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PDCI Damping Controller Summary of Project Achievements

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ABSTRACT

This report presents a complete listing, as of May 2019, of the damping controller (DCON) project accomplishments including a project overview, project innovations, awards, patent application, journal papers, conference papers, project reports, and project presentations. The purpose of the DCON is to mitigate inter-area oscillations in the WI by active improvement of oscillatory mode damping using phasor measurement unit (PMU) feedback to modulate power flow in the PDCI. The DCON project is the result of a collaboration between Sandia National Laboratories (SNL), Montana Technological University (MTU), Bonneville Power Administration (BPA), and the Department of Energy Office of Electricity (DOE-OE).

ACKNOWLEDGEMENTS

We gratefully acknowledge the support of the BPA Office of Technology Innovation (Project No. 289, Project Managers: Mr. Gordon Matthews and Dr. Jisun Kim, Technical Point of Contact: Dr. Dmitry Kosterev), the DOE Office of Electricity (OE) Transmission Reliability Program (Program Manager: Mr. Phil Overholt), and the DOE-OE Energy Storage Program (Program Manager: Dr. Imre Gyuk). We express our sincere gratitude to BPA staff who have provided us with valuable guidance and advice throughout the project: Mr. Michael Overeem, Mr. Mark Yang, Mr. Jeff Barton, Mr. Greg Stults, Mr. Tony Faris, Mr. Dan Goodrich, Mr. Shawn Patterson, Mr. Alex Chavez, and Dr. Judith Estep. We also express our sincere appreciation for the design guidance of Prof. Matt Donnelly of Montana Technological University.

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EXECUTIVE SUMMARY

Project Background

A collaborative effort between Sandia National Laboratories (SNL), Montana Tech University (MTU), and Bonneville Power Administration (BPA), dating back to 2013, was launched to design, develop, and demonstrate an active damping control system (DCON) to improve damping of inter-area oscillations in the Western Interconnection (WI). The control system accomplishes this goal by using real-time measurements acquired from phasor measurement units (PMUs) to construct a feedback signal that modulates power flow through the Pacific DC Intertie (PDCI).

There are two primary motivations to increase damping of inter-area oscillations. First, if damping is insufficient, oscillations may lead to system-wide tripping events, and in turn to a series of cascading outages. The 1996 system break-up across the west coast of North America can in part be attributed to undamped oscillations. Avoiding these large-scale power outages provides a significant financial incentive in damping inter-area oscillations. Second, power transfer through long transmission corridors in western North America is often constrained due to stability concerns and limited by poorly damped electromechanical oscillations. Thus, additional damping may increase the power transfer capacity. Recent developments in reliable real-time wide-area measurement systems (WAMS) based on PMUs has enabled the potential for large-scale damping control approaches to stabilize critical oscillation modes.

The original idea to modulate PDCI power flow to damp inter-area oscillations was first designed and tested in 1975. The original design utilized the time rate of change of the parallel AC real power flow as the feedback signal. Even though this method provided damping to low frequency modes of oscillation, further analysis determined that it introduced a right-half plane transfer function zero which limited the gain of the controller and worsened oscillations at higher frequencies. The DCON is able to avoid this problem because it employs GPS time-synchronized PMUs to infer the frequency difference between the PDCI terminals. This data is now available due to the recent deployment of PMUs in the WI, which provide reliable, low-latency, system-wide measurements.

Currently, the primary approach to mitigate grid oscillations and avoid blackouts in the WI is to operate well below transmission capacity, which is not economical. The DCON uses measurement data, acquired in real time from PMUs, to serve as a feedback signal to inform the controller as to how much power to add (or subtract) to the power flow on the PDCI. This carefully controlled "injection" of power to the PDCI is the action that damps oscillations in the grid. This control strategy provides damping to the primary north-south oscillatory modes in the WI without interacting with speed governor actions. A supervisory system, integrated into the controller, ensures a "do no harm" policy for the grid in which damping is never worsened. By improving the damping of these inter-area oscillations, the DCON has the potential to allow increased power transfers in the WI.

The DCON is the first successful wide-area grid demonstration of real-time feedback control using PMUs in North America. This is a game-changer, enabling the use of widely-distributed networked energy resources that have the potential to transform the existing power grid into the emerging network-enabled power grid. Benefits that the DCON is capable of delivering, once operational, include: (1) Additional reliability to the grid from improved damping of electromechanical oscillations. (2) Additional contingency management of the grid under stressed system conditions. (3) Higher power limits in specific transmission corridors. (4) Reduction and/or postponement in new transmission capacity expansion.

ACRONYMS AND DEFINITIONS

Abbreviation	Definition
AC	Alternating Current
BC	British Columbia, Canada
BCA	Bulk Energy System Cyber Asset
BES	Bulk Energy System
BPA	Bonneville Power Administration
CIP	Critical Infrastructure Protection
COI	California-Oregon Intertie
DAQ	Data Acquisition
DC	Direct Current
DCON	Damping Controller
DOE	Department of Energy
DOE-OE	Department of Energy Office of Electricity
FERC	Federal Energy Regulatory Commission
FISMA	Federal Information Security Management Act
GPS	Global Positioning System
HVDC	High Voltage Direct Current
Hz	Hertz (cycles per second)
I/O	Input-Output
IEEE	Institute of Electrical and Electronics Engineers
kV	Kilo-Volts
KVM	Keyboard Video Monitor
MSF	Multi-Sine Function
MTU	Montana Technological University
MW	Mega-Watts
NERC	North American Electricity Reliability Corporation
NI	National Instruments
PDCI	Pacific Direct Current Intertie
PMU	Phasor Measurement Unit
SNL	Sandia National Laboratories
WAMS	Wide Area Measurement System
WECC	Western Electricity Coordinating Council
WI	Western Interconnection

1. PROJECT OVERVIEW

Supplementing the PDCI with a real-time damping controller dates back to the 1970s when BPA engineers experimented with the concept. Review of this work via reports and oral interviews with engineers in charge of the project revealed two primary conclusions: 1) the HVDC modulation considerably improved inter-area mode damping; and 2) the feedback signal, which was derived from a localized AC power flow, actually caused the PDCI controller to make oscillations at a higher frequency worse. This issue, along with lack of a WAMS, was a primary reason that the control was not considered for production.

Based upon several low-damping events, BPA initiated the TIP-50 project in 2007. The goal was to investigate several potential solutions to improve system oscillatory stability. One component of TIP-50 was to re-visit PDCI damping control. Initial research focused on understanding why the 1970s experiments failed and if a safe PDCI damping control strategy could actually be constructed. The primary results were presented in conference paper [25] (see p. 21 for reference), which was an IEEE prize paper. This paper explained why the 1970s approach failed and why wide-area feedback was needed to safely implement a PDCI damping controller. The paper demonstrated an effective and safe control strategy via simulation.

After the successful conclusions from TIP-50, the TIP-289 project was initiated to fully investigate and demonstrate a PDCI damping controller. The primary deliverable of TIP 289 was the design, simulation, testing, and demonstration of a wide-area damping control system that modulates the power flow on the PDCI based on real-time wide-area feedback information acquired from PMUs located throughout the BPA region. Major breakthroughs include:

- An effective and safe feedback control strategy based upon further refinement of the concept developed under TIP-50. This included thousands of simulation tests to verify the approach.
- An automated supervisory system to monitor and operate the controller to maintain system safety and integrity. This system utilizes state-of-the-art algorithms to assure the safe operation of the damping controller under all conditions.
- The first wide-area large-scale damping controller ever constructed and operated in the world. This system utilizes real-time PMU feedback from hundreds of miles to stabilize the entire interconnect. To our knowledge, no other system has ever been built and operated on an actual system.

In the following sections, details are provided for a project overview, project innovations, relevant awards attained by project staff during the tenure of the project, project patent application filed, journal papers, conference papers, project reports, and project presentations, respectively.

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2. PROJECT INNOVATIONS

The following list describes the primary innovations to come out of the DCON project.

1. First successful demonstration of wide-area control using real-time PMU feedback in North America ➔ much knowledge gained for networked control systems on the grid.
2. Control design is actuator agnostic ➔ easily adaptable to other sources of power injection (e.g., wind turbines, energy storage).
3. Supervisory system architecture and design is modular and readily reusable for future real-time control systems to ensure "Do No Harm" to the grid.
4. Algorithms, models, and simulations created to support future implementation of control strategies using distributed grid assets.
5. Extensive eigensystem analysis, visualization, and mapping tools developed to support simulation studies and analysis of test results.
6. Model development and validation supports multiple levels of fidelity in analysis, design, and simulation studies.

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3. AWARDS

The following list enumerates the awards attained by project staff during the tenure of the project. All of these awards have a significant component directly related to the work of this project.

1. David A. Schoenwald, Brian J. Pierre, Felipe Wilches-Bernal, Ryan T. Elliott, Raymond H. Byrne, Jason C. Neely, Daniel J. Trudnowski, and Dmitry N. Kosterev, "Control System for Active Damping of Inter-Area Oscillations," R&D 100 Award, Project video available at https://www.youtube.com/watch?v=wAJTISpkoeo&feature=youtu.be, 2017.
2. David A. Schoenwald, Brian J. Pierre, Felipe Wilches-Bernal, Ryan T. Elliott, Raymond H. Byrne, and Jason C. Neely, "Power Grid Oscillation Damping Control Design Team," Sandia Employee Recognition Award, 2017.
3. David A. Schoenwald, Outstanding Engineer, Albuquerque IEEE Section, "For contributions to the development and realization of next generation Smart Grid technologies," 2017.
4. Daniel J. Trudnowski, "Lifetime Distinguished Researcher" Award, Montana Technological University, 2017.
5. Felipe Wilches-Bernal, Outstanding Young Engineer Award, Albuquerque IEEE Section, "For outstanding development of control algorithms for distributed energy resources and wide area damping control," 2019.
6. Daniel J. Trudnowski, Dmitry N. Kosterev, and John Undrill, "PDCI Damping Control Analysis for the western North American Power System," Best of the Best Paper Award, IEEE Power & Energy Soc. General Meeting, Vancouver, Canada, July 21-25, 2013.
7. Brian J. Pierre, Ryan T. Elliott, David A. Schoenwald, Jason C. Neely, Raymond H. Byrne, Daniel J. Trudnowski, and James Colwell, "Supervisory System for a Wide Area Damping Controller Using PDCI Modulation and Real-Time PMU Feedback," Best Conference Paper Session Award, IEEE Power & Energy Society General Meeting, Boston, MA, July 17-21, 2016.
8. Felipe Wilches-Bernal, Brian J. Pierre, Ryan T. Elliott, David A. Schoenwald, Raymond H. Byrne, Jason C. Neely, and Daniel J. Trudnowski, "Time Delay Definitions and Characterizations in the Pacific DC Intertie Wide Area Damping Controller," Best Conference Paper Session Award, IEEE Power & Energy Society General Meeting, Chicago, IL, July 16-20, 2017.

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4. PATENT APPLICATION

The following patent application, based on work from this project, is pending as of May 2019.

1. David A. Schoenwald, Raymond H. Byrne, Ryan T. Elliott, Jason C. Neely, Brian J. Pierre, Felipe Wilches-Bernal, and Daniel J. Trudnowski, "Systems and Methods for Active Damping Control of Inter-Area Oscillations in Large-Scale Interconnected Power Systems," Non-Provisional Patent Application filed with the US Patent and Trademark Office, Application Number: 15/926,658, Filed: March 20, 2018.

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5. JOURNAL PAPERS

The following list provides the citations with hyperlinks for published journal papers whose content was primarily derived from this project.

1. B. J. Pierre, F. Wilches-Bernal, D. A. Schoenwald, R. T. Elliott, D. J. Trudnowski, R. H. Byrne, and J. C. Neely, "Design of the Pacific DC Intertie Wide Area Damping Controller," DOI 10.1109/TPWRS.2019.2903782, *IEEE Transactions on Power Systems*, 2019, SAND2019-3169J.
2. C. Lackner, F. Wilches-Bernal, B.J. Pierre, D. A. Schoenwald, "A Tool to Characterize Delays and Packet Losses in Power Systems with Synchrophasor Data," *IEEE Power and Energy Technology Systems Journal*, Vol. 5, Issue 4, pp.117-128, December 2018, SAND2018-12066J.
3. M. Elizondo, R. Fan, H. Kirkham, M. Ghosal, F. Wilches-Bernal, D. Schoenwald, and J. Lian, "Interarea Oscillation Damping Control Using High Voltage DC Transmission: A Survey," *IEEE Trans. Power Syst.*, Vol. 33, Issue 6, pp. 6915 – 6923, November 2018, SAND2019-5884J.
4. D. A. Schoenwald, "Active Damping of Inter-Area Oscillations in the Western Interconnection: Recent Developments," *IEEE Smart Grid Newsletter*, http://smartgrid.ieee.org/newsletters/july-2017, July 2017, SAND2017-6944J.
5. D. A. Schoenwald, B. J. Pierre, F. Wilches-Bernal, and D. J. Trudnowski, "Design and Implementation of a Wide-Area Damping Controller Using High Voltage DC Modulation and Synchrophasor Feedback," *IFAC-PapersOnLine*, ISSN 2405-8963, Vol. 50, Issue 1, pp. 67-72, July 2017, SAND2019-5883J.
6. J. C. Neely, J. Johnson, R. H. Byrne, and R. T. Elliott, "Structured Optimization for Parameter Selection of Frequency-Watt Grid Support Functions for Wide-Area Damping," *International Journal of Distributed Energy Resources and Smart Grids*, pp. 69-94, Vol. 11, No. 1, January 2015, SAND2015-5335J.

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6. CONFERENCE PAPERS

The following list provides the citations with hyperlinks for published conference papers whose content was primarily derived from this project.

1. D. A. Schoenwald, F. Wilches-Bernal, B. J. Pierre, R. T. Elliott, and D. J. Trudnowski, "Data Considerations in Real-Time PMU Feedback Control Systems," North American SynchroPhasor Initiative (NASPI) Work Group Meeting, San Diego, CA, April 15-17, 2019, SAND2019-1157A.
2. F. Wilches-Bernal, D. A. Copp, G. Bacelli, and R. H. Byrne, "Structuring the Optimal Output Feedback Control Gain: A Soft Constraint Approach," 57th IEEE Conference on Decision and Control, Miami Beach, FL, December 17-19, 2018, SAND2018-10464C.
3. R. A. Biroon, P. Pisu, and D. A. Schoenwald, "Inter-Area Oscillation Damping in Large-Scale Power Systems using Decentralized Control," 2018 ASME Dynamic Systems and Control Conference, Atlanta, GA, September 30-October 3, 2018, SAND2019-5891C.
4. F. Wilches-Bernal, D. A. Copp, D. A. Schoenwald, and I. Gravagne, "Stability Criteria for Power Systems with Damping Control and Asymmetric Feedback Delays," 50th North American Power Symposium, Fargo, ND, September 9-11, 2018, SAND2018-7689C.
5. F. Wilches-Bernal, B. J. Pierre, D. A. Schoenwald, R. T. Elliott, and D. J. Trudnowski, "Time Synchronization in Wide Area Damping Control of Power Systems," 2018 Probabilistic Methods Applied to Power Systems (PMAPS) Conference, Boise, ID, June 24-28, 2018, SAND2018-2804C.
6. D. A. Copp, F. Wilches-Bernal, D. A. Schoenwald, and I. Gyuk, "Power System Damping Control via Power Injections from Distributed Energy Storage," SPEEDAM 2018, Amalfi Coast, Italy, June 20-22, 2018, SAND2017-12926C.
7. B. J. Pierre, F. Wilches-Bernal, D. A. Schoenwald, R. T. Elliott, R. H. Byrne, J. C. Neely, and D. J. Trudnowski, "The Pacific DC Intertie Wide Area Damping Controller Utilizing Real-Time PMU Feedback," North American Synchrophasor Initiative (NASPI) Spring Meeting, Albuquerque, NM, April 24-26, 2018, SAND2018-5252C.
8. F. Wilches-Bernal, D. Schoenwald, R. Fan, M. Elizondo, and H. Kirkham, "Analysis of the Effect of Communication Latencies on HVDC-Based Damping Control," 2018 IEEE PES T&D Conference & Exposition, Denver, CO, April 16-19, 2018, SAND2018-2285C.
9. R. Fan, M. Elizondo, H. Kirkham, J. Lian, F. Wilches-Bernal, and D. Schoenwald, "Oscillation Damping Control Using Multiple High Voltage DC Transmission Lines: Controllability Exploration," 2018 IEEE PES T&D Conference & Exposition, Denver, CO, April 16-19, 2018, SAND2019-5888C.
10. D. A. Copp, F. Wilches-Bernal, I. Gravagne, and D. A. Schoenwald, "Time Domain Analysis of Power System Stability with Damping Control and Asymmetric Feedback Delays," 49th North American Power Symposium, Morgantown, WV, September 17-19, 2017, SAND2017-6454C.
11. F. Wilches-Bernal, R. Concepcion, J. C. Neely, D. A. Schoenwald, R. H. Byrne, B. J. Pierre, and R. T. Elliott, "Effect of Time Delay Asymmetries in Power System Damping Control," IEEE Power & Energy Soc. General Meeting, Chicago, IL, July 16-20, 2017, SAND2017-6331C.
12. F. Wilches-Bernal, B. J. Pierre, R. T. Elliott, D. A. Schoenwald, R. H. Byrne, J. C. Neely, and D. J. Trudnowski, "Time Delay Definitions and Characterizations in the Pacific DC Intertie Wide

Area Damping Controller," IEEE Power & Energy Society General Meeting, Chicago, IL, July 16-20, 2017, SAND2017-6330C.

13. D. J. Trudnowski, B. J. Pierre, F. Wilches-Bernal, D. A. Schoenwald, R. T. Elliott, J. C. Neely, R. H. Byrne, and D. N. Kosterev, "Initial Closed-Loop Testing Results for the Pacific DC Intertie Wide Area Damping Controller," IEEE Power & Energy Society General Meeting, Chicago, IL, July 16-20, 2017, SAND2019-5887C.

14. 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," IEEE Power & Energy Society General Meeting, Chicago, IL, July 16-20, 2017, SAND2017-6099C.

15. D. A. Schoenwald, B. J. Pierre, F. Wilches-Bernal, and D. J. Trudnowski, "Design and Implementation of a Wide-Area Damping Controller Using High Voltage DC Modulation and Synchrophasor Feedback," IFAC World Congress, Toulouse, France, July 9-14, 2017, SAND2016-11534C.

16. B. J. Pierre, F. Wilches-Bernal, D. A. Schoenwald, R. T. Elliott, J. C. Neely, R. H. Byrne, "Open-Loop Testing Results for the Pacific DC Intertie Wide Area Damping Controller," 12th IEEE Power & Energy Society PowerTech Conference, Manchester, UK, June 18 – 22, 2017, SAND2018-3327C.

17. B. J. Pierre, R. T. Elliott, D. A. Schoenwald, J. C. Neely, R. H. Byrne, D. J. Trudnowski, and J. Colwell, "Supervisory System for a Wide Area Damping Controller Using PDCI Modulation and Real-Time PMU Feedback," IEEE Power & Energy Society General Meeting, Boston, MA, July 17-21, 2016, SAND2016-6871C.

18. R. H. Byrne, D. J. Trudnowski, J. C. Neely, D. A. Schoenwald, D. G. Wilson, and L. J. Rashkin, "Small Signal Stability Analysis and Distributed Control with Communications Uncertainty," SPEEDAM 2016, Capri Island, Italy, June 22-24, 2016, SAND2016-4634C.

19. R. H. Byrne, R. J. Concepcion, J. C. Neely, F. Wilches-Bernal, R. T. Elliott, O. Lavrova, and J. E. Quiroz, "Small Signal Stability of the Western North American Power Grid with High Penetrations of Renewable Generation," 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC 2016), Portland, OR, June 5-10, 2016, SAND2016-5487C.

20. J. C. Neely, R. H. Byrne, D. A. Schoenwald, R. T. Elliott, D. J. Trudnowski, and M. K. Donnelly, "Optimal Control of Distributed Networked Energy Storage for Improved Small-Signal Stability," Proceedings of the 2015 Biennial International Conference on Electrical Energy Storage Applications and Technologies (EESAT 2015), San Diego, CA, September 21-24, 2015, SAND2015-7880C.

21. R. H. Byrne, D. J. Trudnowski, J. C. Neely, R. T. Elliott, D. A. Schoenwald, and M. K. Donnelly, "Optimal Locations for Energy Storage Damping Systems in the Western North American Interconnect", IEEE Power & Energy Society General Meeting, National Harbor, MD, July 27-31, 2014, SAND2013-10451C.

22. R. T. Elliott, R. H. Byrne, A. Ellis, and L. Grant, "Impact of increased photovoltaic generation on inter-area oscillations in the western north american power system," IEEE Power & Energy Society General Meeting, National Harbor, MD, July 27-31, 2014, SAND2013-10466C.

23. D. Trudnowski, D. Kosterev, J. Wold, "Open-Loop PDCI Probing Tests for the Western North American Power System," IEEE Power & Energy Society General Meeting, National Harbor, MD, July 27-31, 2014.
24. J. C. Neely, R. T. Elliott, R. H. Byrne, D. A. Schoenwald, and D. J. Trudnowski, "The Benefits of Energy Storage Combined with HVDC Transmission Power Modulation for Mitigating Inter-Area Oscillations," Proceedings of the 2013 Biennial International Conference on Electrical Energy Storage Applications and Technologies (EESAT 2013), San Diego, CA, October 20-23, 2013, SAND2013-10240C.
25. D. J. Trudnowski, D. N. Kosterev, and J. Undrill, "PDCI Damping Control Analysis for the western North American Power System," IEEE Power & Energy Soc. General Meeting, Vancouver, Canada, July 21-25, 2013.
26. J. C. Neely, R. H. Byrne, C. A. Silva Monroy, R. T. Elliott, D. A. Schoenwald, D. Trudnowski, and M. Donnelly, "Damping of Inter-Area Oscillations using Energy Storage", IEEE Power & Energy Society General Meeting, Vancouver, Canada, July 21-25, 2013, SAND2012-10458C.
27. C. A. Silva Monroy, J. C. Neely, R. H. Byrne, R. T. Elliott, D. A. Schoenwald, "Wind Generation Controls for Damping of Inter-Area Oscillations", IEEE Power & Energy Society General Meeting, Vancouver, Canada, July 21-25, 2013, SAND2012-10459C.
28. R. H. Byrne, J. C. Neely, C. A. Silva Monroy, D. A. Schoenwald, D. Trudnowski, and M. Donnelly, "Energy Storage Controls for Grid Stability", ECI Conference on Modeling, Simulation, and Optimization for the 21st Century Electric Power Grid Conference, Lake Geneva, WI, October 21-25, 2012, SAND2012-9074C.

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7. PROJECT REPORTS

The following list provides the citations with hyperlinks for formal SAND reports whose content was entirely derived from this project. Citations without hyperlinks refer to project reports whose content is OUO (Official Use Only). To request permission for OUO reports, contact the project lead, David Schoenwald, daschoe@sandia.gov.

1. David A. Schoenwald, Daniel J. Trudnowski, Brian J. Pierre, Felipe Wilches-Bernal, Ryan T. Elliott, Raymond H. Byrne, and Jason C. Neely, "PDCI Damping Controller Test Results and Project Summary," Sandia National Laboratories Technical Report, SAND2019-5972, Albuquerque, NM, June 2019.
2. David A. Schoenwald, Daniel J. Trudnowski, Brian J. Pierre, Felipe Wilches-Bernal, Ryan T. Elliott, Raymond H. Byrne, and Jason C. Neely, "PDCI Damping Controller Summary of Project Achievements," Sandia National Laboratories Technical Report, SAND2019-5971, Albuquerque, NM, June 2019.
3. D. Schoenwald, C. Rawlins, B. Pierre, F. Wilches-Bernal, and R. Elliott, "Executive Summary to PDCI Oscillation Damping Controller Software Documentation," Sandia National Laboratories Tech. Report, SAND2018-10049, Albuquerque, NM, September 2018.
4. C. Rawlins, D. Schoenwald, B. Pierre, F. Wilches-Bernal, and R. Elliott, "PDCI Oscillation Damping Controller Software Documentation," Sandia National Laboratories Technical Report, SAND2018-10048, Albuquerque, NM, September 2018.
5. D. Schoenwald, B. Pierre, F. Wilches-Bernal, R. Elliott, R. Byrne, J. Neely, and D. Trudnowski, "PDCI Oscillation Damping Controller Documentation and Specifications," Sandia National Laboratories Technical Report, SAND2018-2389, Albuquerque, NM, March 2018.
6. F. Wilches-Bernal, B. Pierre, R. Elliott, D. Schoenwald, R. Byrne, J. Neely, D. Trudnowski, and M. Donnelly, "PDCI Wide-Area Damping Control: PSLF Simulations of the 2017 Test Plan - Dual Export Case," Sandia National Laboratories Technical Report, SAND2017-6196, Albuquerque, NM, June 2017.
7. F. Wilches-Bernal, B. Pierre, R. Elliott, D. Schoenwald, R. Byrne, J. Neely, D. Trudnowski, and M. Donnelly, "PDCI Wide-Area Damping Control: PSLF Simulations of the 2017 Test Plan - Heavy Summer Case," Sandia National Laboratories Technical Report, SAND2017-6195, Albuquerque, NM, June 2017.
8. F. Wilches-Bernal, B. Pierre, R. Elliott, D. Schoenwald, R. Byrne, J. Neely, D. Trudnowski, and M. Donnelly, "PDCI Wide-Area Damping Control: PSLF Simulations of the 2017 Test Plan - Light Summer Case," Sandia National Laboratories Technical Report, SAND2017-6194, Albuquerque, NM, June 2017.
9. F. Wilches-Bernal, B. Pierre, R. Elliott, D. Schoenwald, R. Byrne, J. Neely, D. Trudnowski, and M. Donnelly, , "PDCI Wide-Area Damping Control: PSLF Simulations of the 2016 Open and Closed Loop Test Plan," Sandia National Laboratories Technical Report, SAND2017-2755, Albuquerque, NM, March 2017.
10. B. Pierre, F. Wilches-Bernal, R. Elliott, D. Schoenwald, J. Neely, R. Byrne, and D. Trudnowski, "PDCI Wide Area Damping Control - Open Loop Data Analysis," Sandia National Laboratories Technical Report, SAND2017-2211, Albuquerque, NM, February 2017.

11. B. Pierre, R. Elliott, and D. Schoenwald, "Telecom Requirements at Celilo for BPA Damping Controller Prototype," Sandia National Laboratories Technical Report, SAND2015-7523, Albuquerque, NM, September 2015.
12. B. Pierre, R. Elliott, and D. Schoenwald, "Quick Start Guide for BPA Damping Controller Prototype," Sandia National Laboratories Technical Report, SAND2015-5885, Albuquerque, NM, July 2015.
13. D. Schoenwald, R. Elliott, J. Neely, and R. Byrne, "Input-Output Data Specifications for BPA Project TIP 289," Sandia National Laboratories Technical Report, SAND2014-16309, Albuquerque, NM, July 2014.

8. PROJECT PRESENTATIONS

The following list provides the presenter name(s), title (with hyperlink), location, and date for oral presentations delivered by project staff whose content was primarily derived from this project. Presentations without hyperlinks are not available.

1. D. Schoenwald and D. Trudnowski, "Wide-Area Damping Control," DOE Transmission Reliability Peer Review Meeting, Washington, DC, June 13, 2019, SAND2019-6592PE.
2. D. Schoenwald, "Challenges in the Use of PMU Data for Real-Time Feedback Control," PNNL PMU Metrology Meeting, Richland, WA, April 16, 2019, SAND2019-4532PE.
3. D. Schoenwald, "Data Considerations in Real-Time PMU Feedback Control Systems," NASPI Spring Meeting, San Diego, CA, April 9, 2019, SAND2019-4119C.
4. D. Schoenwald, "Real-Time Damping of Power Grid Oscillations Using Synchrophasor Feedback," CURENT Industry Seminar, Knoxville, TN, March 1, 2019, SAND2019-2114PE.
5. D. Schoenwald, "Lecture on Technology Transfer at Sandia National Labs," Invited lecture to Portland State University Technology Transfer class, Invited by Dr. Judith Estep, Webinar-based lecture, February 19, 2019, SAND2019-1800PE.
6. F. Wilches-Bernal, "Structuring the Optimal Output Feedback Control Gain: A Soft Constraint Approach," 2018 IEEE Conference on Decision and Control, Miami, FL, December 18, 2018, SAND2018-14349C.
7. D. Schoenwald and F. Wilches-Bernal, "Real-Time Damping Control Using PMU Feedback," JSIS Meeting, Portland, OR, November 9, 2018, SAND2018-12843PE.
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