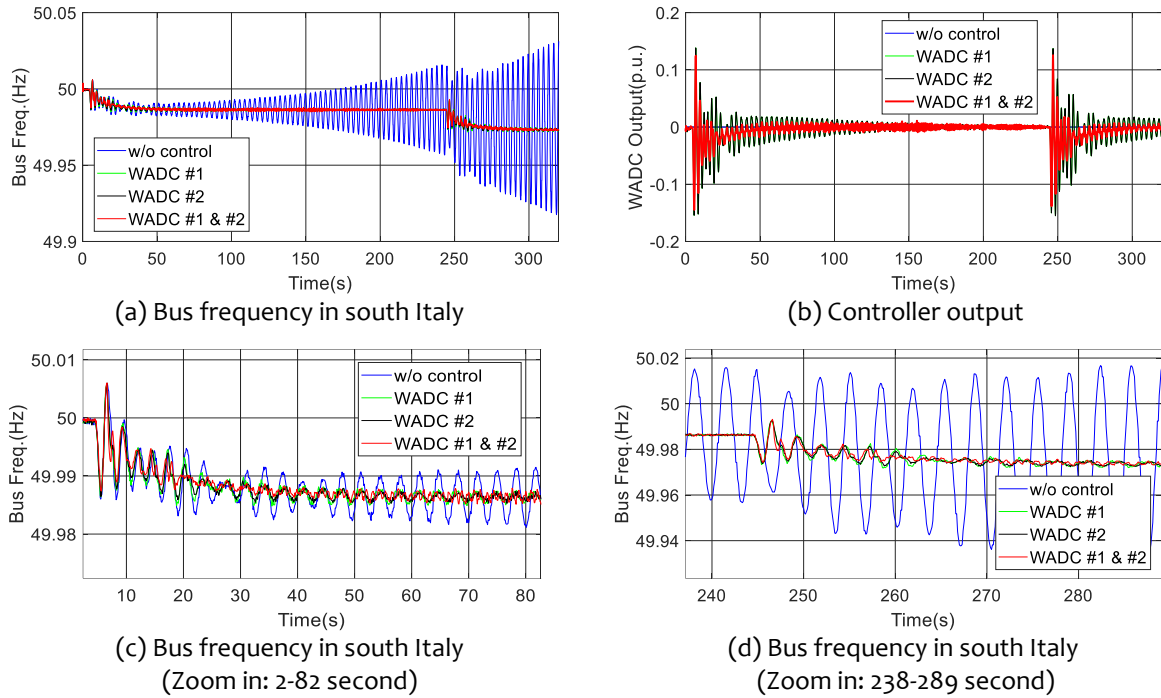


Fig. 9 Closed-loop test results.

ACKNOWLEDGEMENT

This work was primarily supported by Terna and Electric Power Research Institute (EPRI), and partly supported by National Science Foundation under the Award Number 1839684. This work also made use of Engineering Research Center Shared Facilities supported by the Engineering Research Center Program of the National Science Foundation and DOE under NSF Award Number EEC-1041877 and the CURENT Industry Partnership Program.

BIBLIOGRAPHY

- [1] P. Kundur, *Power System Stability and Control*. New York, NY, USA: McGraw-Hill, 1994.
- [2] J. F. Hauer and J. W. Burns, "Roadmap to monitor data collected during the WSCC breakup of August 10, 1996," in PNNL-19459, Pacific Northwest National Laboratory, Richland, WA, USA.
- [3] European Network of Transmission System Operators for Electricity, "Analysis of CE inter-area oscillations of 19 and 24 February 2011 [Online]. Available: <https://www.entsoe.eu/publications/system-operations-reports/>
- [4] European Network of Transmission System Operators for Electricity, "Analysis of CE inter-area oscillations of 1st December 2016," [Online]. Available: <https://www.entsoe.eu/publications/system-operations-reports/>
- [5] European Network of Transmission System Operators for Electricity, System Protection and Dynamics WG, "Oscillation event 03.12.2017," [Online]. Available: <https://www.entsoe.eu/publications/system-operations-reports/>
- [6] A. C. Zolotas, B. Chaudhuri, I. M. Jaimoukha, and P. Korba, "A Study on LQG/LTR Control for Damping Inter-Area Oscillations in Power Systems," *IEEE Trans. Control Systems Technology*, vol. 15, no. 1, pp.151-160, Jan. 2007.

- [7] C. Zhang, D. Ke, Y. Sun, C. Y. Chung, and J. Xu, "Investigations of Large-Scale Voltage-Dependent Loads for Damping Inter-Area Oscillations: Mechanism and Robust Decentralized Control," *IEEE Trans. Power Syst.*, Vol. 33, no. 6, pp. 6037-6048, Nov. 2018.
- [8] C. Hwang, and B. Chen, "Model reference adaptive control via the minimisation of output error and weighting control input," *IEE Proceedings D - Control Theory and Applications*, vol. 136, no. 5, pp. 231 - 237, Sep. 1989.
- [9] A. Fuchs, M. Imhof, T. Demiray, and M. Morari, "Stabilization of large power systems using VSC-HVDC and model predictive control," *IEEE Trans. Power Del.*, vol. 29, no. 1, pp. 480-488, Jan. 2014.
- [10] J. Ma, T. Wang, S. Wang, X. Gao, X. Zhu, Z. Wang, and J. S. Thorp, "Application of dual Youla parameterization based adaptive wide-area damping control for power system oscillations," *IEEE Trans. Power Syst.*, vol. 29, no. 4, pp. 1602-1610, July 2014.
- [11] M. Beiraghi and A. M. Ranjbar, "Additive model decision tree-based adaptive wide-area damping controller design," *IEEE Systems Journal*, vol. 12, no. 1, pp. 328-339, Mar. 2018.
- [12] Y. Shen, W. Yao, J. Wen, H. He, and W. Chen, "Adaptive supplementary damping control of VSC-HVDC for interarea oscillation using GrHDP," *IEEE Trans. Power Syst.*, vol. 33, no. 2, pp. 1777-1789, Mar. 2018.
- [13] J. Zhang, C. Y. Chung, C. Lu, K. Men, and L. Tu, "A Novel Adaptive Wide Area PSS Based on Output-Only Modal Analysis," *IEEE Trans. on Power Syst.*, vol. 30, no. 5, Sept. 2015, pp. 2633 - 2642.
- [14] H. Liu, L. Zhu, Z. Pan, F. Bai, Y. Liu, Y. Liu, M. Patel, E. Farantatos, and N. Bhatt, "ARMAX-based transfer function model identification using wide-area measurement for adaptive and coordinated damping control," *IEEE Trans. on Smart Grid*, vol. 8, no. 3, pp. 1105-1115, May 2017.
- [15] D. Trudnowski, B. Pierre, F. Wilches-Bernal, D. Schoenwald, R. Elliott, J. Neely, R. Byrne, and D. Kosterev, "Initial closed-loop testing results for the pacific DC intertie wide area damping controller," in *Proc. IEEE Power Eng. Soc. General Meeting*, Chicago, IL, USA, July 16-20, 2017.
- [16] B. J. Pierre, F. Wilches-Bernal, R. T. Elliott, D. A. Schoenwald, J. C. Neely, R. H. Byrne, and D. J. Trudnowski, "Simulation results for the pacific DC intertie wide area damping controller," in *Proc. IEEE Power Eng. Soc. General Meeting*, Chicago, IL, USA, July 16-20, 2017.
- [17] L. Zhu, Y. Zhao, Y. Liu, E. Farantatos, M. Patel, P. Dattaray, D. Ramasubramanian, L. Michi, E. Carlini, G. Giannuzzi, and R. Zaottini, "Oscillation damping controller design using ring-down measurements for the Italian power grid," *2019 IEEE PES PowerTech*, Milan, Italy, June 23-26, 2019.
- [18] G. Giannuzzi, D. Lauria, C. Pisani, and D. Villacci, "Real-time tracking of electromechanical oscillations in ENTSO-e Continental European Synchronous Area ", *International Journal of Electrical Power & Energy Systems.*, vol. 64, no. 2, pp. 1147-1158, January 2015.
- [19] D. Lauria, and C. Pisani, "On Hilbert transform methods for low frequency oscillations detection", *IET Gener. Transm. Distrib.*, vol. 8, no. 6, pp. 1061-1074, June 2014.
- [20] OP5600 real-time simulator. [Online]. Available: <https://www.opal-rt.com/simulator-platform-op5600/>
- [21] M. S. Almasa, L Vanfrettiab, and M. Baudettea, "BabelFish—Tools for IEEE C37.118.2-compliant real-time synchrophasor data mediation," *SoftwareX*, vol. 6, pp. 209-216, 2017
- [22] CompactRIO Controller. [Online]. Available: <http://www.ni.com/en-us/shop/select/compactrio-controller?modelId=119752>