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

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<tr>
<td>AC</td>
<td>Alternating Current</td>
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<tr>
<td>BC</td>
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<td>BCA</td>
<td>Bulk Energy System Cyber Asset</td>
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<td>BES</td>
<td>Bulk Energy System</td>
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<td>Bonneville Power Administration</td>
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<td>CIP</td>
<td>Critical Infrastructure Protection</td>
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<td>COI</td>
<td>California-Oregon Intertie</td>
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<td>DAQ</td>
<td>Data Acquisition</td>
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<td>DC</td>
<td>Direct Current</td>
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<td>DCON</td>
<td>Damping Controller</td>
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<td>FISMA</td>
<td>Federal Information Security Management Act</td>
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<tr>
<td>GPS</td>
<td>Global Positioning System</td>
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<td>HVDC</td>
<td>High Voltage Direct Current</td>
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<td>Hz</td>
<td>Hertz (cycles per second)</td>
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<td>I/O</td>
<td>Input-Output</td>
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<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
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<td>kV</td>
<td>Kilo-Volts</td>
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<td>KVM</td>
<td>Keyboard Video Monitor</td>
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<td>MSF</td>
<td>Multi-Sine Function</td>
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<td>MW</td>
<td>Mega-Watts</td>
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<td>North American Electricity Reliability Corporation</td>
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<td>NI</td>
<td>National Instruments</td>
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<td>PDCI</td>
<td>Pacific Direct Current Intertie</td>
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<td>PMU</td>
<td>Phasor Measurement Unit</td>
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<td>WAMS</td>
<td>Wide Area Measurement System</td>
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<td>Western Electricity Coordinating Council</td>
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<td>WI</td>
<td>Western Interconnection</td>
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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.


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.


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4. PATENT APPLICATION

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

5. **JOURNAL PAPERS**

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


6. CONFERENCE PAPERS

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


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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.


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.


17. D. Schoenwald, “2017 R&D 100 Award Winner: Control System for Active Damping of Inter-Area Oscillations,” Briefing on R&D 100 Award Winning Project to DOE-OE Leadership, Washington, DC, March 14, 2018, SAND2018-2963PE.

18. D. Schoenwald, “Control System Design for Active Damping of Large-Scale Power Grids,” Invited seminar in ECE Department at The Ohio State University, Columbus, OH, December 4, 2017, SAND2017-13155PE.


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