21, rue d'Artois, F-75008 PARIS
http : //www.cigre.org

CIGRE US National Committee
2018 Grid of the Future Symposium

Adaptive Wide-Area Damping Control Using Transfer Function Model Derived from Ring-down Measurements

L. ZHU[1], Y. ZHAO[1], Y. MA[1], J. WANG[1], Y. LIU[1, 2],
E. FARANTATOS[3], M. PATEL[3], D. RAMASUBRAMANIAN[3]

[1]The University of Tennessee - Knoxville
USA
[2]Oak Ridge National Laboratory
USA
[3]Electric Power Research Institute
USA

SUMMARY

One of the main drawbacks of existing wide-area oscillation damping controllers (WADC) is their limited adaptive capability to the varying operating conditions of a power system. An adaptive WADC using a measurement-driven transfer function model is proposed in this paper. The proposed WADC utilizes the latest collected ring-down measurements to build a transfer function model of the controlled power system in the closed-loop environment, and updates its parameters to capture the variations in system's operating condition. In this paper, a case study performed using a two-area four-machine system demonstrates the performance of the proposed adaptive WADC. Furthermore, the proposed adaptive WADC has been implemented on a hardware testbed. The advantages of the proposed adaptive WADC over a non-adaptive WADC have also been demonstrated.

KEYWORDS

Adaptive; Ring-down measurements; System identification; Transfer function model; Wide-area damping control (WADC)

lzhu12@utk.edu

1. Introduction

Low-frequency oscillations are a significant issue limiting the power transfer capability across tie-lines and deteriorating power system security due to potential low-damped or even undamped oscillations [1-2]. Typically, local oscillation modes can be damped by power system stabilizers (PSS) on generators using local feedback signals. However, for inter-area modes, local signals are not optimal and a wide-area damping control (WADC) utilizing remote signals is preferable, due to limited observability of an inter-area mode using local signals. Although many designs of WADCs have been proposed, one of the main drawbacks of these WADCs is their limited adaptive capability to the varying power system operating conditions, since they are usually designed based on offline studies using dynamic system models [3-4]. The Western Electricity Coordinating Council (WECC) separation event in 1996 demonstrated that the damping ratio of the North-South inter-area mode kept decreasing when the system was undergoing consecutive events/disturbances [5]. With an adaptive oscillation damping controller, capturing those significant variations in system operating condition, system separation may have been prevented.

The wide deployment of Phasor Measurement Units (PMUs) enables measurement-driven approaches for the design of damping controllers, thus overcoming the disadvantages of the circuit model-based approach. For example, it is feasible to derive a measurement-based transfer function model that describes the oscillatory behaviors of a power system, and use that model for damping control design [6-7]. This transfer function model can be periodically updated to track variations in system's operating condition and make the WADC adaptive [8]. However, one challenge in the design of an adaptive WADC is to identify the open-loop system model (without WADC) in the closed-loop environment (with WADC). In other words, the identification of the transfer function model is on the basis of measurements under closed-loop operating conditions. Reference [9] proposes an approach based on ambient signal and deadband to address this issue. The deadband inside the WADC is used to eliminate the WADC's control effect temporarily to enable an open-loop system model identification using ambient signal. Reference [10] presents another approach which periodically injects probing signal into the control loop and estimates the controller gains. However, the ambient signal or probing signal might not be strong enough, and it is easy to be interfered by measurement errors or other small disturbances during normal operation, such as generation re-dispatch.

Compared with probing and ambient signals, ring-down measurements are much easier to be collected because they can be measured during large disturbances such as line trips, generation trips, etc. This paper proposes a new approach for an adaptive WADC that identifies the system model including the controller in the loop, using ring-down measurements. Considering as an example a generator excitation system being the actuator of the WADC, the required system transfer function model is divided into two parts. One is the transfer function between the voltage set-point of the generator exciter and the generator terminal voltage, which can be easily determined based on the generator and exciter models. The other is the transfer function between the generator terminal voltage and the system response, which can be identified using the generator terminal voltage as a pseudo probing signal.

In the next section, an adaptive WADC is proposed that updates its control parameters online to accommodate variations in system's operating condition. A case study using a two-area four-machine system demonstrates the effectiveness of the proposed approach. Finally, the proposed adaptive WADC is implemented and demonstrated on a hardware testbed, which emulates a reduced WECC system.

2. Adaptive WADC using measurement-driven model

2.1 Overview of the approach

Fig. 1 shows the overall architecture of the adaptive WADC. The adaptive WADC is designed to damp a critical inter-area oscillation mode by providing supplementary damping control signal through the generator excitation system. The entire power system is represented by a simple, low-order transfer function model with the generator (actuator) bus frequency as the output signal. The identified system model is used to update the WADC parameters [11]. The online model identification is triggered by system events including generation trip, load shedding, and topology changes due to line trip, etc. These system events can be detected by existing situational awareness functions based on wide-area measurements. Upon a system event, the transfer function model will be updated when the ring-down data collection is completed.

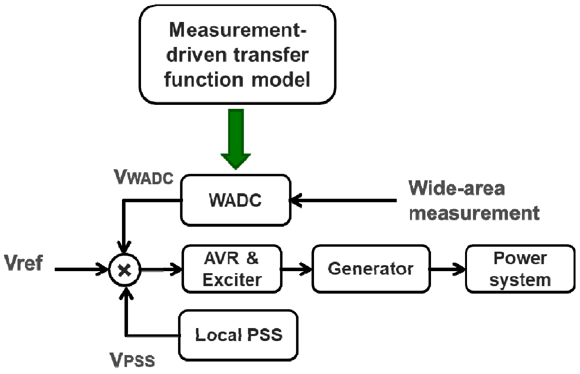


Fig. 1 Adaptive WADC using transfer function model derived from measurements

2.2 Transfer function model identification using ring-down data

The closed-loop system structure with the WADC is shown in Fig. 2. The WADC input signal Δf is the frequency difference between a local bus and a remote bus in this study, since it has better observability. V_{ref} is the voltage reference of the excitation system, while Vt is the machine terminal voltage. Since the wide-area control signal V_{WADC} is added to V_{ref}, the controlled system model should be identified between V_{ref} and Δf. Considering that $G_{V_{ref}-V_t}(s)$ depends only on the generator and exciter structure, it remains the same under different operating conditions and can be identified off-line. The transfer function model between V_t and Δf ($G_{V_t-\Delta f}(s)$) can be identified using online ring-down measurements. In this paper, the generator terminal voltage V_t is selected as the input of the transfer function model $G_{V_t-\Delta f}(s)$, while the bus frequency difference Δf is selected as the output.

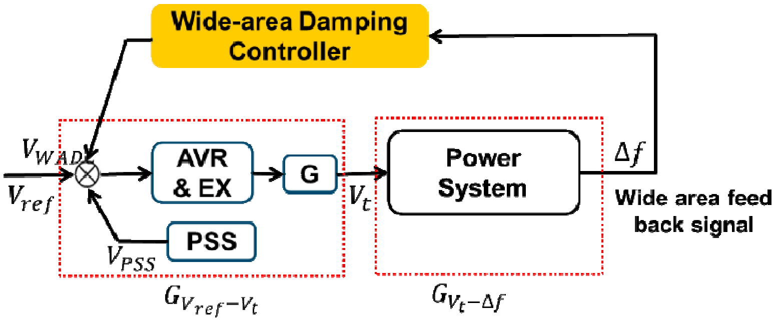


Fig. 2 System structure with wide-area damping controller

2.3 WADC structure

A lead-lag structure, which consists of a filter, a washout block, two lead-lag blocks, and a gain block, is adopted for WADC in this paper [12]. Fig. 3 illustrates the block diagram of the WADC. T_1 and T_2 are the time constants of the lead-lag structure; K_w is the gain of WADC; T_w is the time constant of the washout block which is usually set to be 10s to remove direct current component in the feedback signal. The modulation amplitude of WADC is limited within [-0.05p.u., 0.05p.u.] as labeled Vmax and Vmin in Fig. 3. It is obvious that the time constants and gain are the key parameters that determine the controller performance. These control parameters can be updated online based on the identified transfer function model [11].

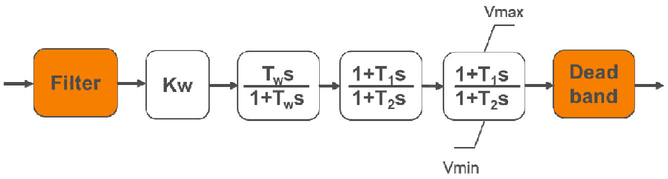


Fig. 3 WADC structure

3. Case study in two-area four-machine system

A two-area four-machine system is selected as the study system [13]. The target oscillation mode is the inter-area oscillation between Area 1 (left) and Area 2 (right), with 0.55Hz oscillation frequency and 8% damping ratio. Fig. 4 shows the diagram of the study system with an adaptive WADC. The controller input is the frequency difference between Bus 6 and Bus 10. The controller output is added to the exciter of generator 3, which has highest controllability of the target mode based on residue analysis.

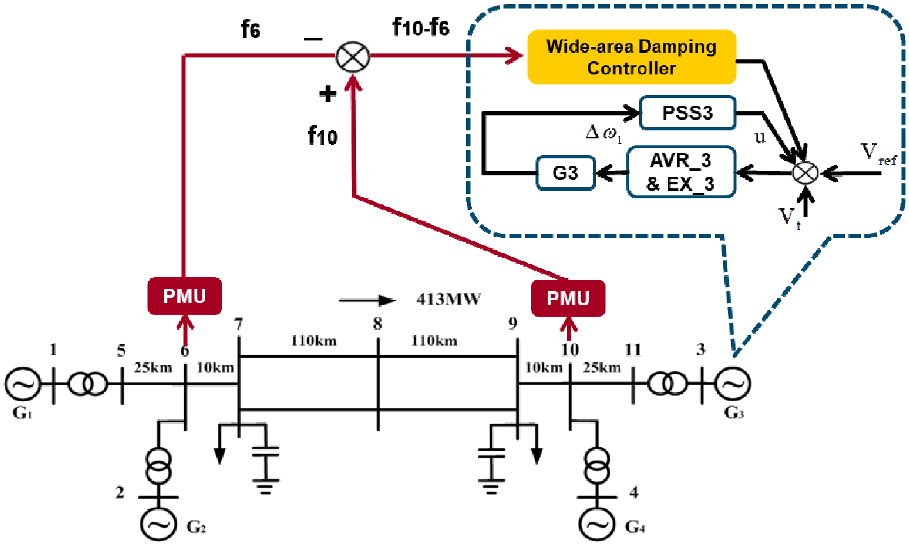
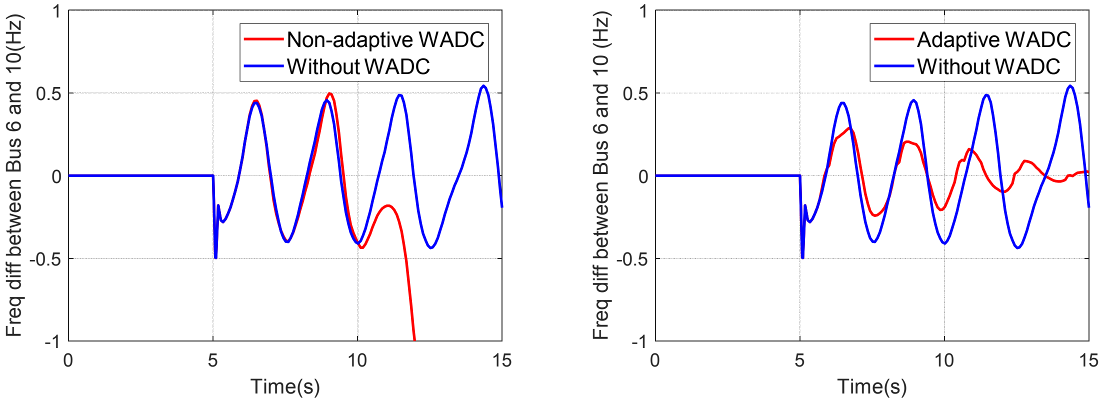


Fig. 4 Diagram of study case with WADC

Starting from the original operating condition, a 100 MW generation decrease occurs on generator 1 to emulate a generator trip disturbance. The ring-down data collected after this disturbance is used to design WADC. Later on, by applying a few consecutive disturbances, including line trip, generation trip and load shedding, the system operating conditions are varying and different from the base case. Moreover, the identified system model indicates that the oscillation frequency is changed to 0.49Hz and damping ratio is reduced to 0.81%. However, the controller parameters do not updated accordingly, referred to as non-adaptive

WADC. Fig. 5(a) shows the non-adaptive WADC performance under a temporary three-phase fault. The fault is applied to the line between Bus 7 and Bus 8, and is cleared after 50 ms without any line trip. When the system is controlled with the non-adaptive WADC, the oscillation in the frequency difference between the two areas is growing and the system is not stable under this situation. On the contrary, the adaptive WADC is able to identify system model using the ring-down data collected from the latest disturbance, and update its parameters accordingly. The performance of the adaptive WADC is tested under the same temporary three-phase fault. Fig. 5(b) is the frequency difference between the two areas when system is controlled with the adaptive WADC using updated parameters. Compared with no WADC, the system with the adaptive WADC is stable under the temporary fault.



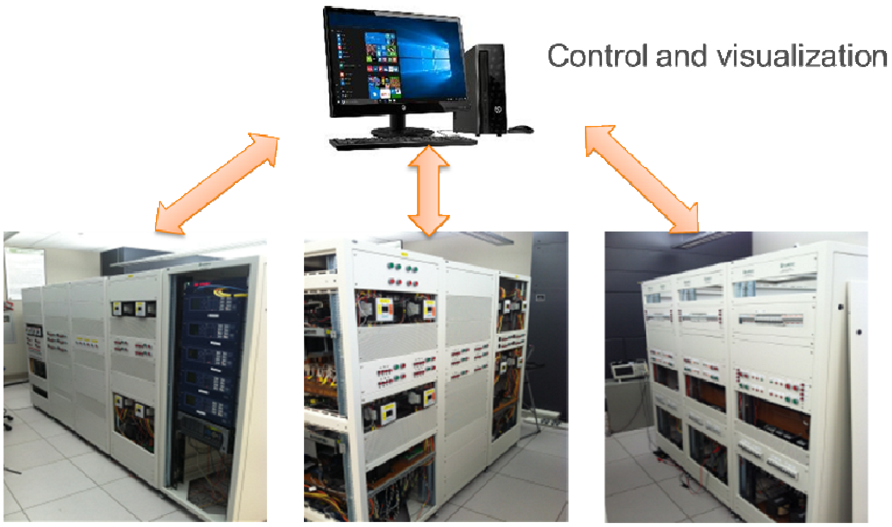
(a) Non-Adaptive WADC performance (b)Adaptive WADC performance

Fig. 5 Performance of non-adaptive and adaptive WADC

4. WADC implementation and experiments on hardware testbed

The proposed approach for the adaptive WADC is further validated on the Hardware Testbed (HTB) at The University of Tennessee, Knoxville (UTK). This HTB is a unique test platform, which emulates large-scale power systems by interconnecting modular and reprogrammable power electronic converters in a reconfigurable structure [14-15]. The converters, also called emulators, can be programmed and controlled in real time to mimic the behaviors of various generation sources (e.g., synchronous machine, solar, and wind), transmission lines, loads, energy storages, HVDC, and other components in power systems with scalable ratings. The framework of the HTB is illustrated in Fig. 6.

Presently, a reduced WECC system with 60% renewable penetration is emulated on the HTB. This system is reduced from the 240-bus WECC system using DYNRED tool [16]. Wind machines are connected to Bus 3 and Bus 4, while solar generation is connected to Bus 6. The target mode is the inter-area oscillation between north and south [17]. Two cases, a winter and a summer case are created to test the proposed WADC, as shown in Fig. 7. The oscillation frequency is 0.425Hz with 9.01% damping ratio in the winter case without the WADC, while the oscillation frequency is 0.521Hz with 8.64% damping ratio in the summer case without the WADC. A WADC is designed to damp this inter-area oscillation mode. Based on residue analysis, Generator at Bus 2 is selected to execute WADC control commands, and the frequency difference between Bus 2 and Bus 7 ($f_2 - f_7$) is chosen as the WADC wide-area feedback signal. Using the ring-down measurements after a generation trip disturbance, the transfer function model can be identified, and the WADC parameters can be determined for both winter case and summer case, as shown in Table I.



Front row

- Areas 1 and 4
- Transmission line cabinet 1
- Physical inductor cabinet
- PMU cabinet

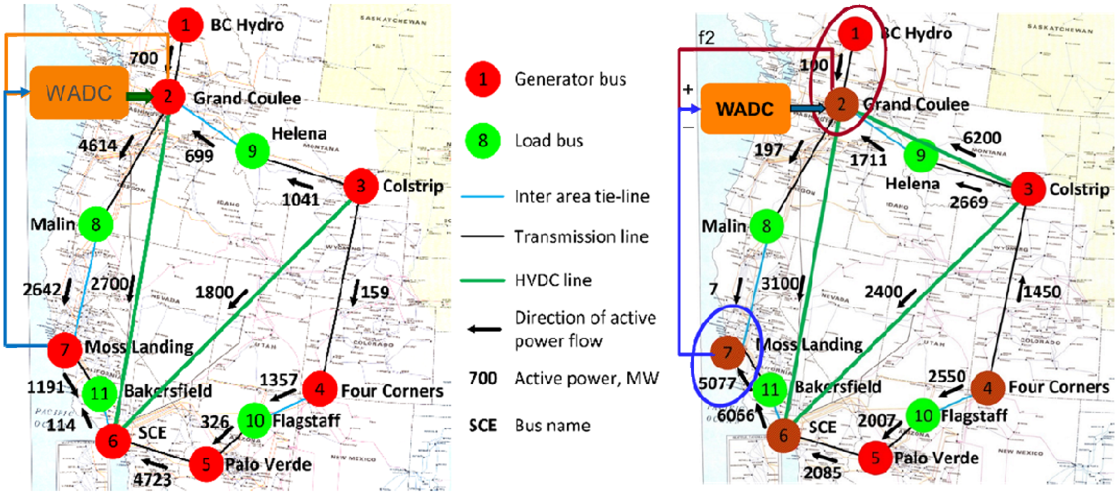
Middle row

- Areas 2 and 3
- Transmission line cabinet 2

Back row

- 2 cabinets for Multi-terminal HVDC system
- 1 wind farm cabinet

Fig.6 UTK's Hardware Testbed



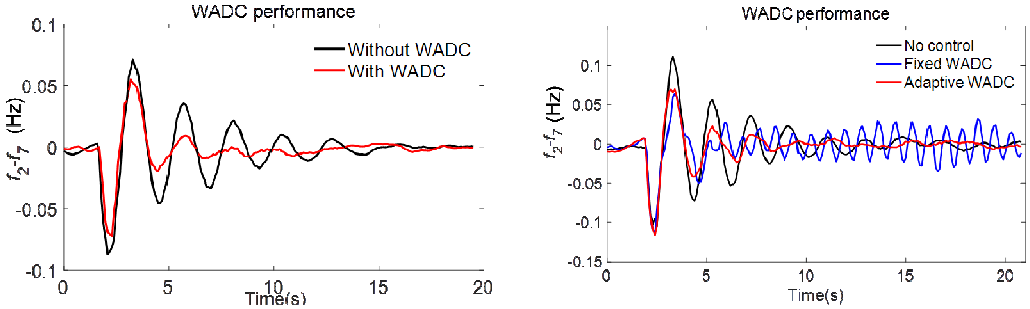
(a)Winter case (b)Summer case

Fig. 7 Reduced four-area WECC system

Table I Controller parameters in different cases

	T1	T2	Kw
Winter	0.302	0.302	21.18
Summer	0.399	0.235	7.20

The WADC is firstly tuned and tested for the winter case. As shown in Fig. 8(a), the WADC improves the damping ratio of the oscillations. Next, the summer case is tested under two scenarios, 1) WADC with parameters tuned for the winter case (considered as a non-adaptive controller with outdated parameters) and 2) WADC with updated parameters tuned for the summer case (considered as an adaptive controller). As shown in Fig. 8(b), with the WADC designed for the winter case, a 1.169 Hz oscillation mode will be excited, and the system becomes unstable. However, when using the adaptive WADC designed with ring-down measurements, the damping ratio is increased to 13.66% and the local oscillation mode is not excited.



(a)Winter case (b)Summer case

Fig. 8 WADC control effect

5. Conclusion and future work

An adaptive WADC using a measurement-driven transfer function model is proposed in this paper. This transfer function model can be identified and updated using ring-down measurements with the WADC in the loop. The WADC can be tuned online based on this transfer function model to improve its adaptive capability. A case study in Kundur's test grid has demonstrated the performances of the proposed adaptive WADC. Furthermore, an adaptive WADC using measurement-driven approach is designed and demonstrated on a hardware testbed, where a reduced 4-area WECC system is emulated. The test results illustrated that a WADC with outdated parameters designed for a winter case will result in system instability when the system is emulated for a summer case. However, an adaptive WADC with updated parameters improves the system's oscillatory behavior. Future work may focus on 1) impact of measurement noise/error, 2) impacts of signal latency and communication failure, and 3) coordination of multiple oscillation modes for the WADC design.

ACKNOWLEDGEMENT

This work was supported primarily by the Electric Power Research Institute (EPRI). 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] Graham Rogers, "Power system oscillation", *Springer*, 2000.
[2] Bikash Pal, and Balarko Chaudhuri, "Robust control in power systems", *Springer*, 2005.
[3] 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.
[4] Y. Zhang and A. Bose, "Design of Wide-Area damping controllers for interarea oscillations," *IEEE Trans. Power Syst.*, vol. 23, no. 3, pp. 1136-1145, August 2008.
[5] Wei Yao, L. Jiang, Jinyu Wen, Q. H. Wu, and Shijie Chen, "Wide-area damping controller of FACTS devices for inter-area oscillations considering communication time delay", *IEEE Trans. Power Syst.*, vol. 29, no. 1, pp. 318-329, January 2014.

[6] Eriksson, R., X. So, and L. Der, "Wide-area measurement system-based subspace identification for obtaining linear models to centrally coordinate controllable devices". *IEEE Trans. Power Del.*, vol. 26, no.2, pp. 988-997, Apr., 2011.

[7] P. Zhang, D.Y. Yang, K.W. Chan, and G.W. Cai, "Adaptive wide-area damping control scheme with stochastic subspace identification and signal time delay compensation", *IET Gener. Transm. Distrib.*, vol. 6, no. 9, pp. 844–852, 2012.

[8] Hesen Liu, Lin Zhu, Zhuohong Pan, Feifei Bai, Yong Liu, Yilu Liu, Mahendra Patel, Evangelos Evangelos, and Navin 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.

[9] Trudnowski, Daniel, Brian Pierre, Felipe Wilches-Bernal, David Schoenwald, Ryan Elliott, Jason Neely, Raymond Byrne, and Dmitry Kosterev. "Initial closed-loop testing results for the pacific DC intertie wide area damping controller.*" 2017 IEEE Power & Energy Society General Meeting (PESGM).* Chicago, IL, USA: IEEE, 2017.

[10] Junbo Zhang ; C. Y. Chung ; Chao Lu ; Kun Men ; Liang Tu, A Novel Adaptive Wide Area PSS Based on Output-Only Modal Analysis, *IEEE Transactions on Power Systems*, Volume: 30, Issue: 5, Sept. 2015, pp. 2633 - 2642

[11] Lin Zhu, Hesen Liu, Zhuohong Pan, Yilu Liu, Evangelos Farantatos, Mahendra Patel, Sean McGuinness, and Navin Bhatt, "Adaptive wide-area damping control using measurement-driven model considering random time delay and data packet loss," *IEEE PES General Meeting*, Boston, MA, USA, July 17-21, 2016.

[12] M. E. Aboul-Era, A. A. Sallam, J. D. Mccalley, and A. A. Fouad, “Damping controller design for power system oscillations using global signals,” *IEEE Trans. Power Syst.*, vol. 11, no. 2, pp. 767–773, 1996.

[13] Benchmark Systems for Small-Signal Stability Analysis and Control. http://www.sel.eesc.usp.br/ieee/

[14] L. Yang, Y. W. Ma, J.X. Wang, J.Wang, X.H. Zhang, L. M. Tolbert, F. Wang, K. Tomsovic, "Development of coverter based reconfigurable power grid emulator," in Proc. of IEEE ECCE, Pittsburgh, USA, Sep. 13-18, 2014.

[15] Demonstration of Oscillation Damping Control Using Measurement-Based Transfer Function Model on the CURENT Hardware Testbed, EPRI Technical Update, December 2016. https://www.epri.com/#/pages/product/3002008407/

[16] J. E. Price, J. Goodin, “Reduced Network Modeling Of WECC as a Market Design Prototype,” IEEE PES General Meeting, Detroit, MI, July 14-29, 2011.

[17] Deepak Ramasubramanian, Ryan Quint and Mohamed Osman, "PMU-Based Oscillation Analysis of the North American Interconnections," 2016 Grid of the Future Symposium, CIGRE US National Committee, Philadelphia, PA, 2016