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Wide-Area Damping Control Using PMU Feedback

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Project Summary

Problem:

- Poorly damped inter-area oscillations in congested transmission corridors can lead to system breakups and widespread outages
- To prevent this, power flows are constrained well below rated transmission limits ➔ inefficient use of expensive capital investments

Solution:

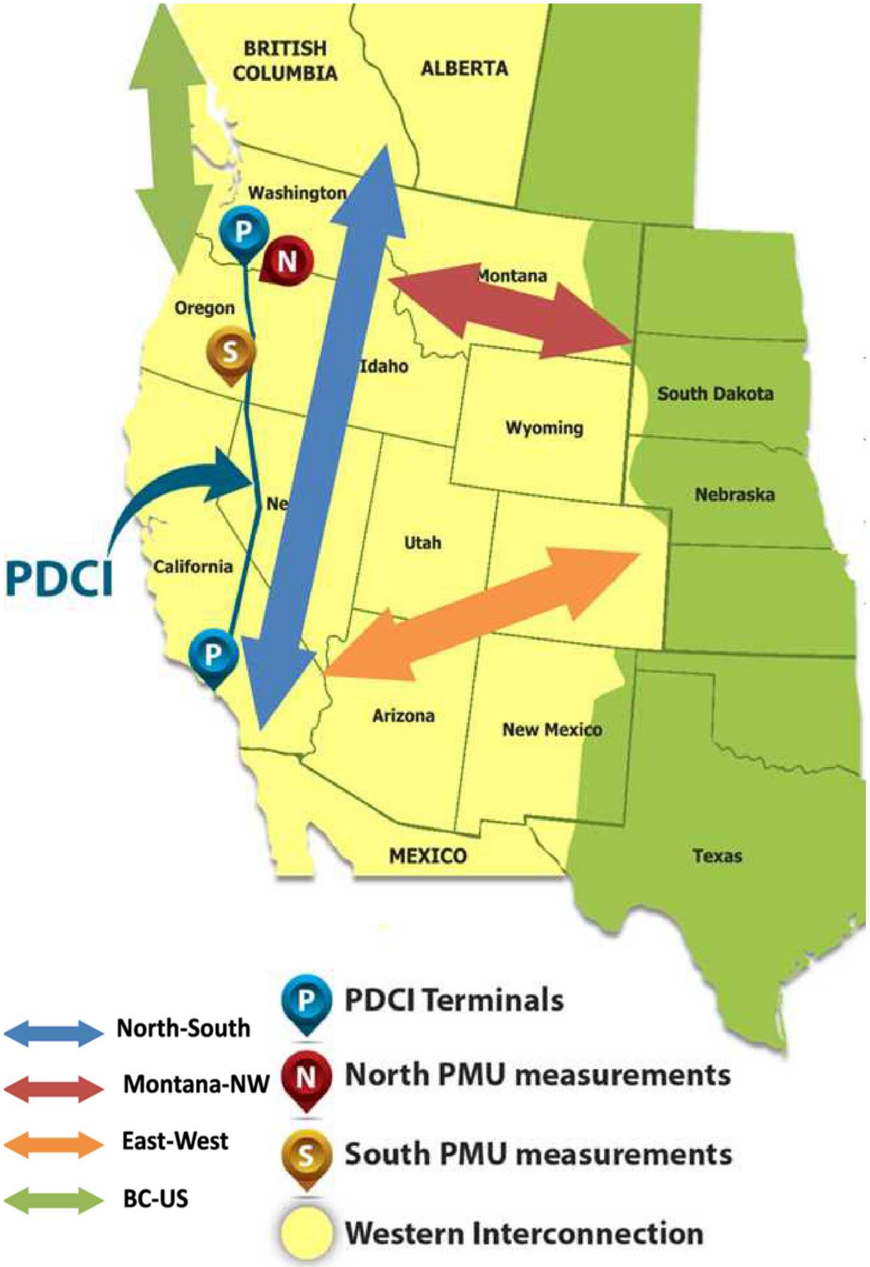
- Feedback control using real-time PMU data: First demonstration of this in North America
- Real power injection by modulating PDCI power
- Supervisory system integrated with controller for ensuring "Do No Harm" to grid

Benefits:

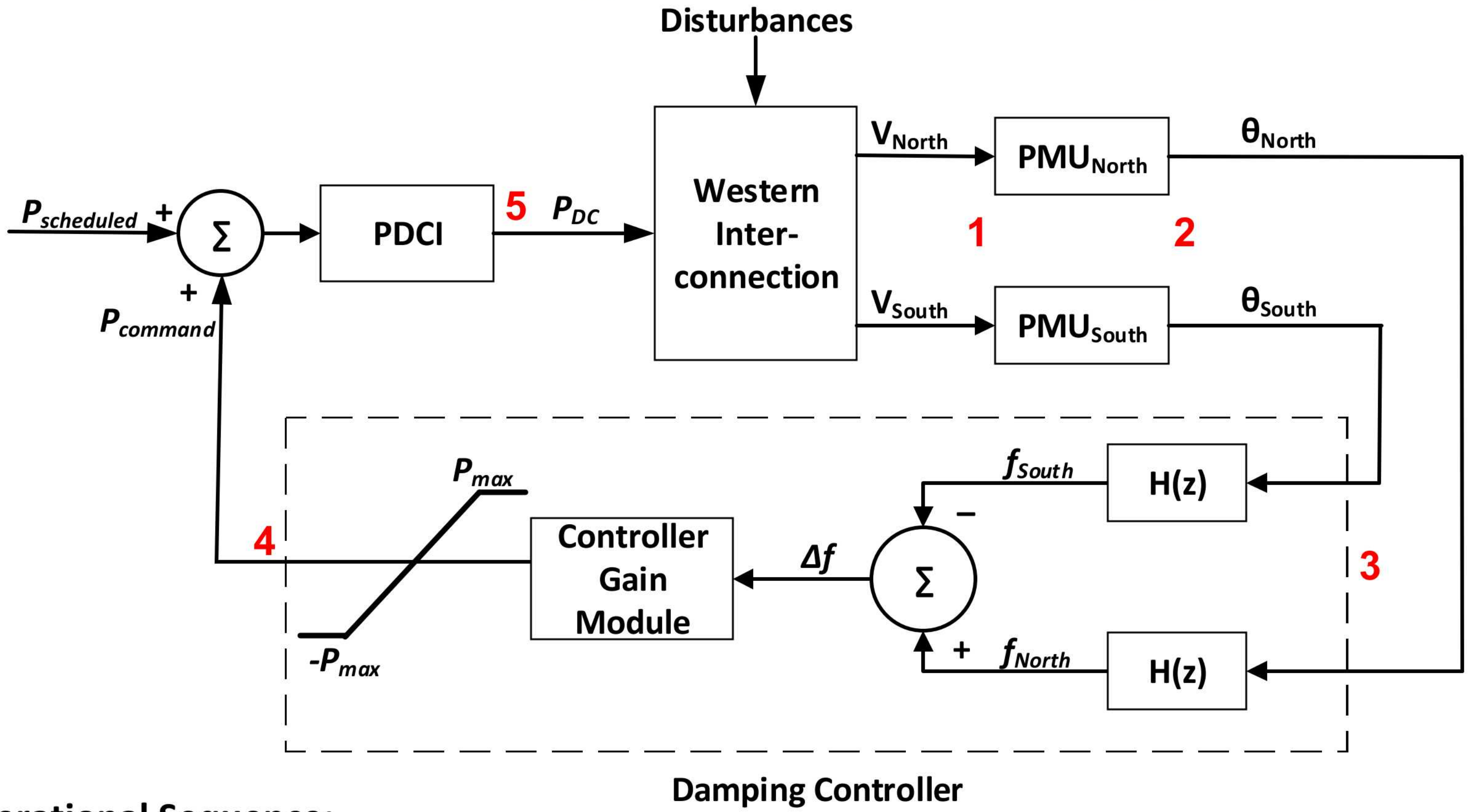
- Improved grid reliability
- Additional contingency for stressed grid conditions
- Avoided costs from a system-wide blackout
- Reduced or postponed need for new transmission capacity
- Enables higher power flows on congested transmission corridors

Project Background

- Based on 1970s BPA experiments on PDCI later shown to have destabilized BC-US mode
- Revived in 2007 – 2012 by BPA with Montana Tech leveraging PMU deployments in WECC
- Current project launched in June 2013 as a collaboration of SNL, MT, BPA, and DOE to develop and demonstrate damping control
- Phase 1 (June 2013 – Sept 2015)
  - Controller design based on extensive simulation studies & eigensystem analysis
  - Open-loop tests – study PMU data quality
- Phase 2 (Oct 2015 – Sept 2017)
  - System install at Celilo in The Dalles, OR
  - Closed-loop demonstration on Western Interconnection using modulation of PDCI
  - Documentation and publishing of results; engagement of power systems community
- Phase 3 (Oct 2017 and beyond)
  - Conduct longer-term tests
  - Study transient stability potential
  - Assess impacts with DC side
  - Explore other sources of actuation



Damping Controller Strategy



Operational Sequence:

1 PMUs take measurements

2 PMUs send data packets over network

3 Packets arrive at damping controller

4 Controller sends power command to PDCI

5 PDCI injects power command into grid

$$P_{command}(t) = K\left(f_{North}(t-\tau_{d1}) - f_{South}(t-\tau_{d2})\right)$$

K is a constant gain in MW/mHz

Real-time PMU feedback is the key to stable control

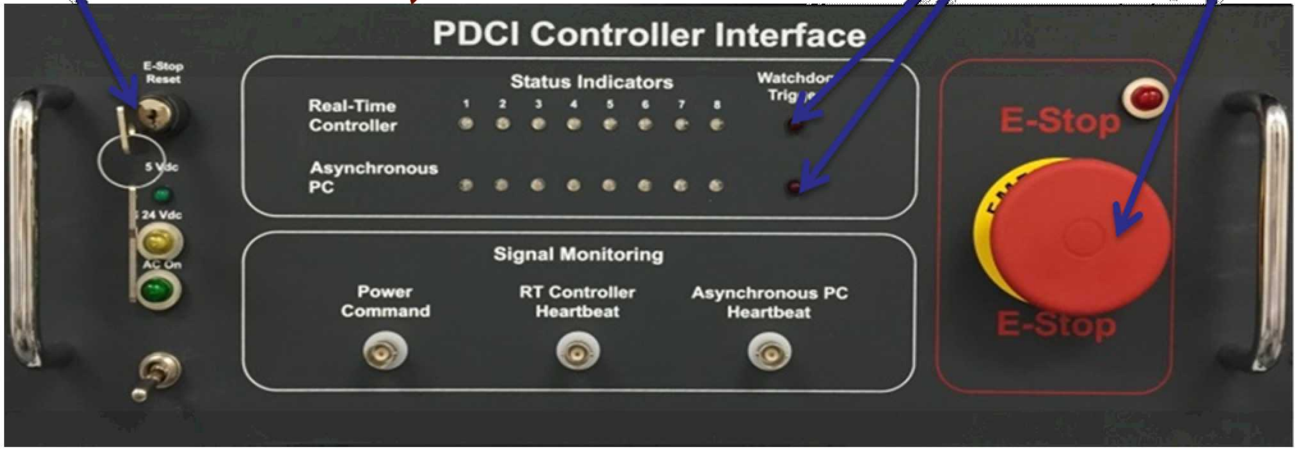
Damping Controller Hardware

Watchdog circuit module

Key switch

Heartbeat indicators

E-Stop button



Server for select supervisory functions ("Do No Harm")

Real-time Control platform

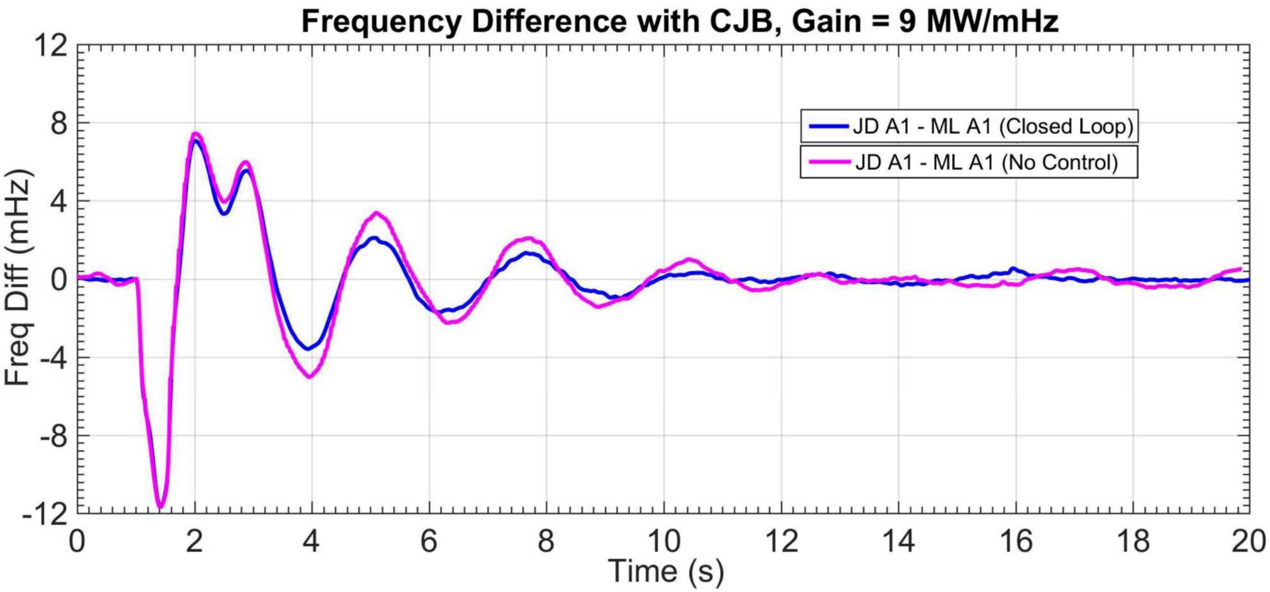
Status on FY18 Tasks

- Testing
  - CJBs, FOs using PDCI PSG (May 23, 2018)
  - “Tuning” of DCON Gain (May 23, 2018)
  - Implement +/- 0.2 mHz dead-zone (May 23, 2018)
  - “Walkaway” Test (May 24, 2018 – June 21, 2018)
- Transient Stability
  - PDCI-based with DCON
  - Other actuators – thyristor brakes, storage
- Forced Oscillations
  - AC side
  - DC side

Latest Tests Confirm Previous Test Results
(Tests conducted at Celilo on May 23, 2018)

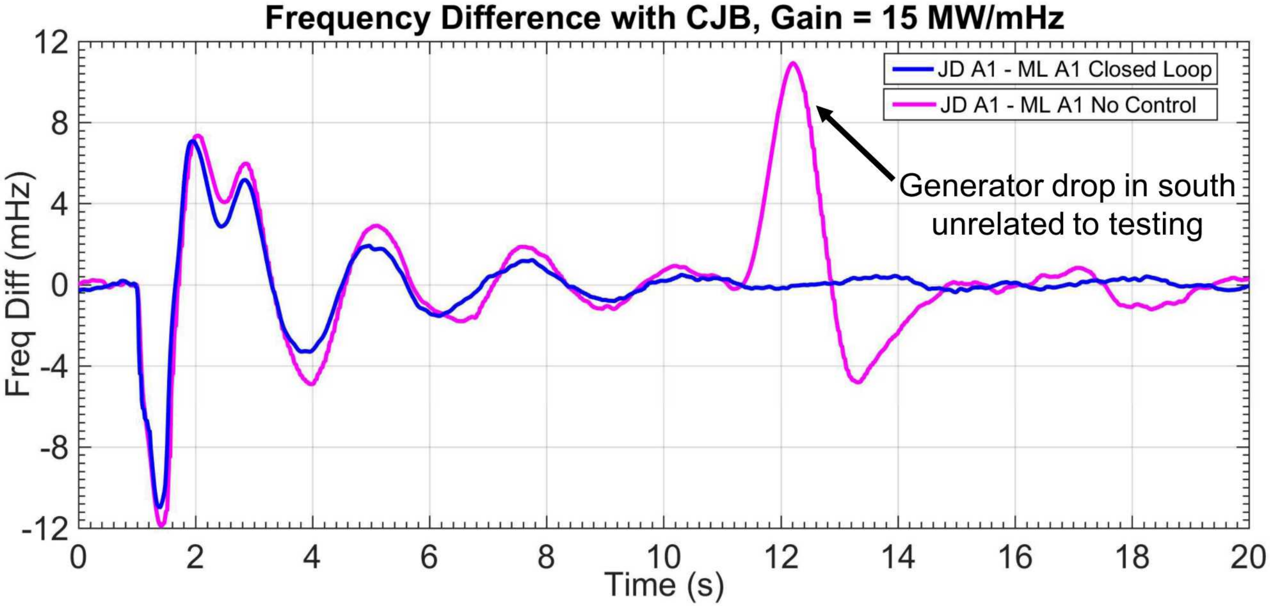
Chief Joseph brake test

Gain = 9 MW/mHz
Damping improved by 6 percentage points (10.0% to 16.0%)



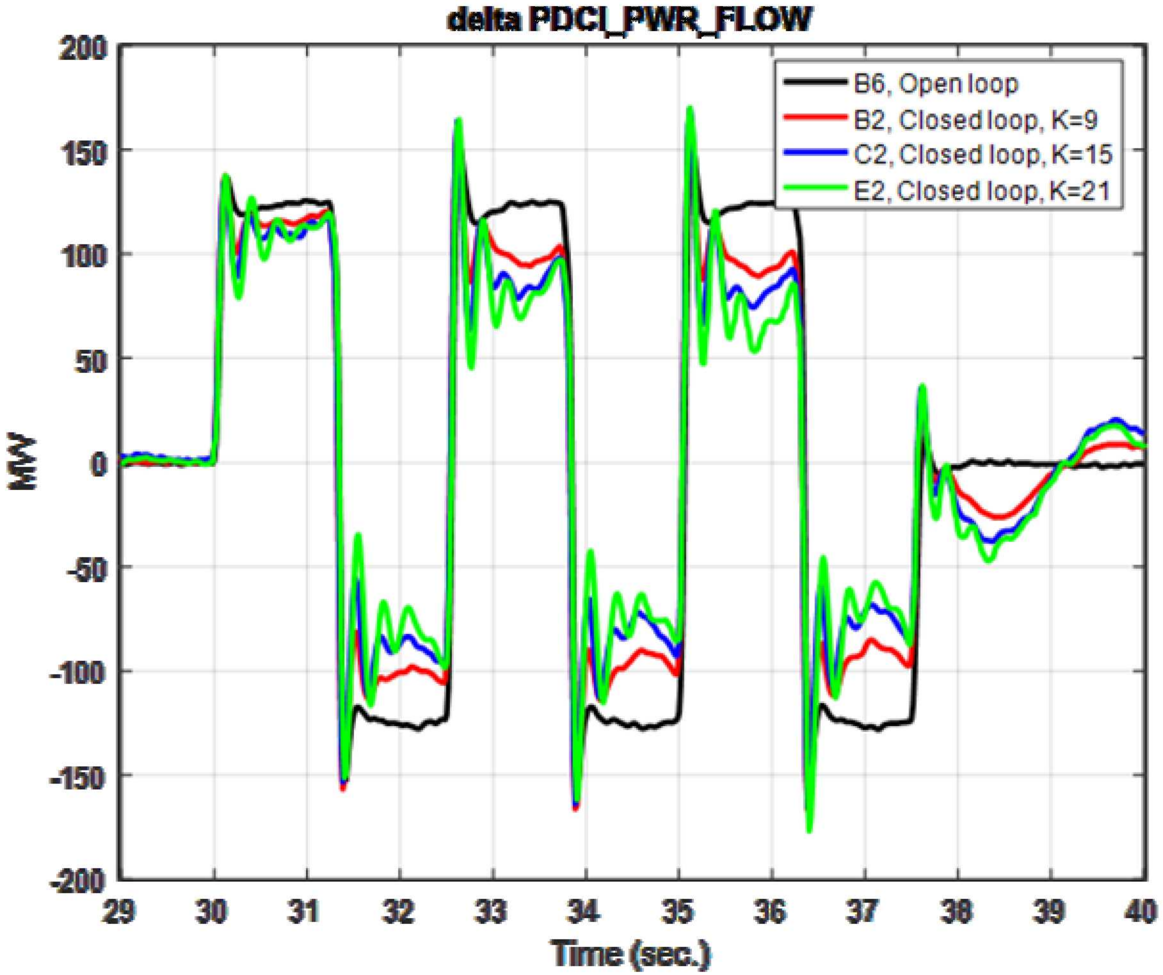
Chief Joseph brake test

Gain = 15 MW/mHz
Damping improved by 4.5 percentage points (10.0% to 14.5%)



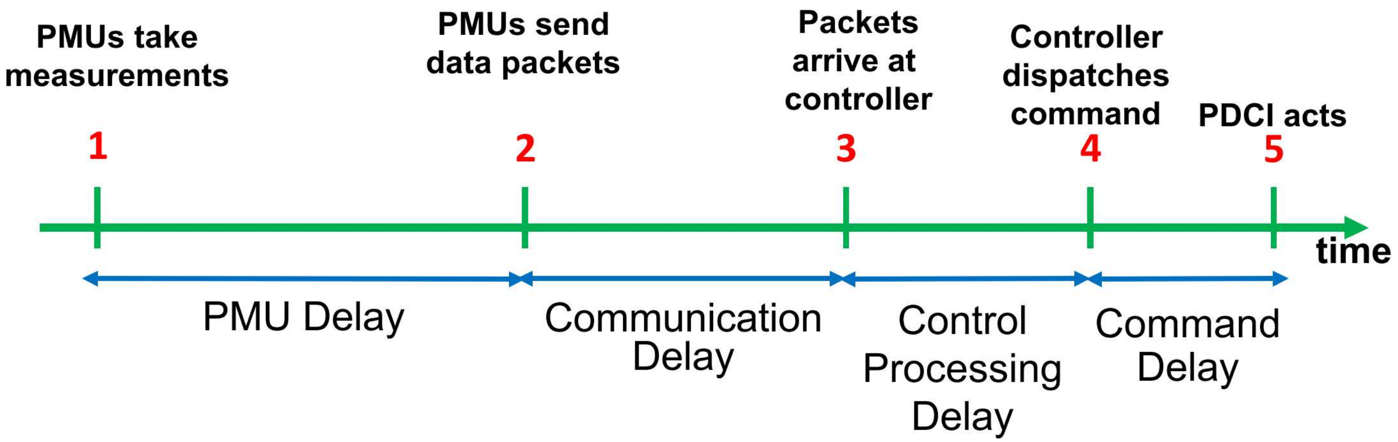
Gain Tuning was Informed by Square Wave Pulses

(Tests conducted at Celilo on May 23, 2018)



Lower gains ➔ less damping improvement
Higher gains ➔ more "ringing" on the DC side
Sweet spot ➔ K = 12 to 15 MW/mHz

Communication and Delays

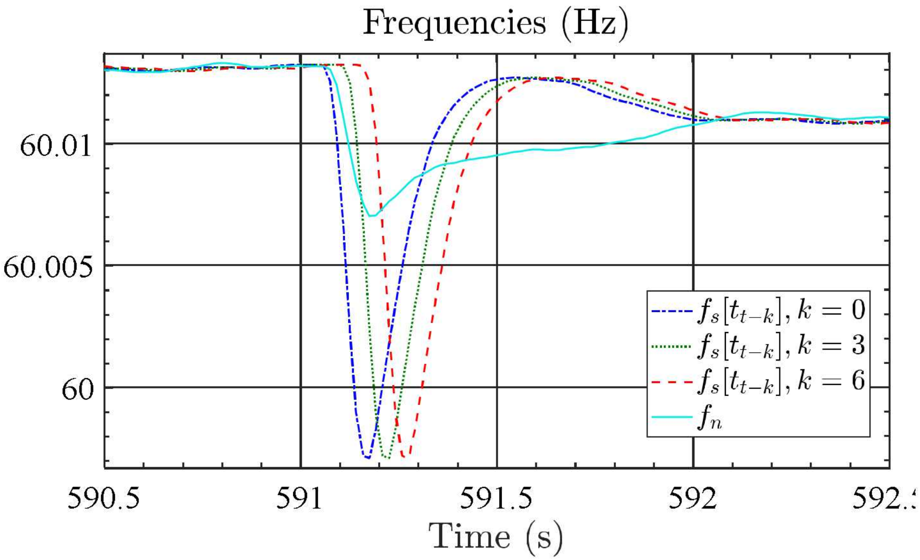


Name	Mean	Range	Note
PMU Delay	44	40 – 48	Dependent on PMU settings. Normal distribution.
Communication Delay	16	15 – 40	Heavy tail
Control Processing Delay	11	2 – 17	Normal around 9 ms, but a peak at 16 ms due to control windows when no data arrives (inconsistent data arrival)
Command Delay	11	11	Tests were consistent, fixed 11 ms
Effective Delay	**82**	**69 – 113**	**Total delay**

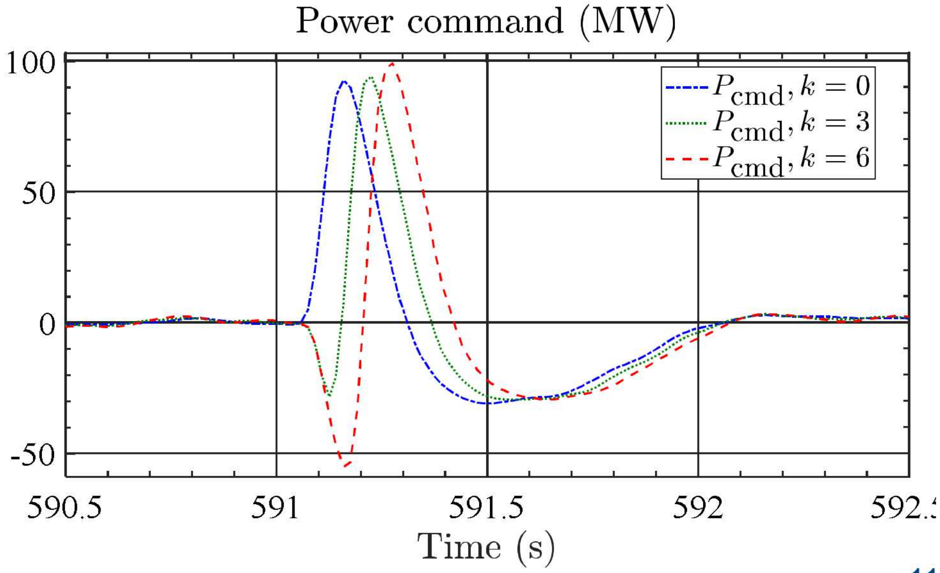
Total time delays are well within our tolerances (<< 150 ms)

Other PMU Data Considerations

- Data dropout
  - Supervisory system catches data dropouts and disables that controller instance (16 total)
- Corrupted data
- Time alignment
  - The North and South measurements need to have the same PMU timestamp
  - Supervisory system time aligns the data. If data is too far apart, the control instance is disabled
- Inconsistent data arrival – asymmetric time delays



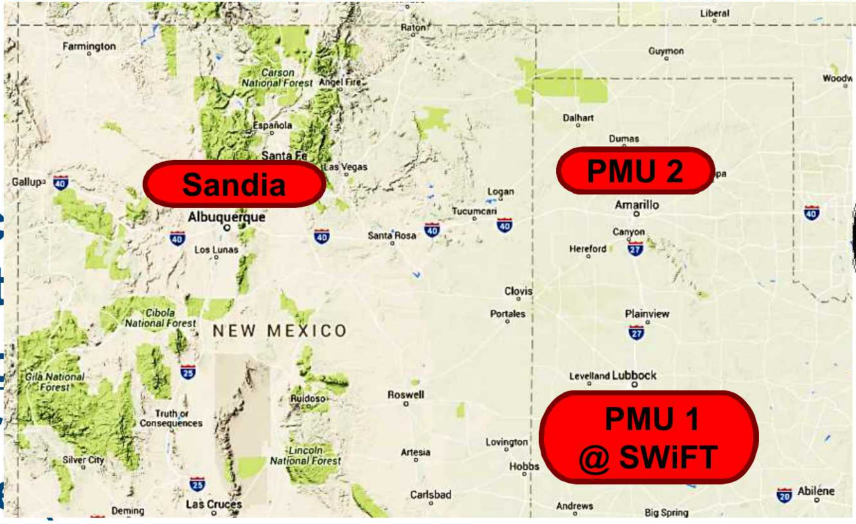
Frequencies (Hz)

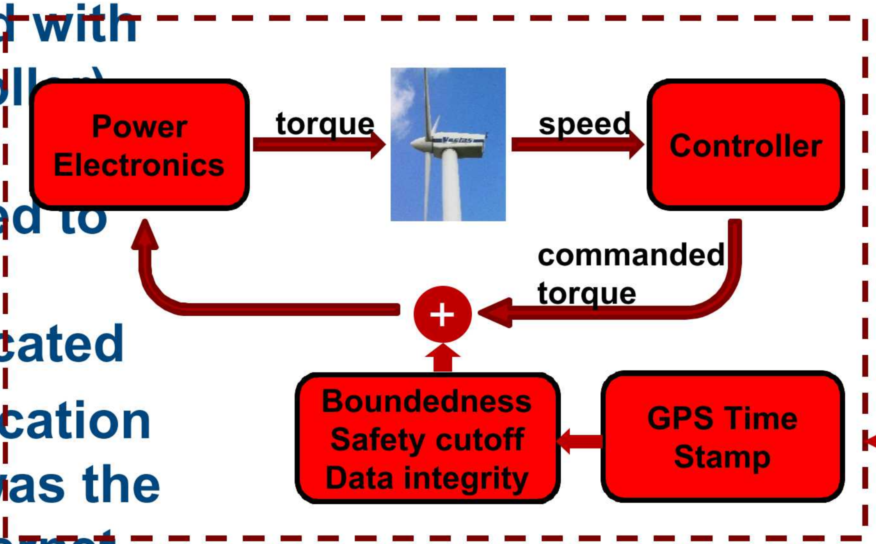


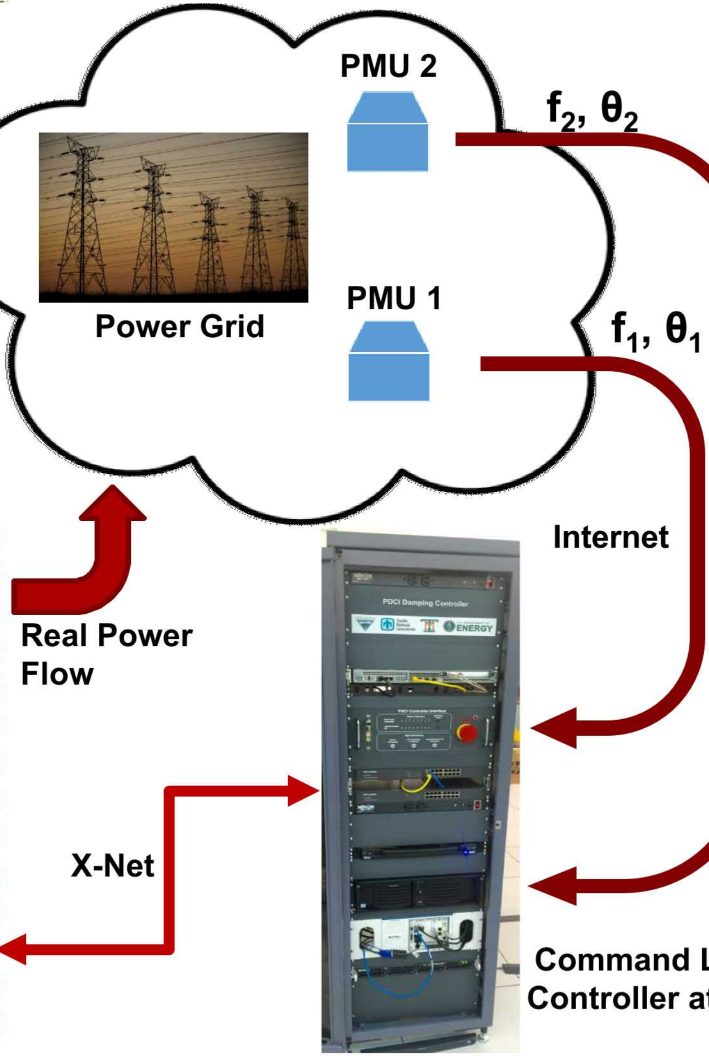
Power command (MW)

Damping Control Using Wind Turbines

- **Based on the experience with damping controller modulating the torque command of a WTG at the SNL wind facility (SWiFT).**
- **Similar c architect**
- **Differenc Actuator is remot co-located with the controll command signal need to be communicated**
- **Communication channel was the public internet**





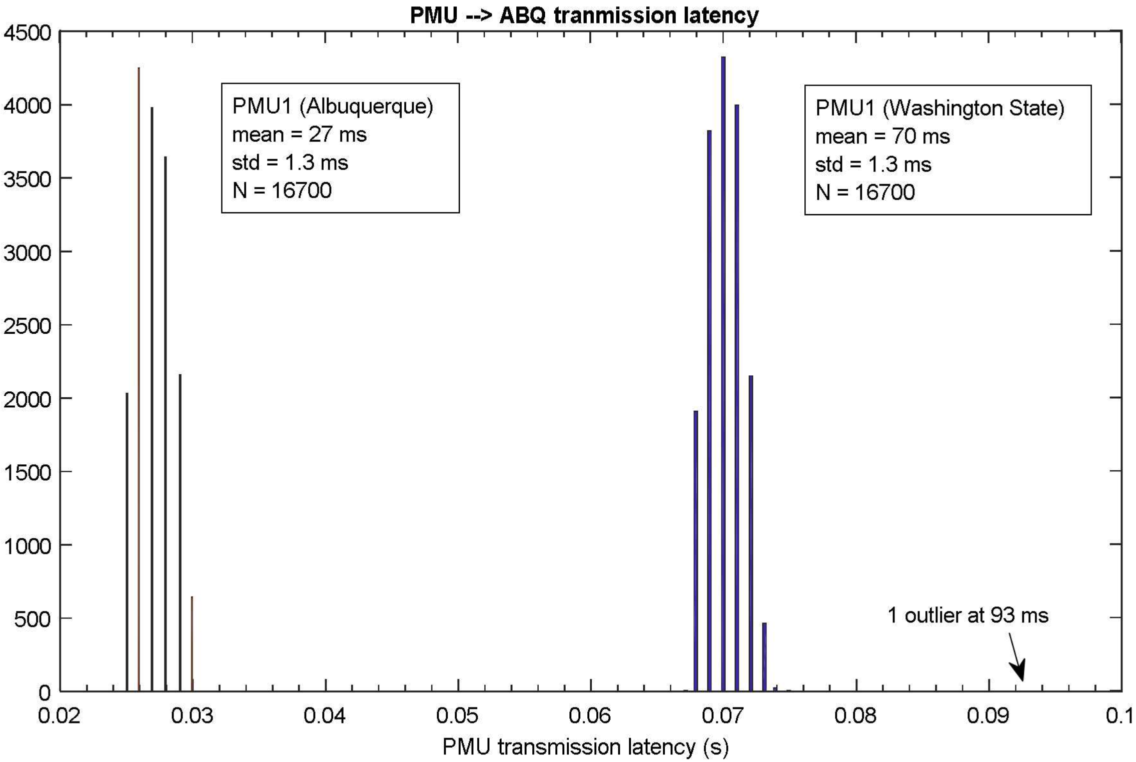


Delays in WTG Damping Control

- **2 PMUs used, one at the same location of the controller (PMU1), another in Washington State (PMU2)**

- **PMU1 was directly connected to the controller –delay is mostly due to measurement and processing**

- **PMU2 data was streamed through the public internet**



- **<u>Note:</u> Actual testing took place on Sept. 27 2017 and also included frequency regulation**

Key Takeaways and Lessons Learned

- Control design is actuator agnostic ➔ easily adaptable to other sources of power injection (e.g., wind turbines, energy storage)
- First successful demonstration of wide-area control using real-time PMU feedback in North America.
- Supervisory system architecture and design can be applied to future real-time grid control systems to ensure “Do No Harm”.
- Developed algorithms, simulations, and models for eventual implementation of grid control strategies leveraging widespread adoption of energy storage.
- Extensive eigensystem analysis and visualization tools developed for simulation studies and analysis of test results.
- Model development and validation for multiple levels of fidelity to support analysis, design, and simulation studies.

Future Research Recommendations

- Resilience
  - Design architectures that are more robust to single points of failure (e.g. decentralized control)
  - Leverage large #'s of assets (sensors and actuators) over a wide area to improve performance of grid control systems.
- Big Data
  - Real-time PMU data represents an enormous amount of data
  - How does one manage this amount of data?
  - How can one leverage the data for key information?
  - Possible techniques include machine learning
- Cyber Security
  - Understand full range of potential vulnerabilities from networks
  - Leverage work of cyber experts from other fields to reduce vulnerabilities

Project Achievements

- First successful demonstration of wide-area control using real-time PMU feedback in North America.
- 19 published papers (17 conference papers, 2 journal papers, several more journal papers in review process)
- 2017 R&D 100 Award
- US Patent application filed March 2018
- Commercialization of DCON being pursued jointly with BPA