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Real-Time Damping of Power Grid Oscillations Using Synchrophasor Feedback

David Schoenwald
Electric Power Systems Research Department
Sandia National Laboratories

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Outline of Talk

- Project Background
- Control Approach
- Test Results
- PMU Data Considerations
- Studies with other Actuators
- Conclusions and Future Research

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  - Dave Schoenwald (PI)
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Damping Controller Overview

Problem:

- Large generation and load centers separated by long transmission corridors can develop inter-area oscillations
- Poorly damped inter-area oscillations jeopardize grid stability and can lead to widespread outages during high demand
- To prevent this, utilities constrain power flows well below transmission ratings ➔ inefficient

Solution:

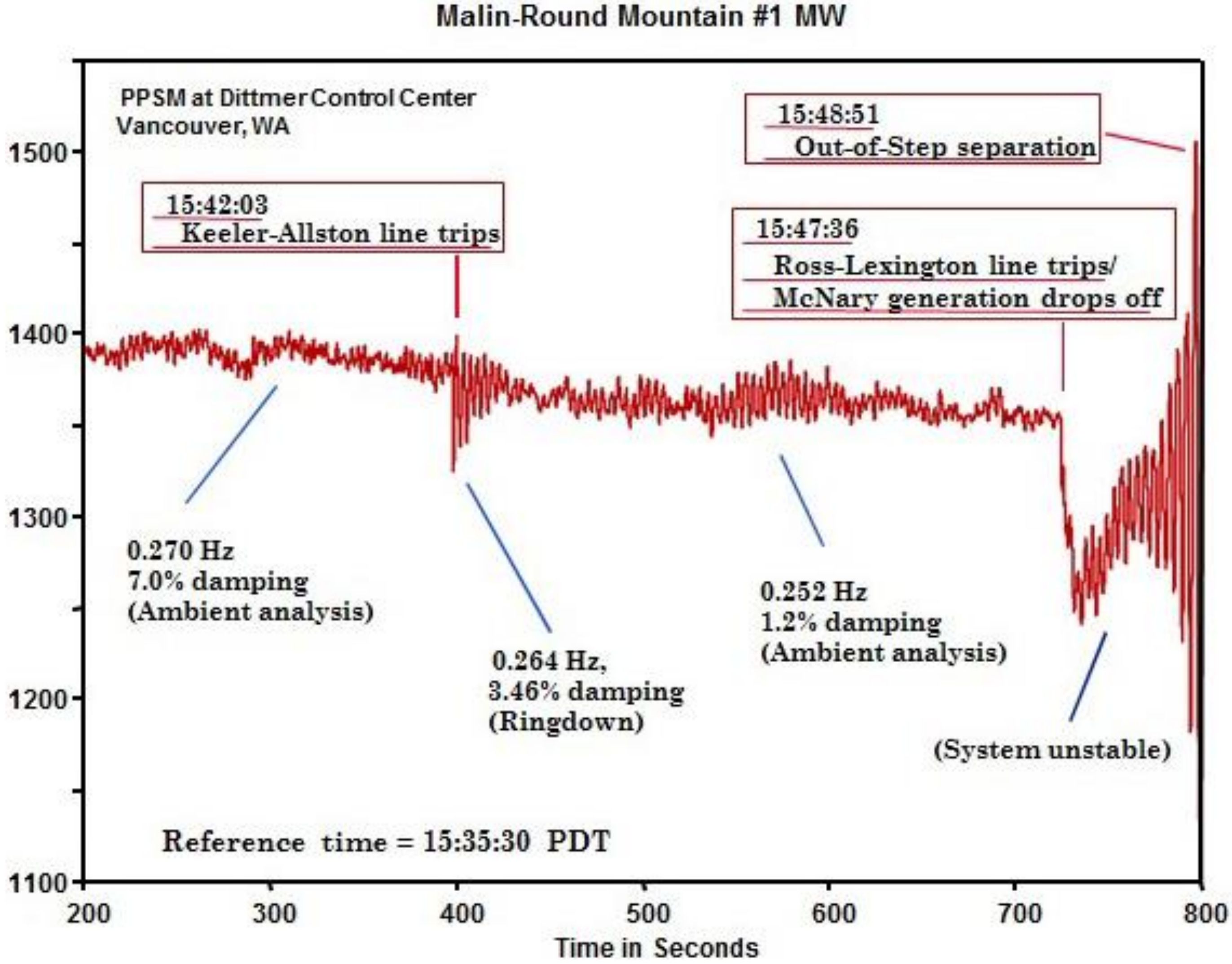
- Construct closed-loop feedback signal using real-time PMU (Phasor Measurement Unit) data: 1st demonstration of this in North America
- Modulate power flow on PDCI (Pacific DC Intertie) up to +/- 125 MW
- Implement a supervisory system to ensure "Do No Harm" to grid and monitor damping effectiveness

Benefits:

- Improved grid reliability
- Additional contingency for stressed grid conditions
- Avoided costs from a system-wide blackout (>> $1B)
- Reduced or postponed need for new transmission capacity: $1M–$10M/mile
- Helps meet growing demand by enabling higher power flows on congested corridors

Inter-Area Oscillations Jeopardize Grid Stability

Western Power System Breakup on August 10, 1996



Project Background

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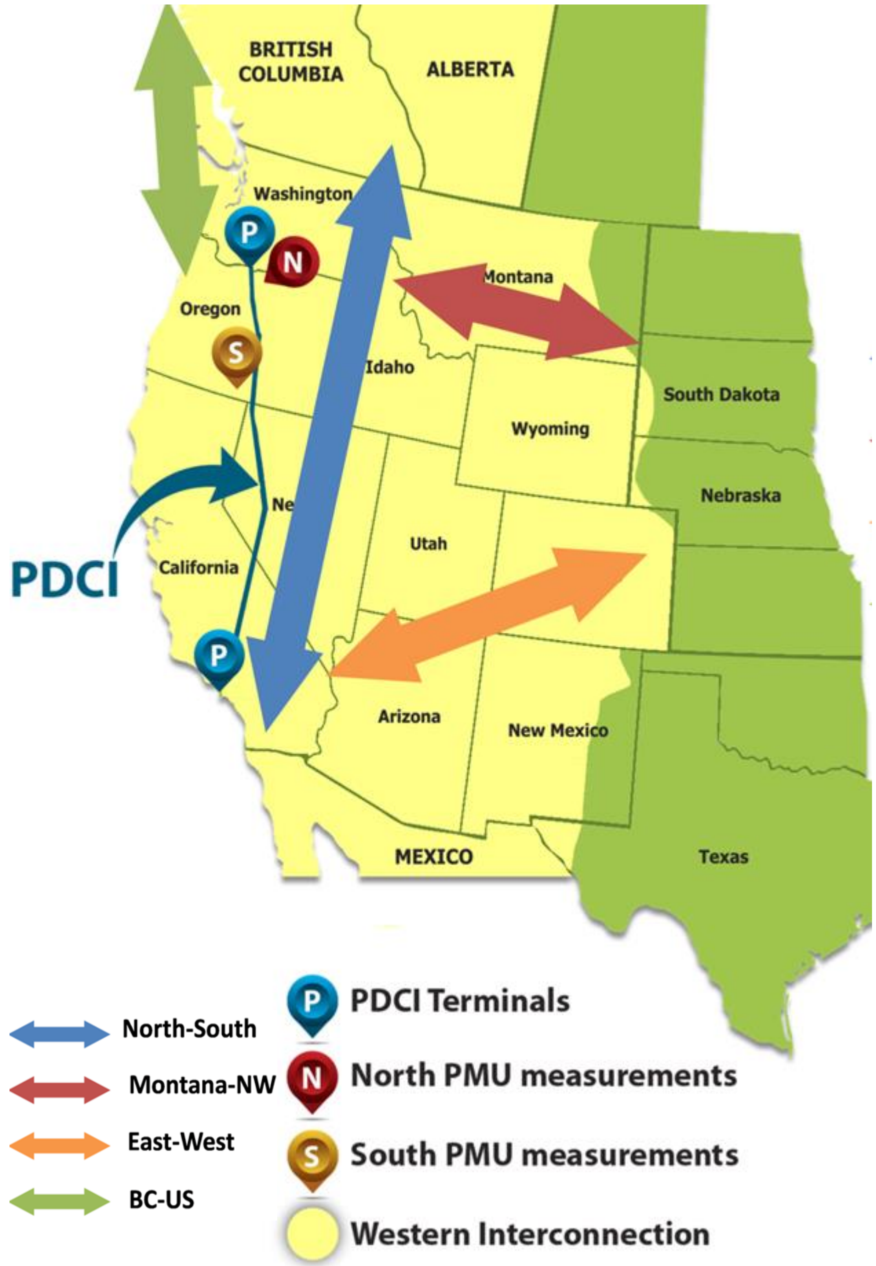
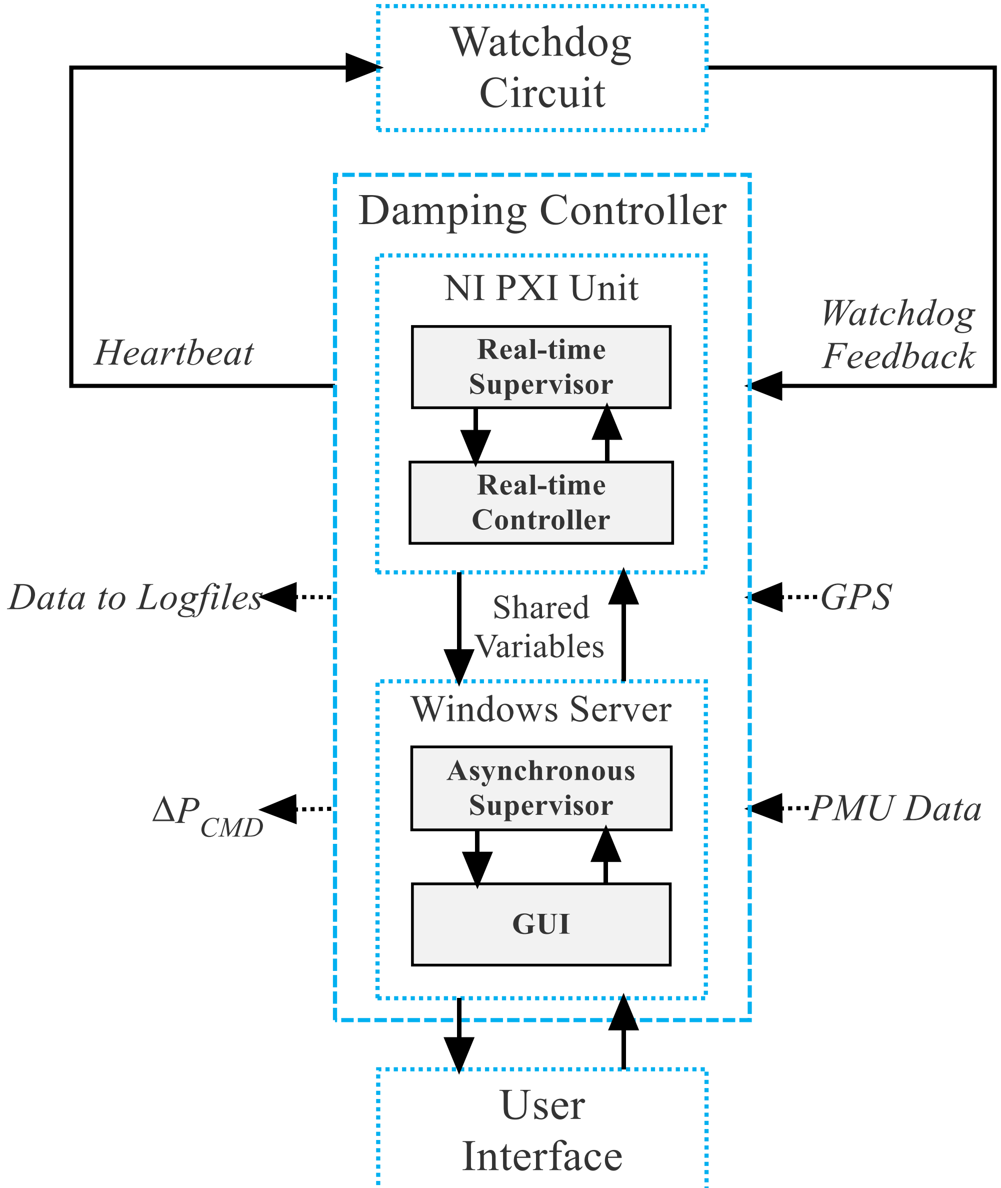
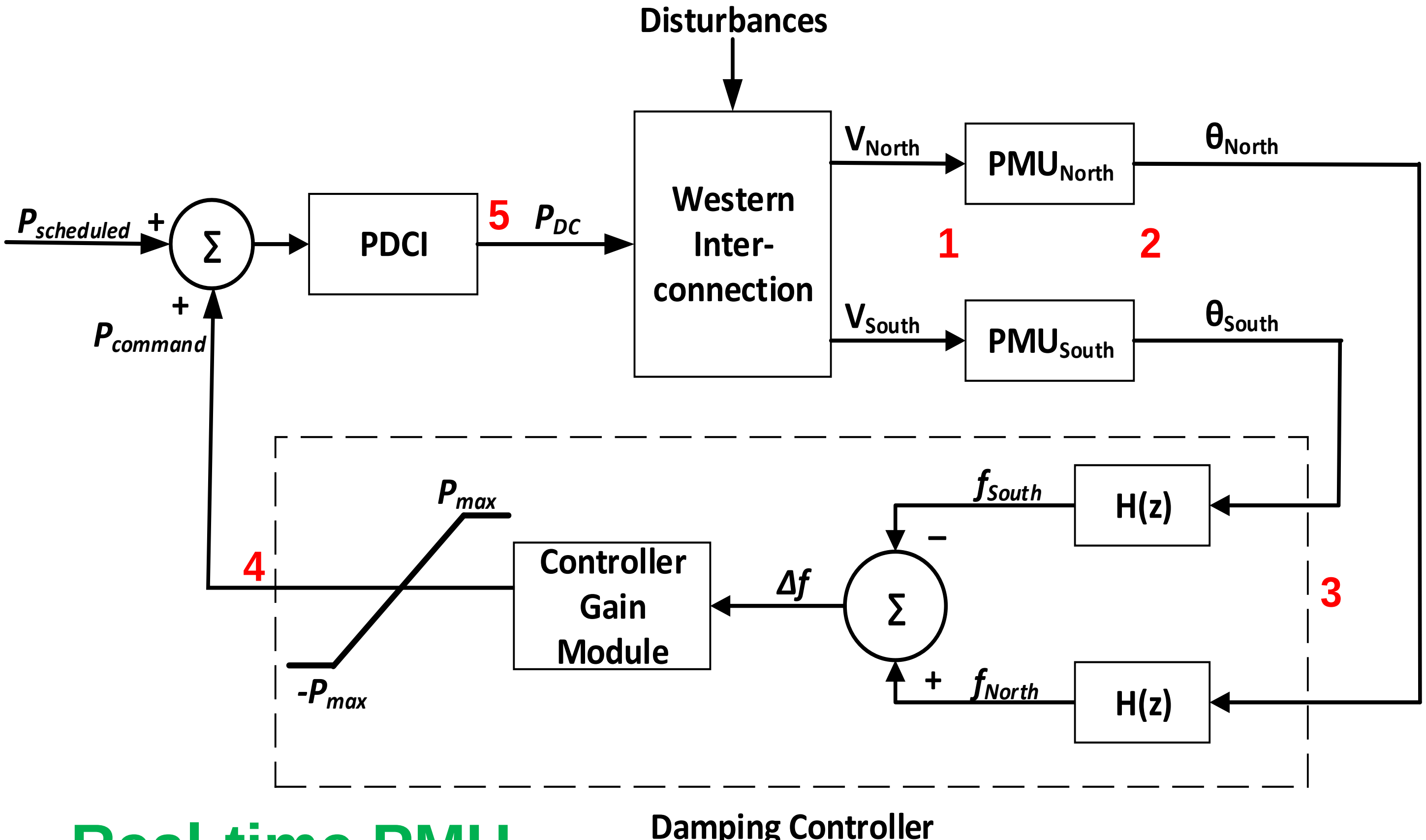
- Based on 1970s BPA experiments on PDCI later shown to have destabilized BC-US mode
- Revived in 2007 – 2012 by BPA with Montana Tech leveraging PMU deployments in WECC
- Current project launched in June 2013 as a collaboration of SNL, MT, BPA, and DOE to develop and demonstrate damping control
- Phase 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 Overview



Damping Controller Strategy



Real-time PMU feedback is the key to stable control

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

K is a constant gain with units of MW/mHz

1 PMUs take measurements

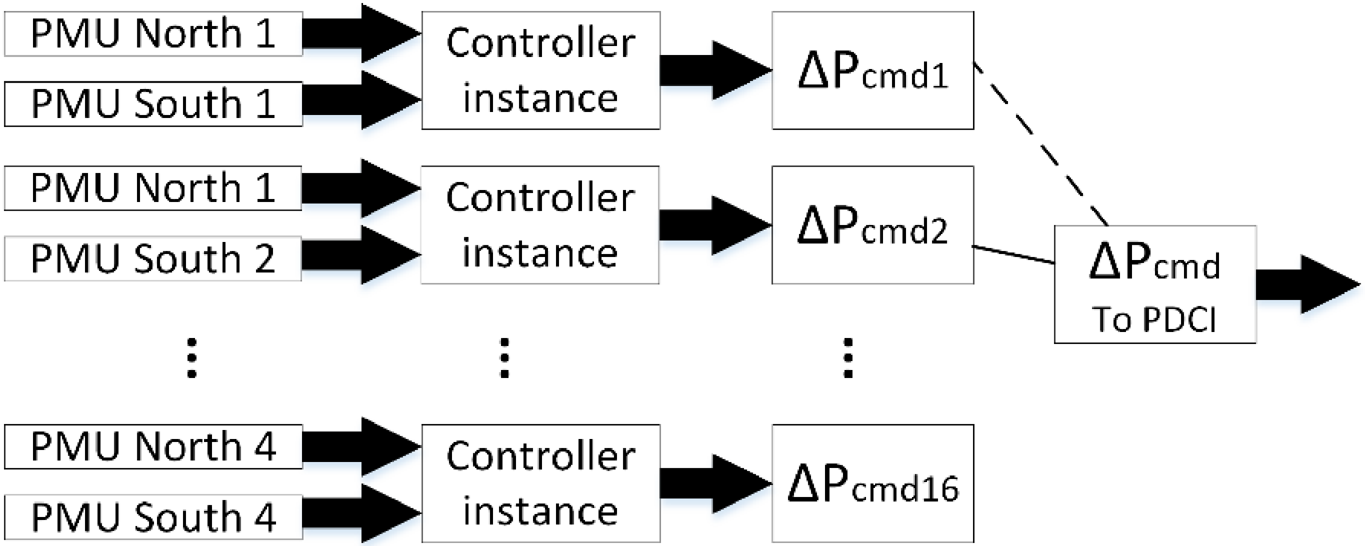
2 PMUs send data packets over network

3 Packets arrive at damping controller

4 Controller sends power command to PDCI

5 PDCI injects power command into grid

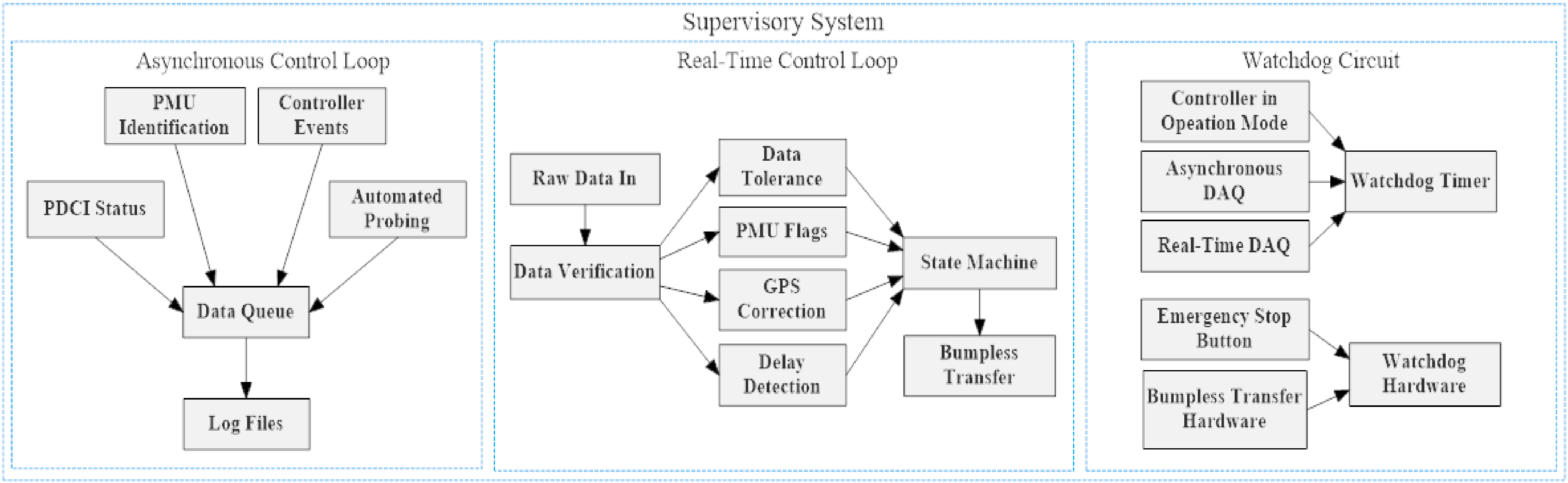
Controller Employs Diversity and Redundancy in Feedback



- **Diversity = Geographical Robustness**
- **Redundancy = Site Measurement Robustness**
- **Controller evaluates 16 feedback pairs every update cycle to provide options due to any network issues**
- **Controller seamlessly switches between feedback pairs to avoid injecting step functions into the system**

Supervisor Design Philosophy

Design was driven by the need to detect and respond to certain system conditions in real-time as well as asynchronous monitoring functions at slower than real time



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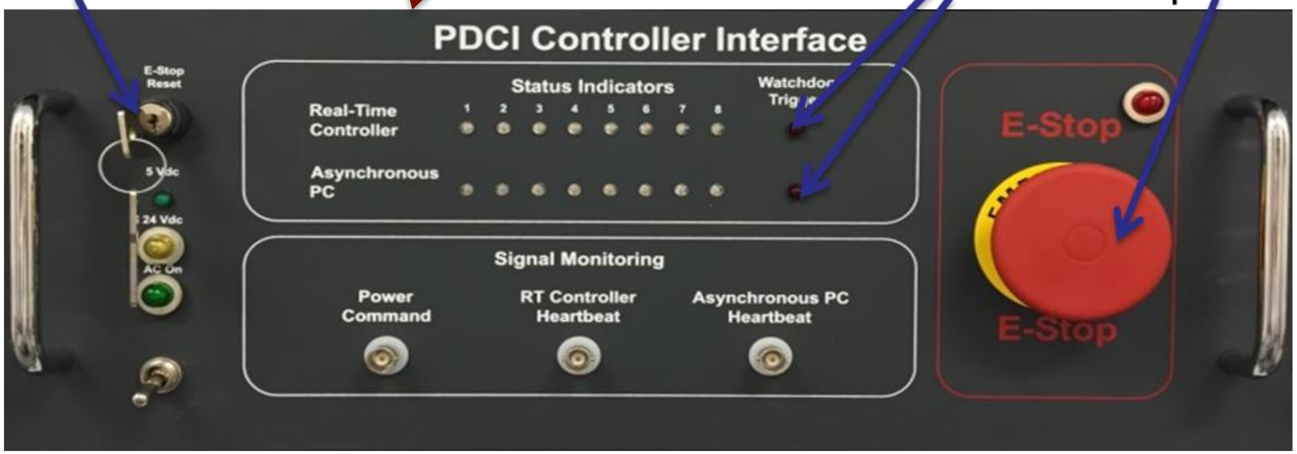
Damping Controller Hardware

Watchdog circuit module

Key switch

Heartbeat indicators

E-Stop button

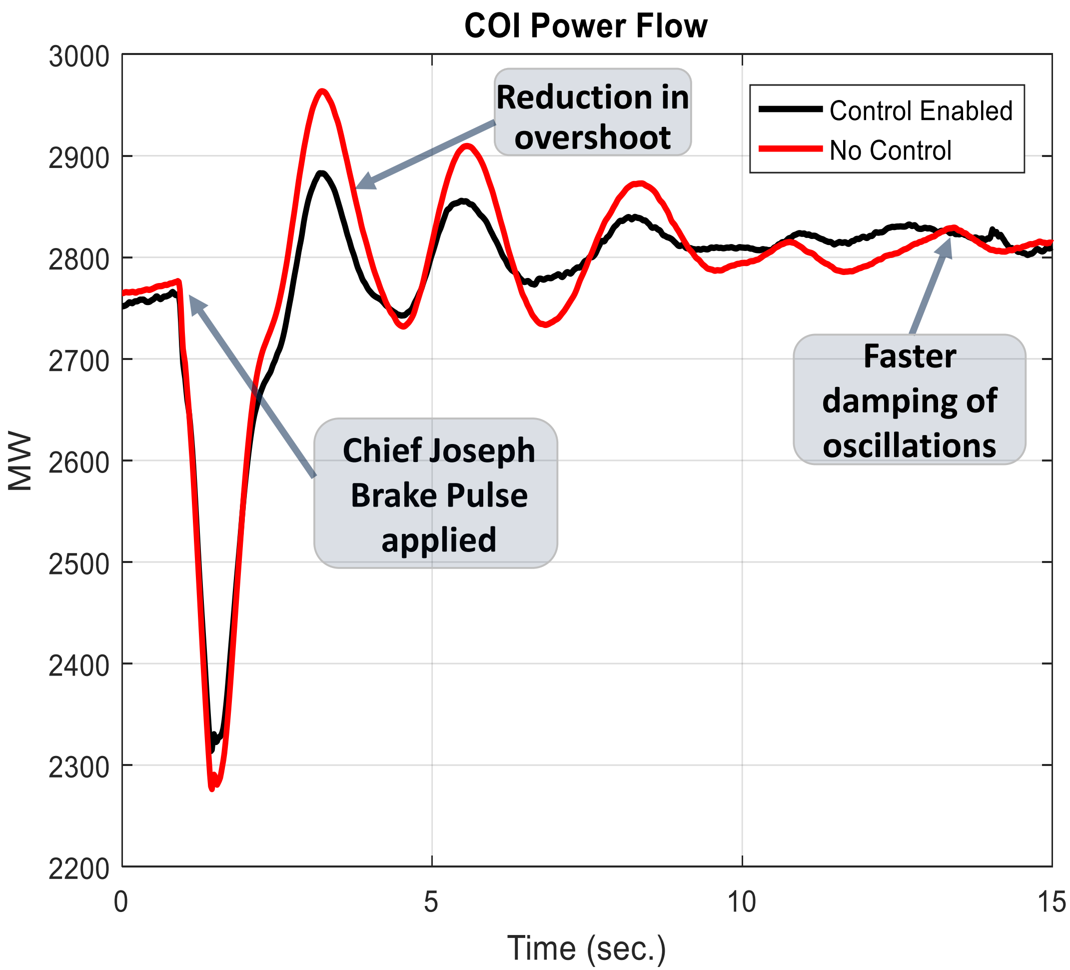


Server for select supervisory functions (“Do No Harm”)

Real-time Control platform

Grid Demonstrations Showed Significant Improvements in Damping with Controller Operational

Experiments conducted at Celilo Converter Station in Sept 2016
Repeated (confirming initial results) in May/June 2017 and May/June 2018

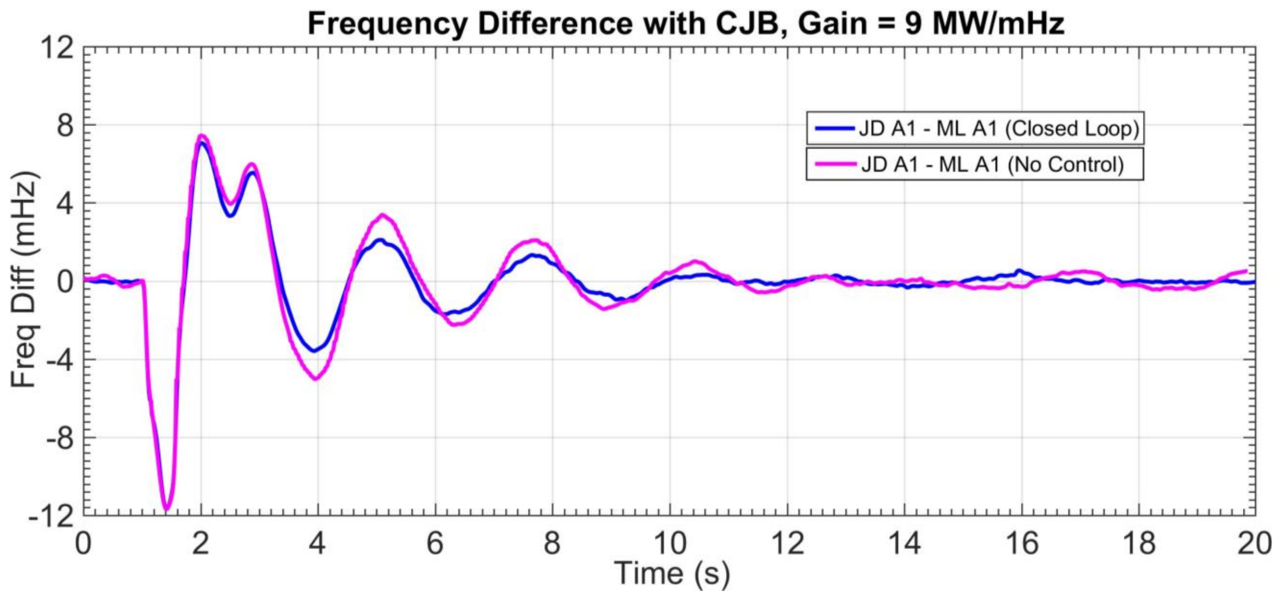


Chief Joseph brake test	Damping of North-South B Mode improved 4.5 percentage points (11.5% to 16.0%) in closed-loop vs. open-loop operation.
Square wave pulse test	Damping controller significantly reduces amplitude of North-South B mode oscillations in 15 seconds vs. 23 seconds in open-loop tests for the same reduction.
All tests	Controller consistently improves damping and does no harm to grid.

Latest Tests Confirm 2016-2017 Test Results
(Tests conducted at Celilo on May 23, 2018)

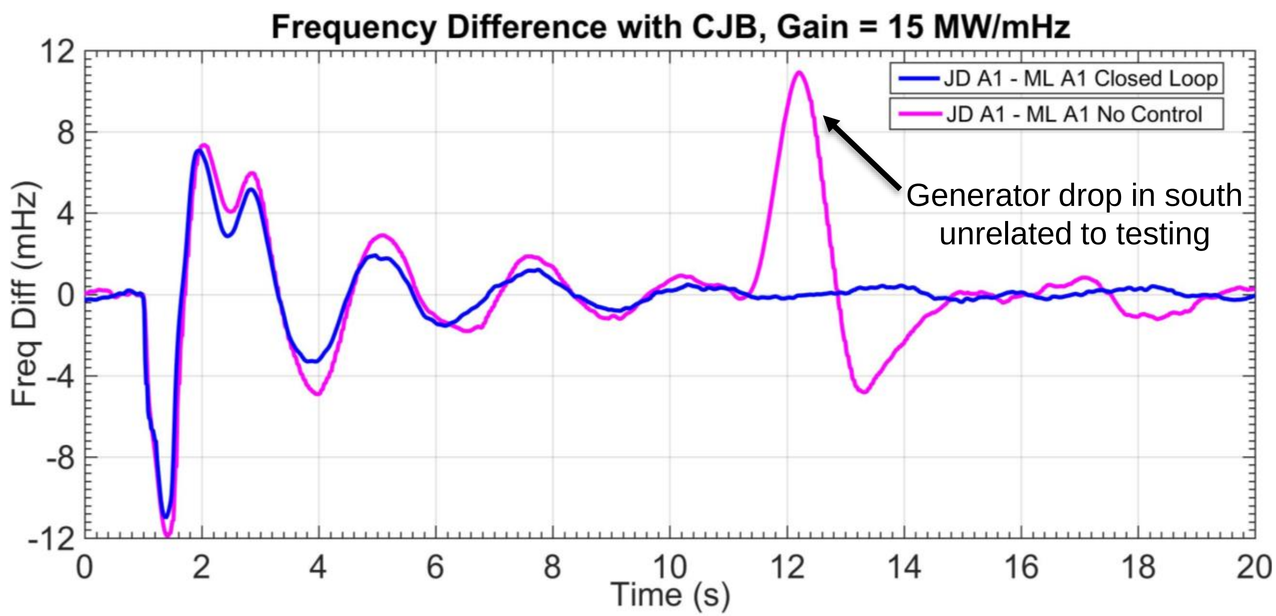
Chief Joseph brake test

Gain = 9 MW/mHz
Damping improved by 4.5 percentage points (10.0% to 14.5%)

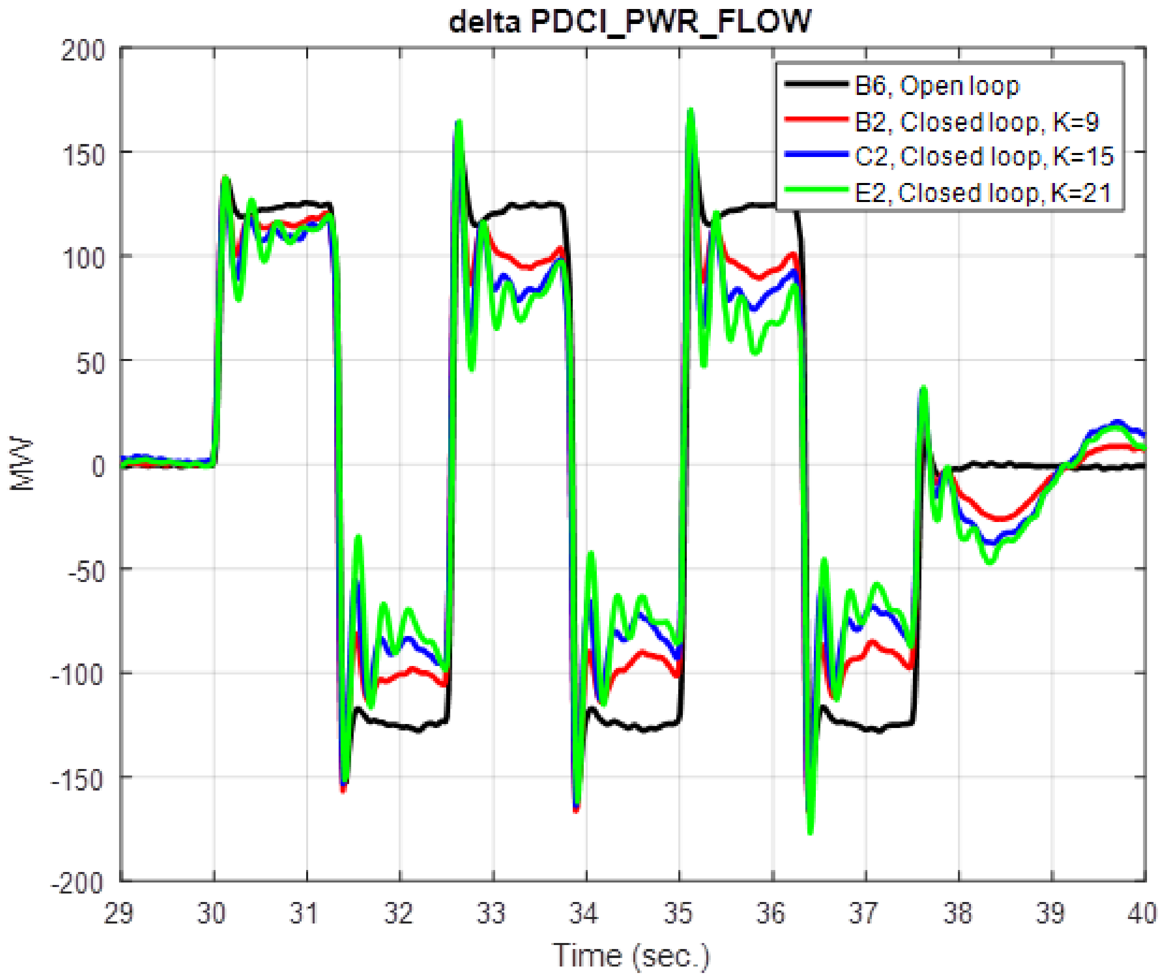


Chief Joseph brake test

Gain = 15 MW/mHz
Damping improved by 6 percentage points (10.0% to 16.0%)

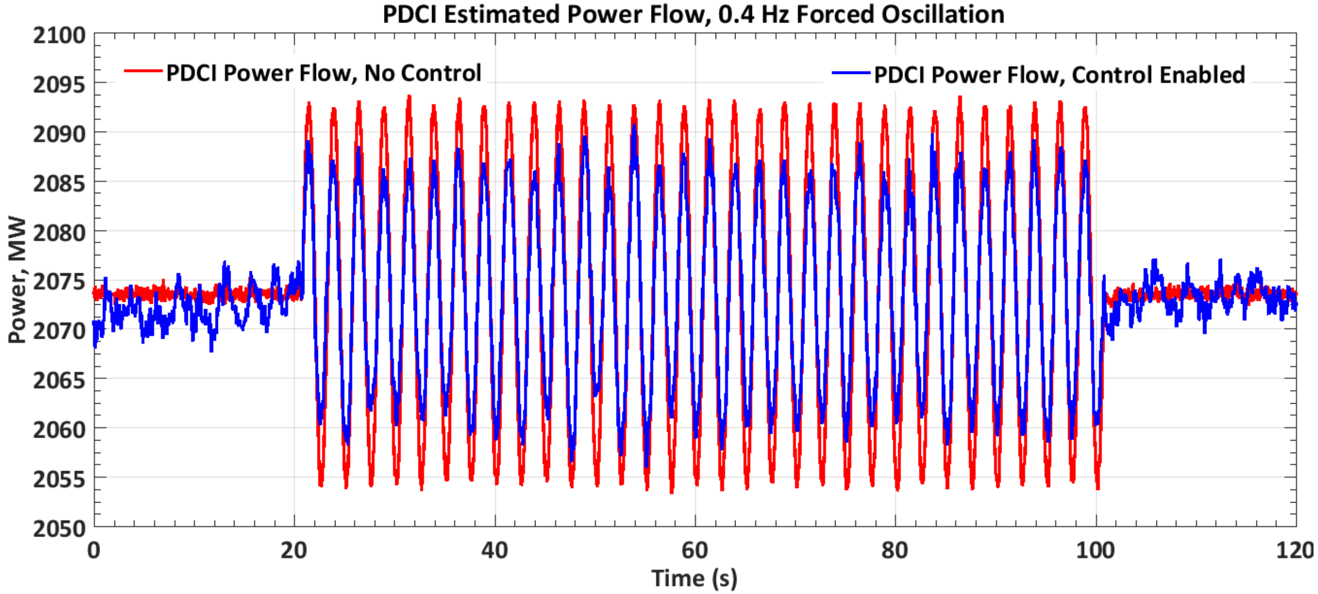


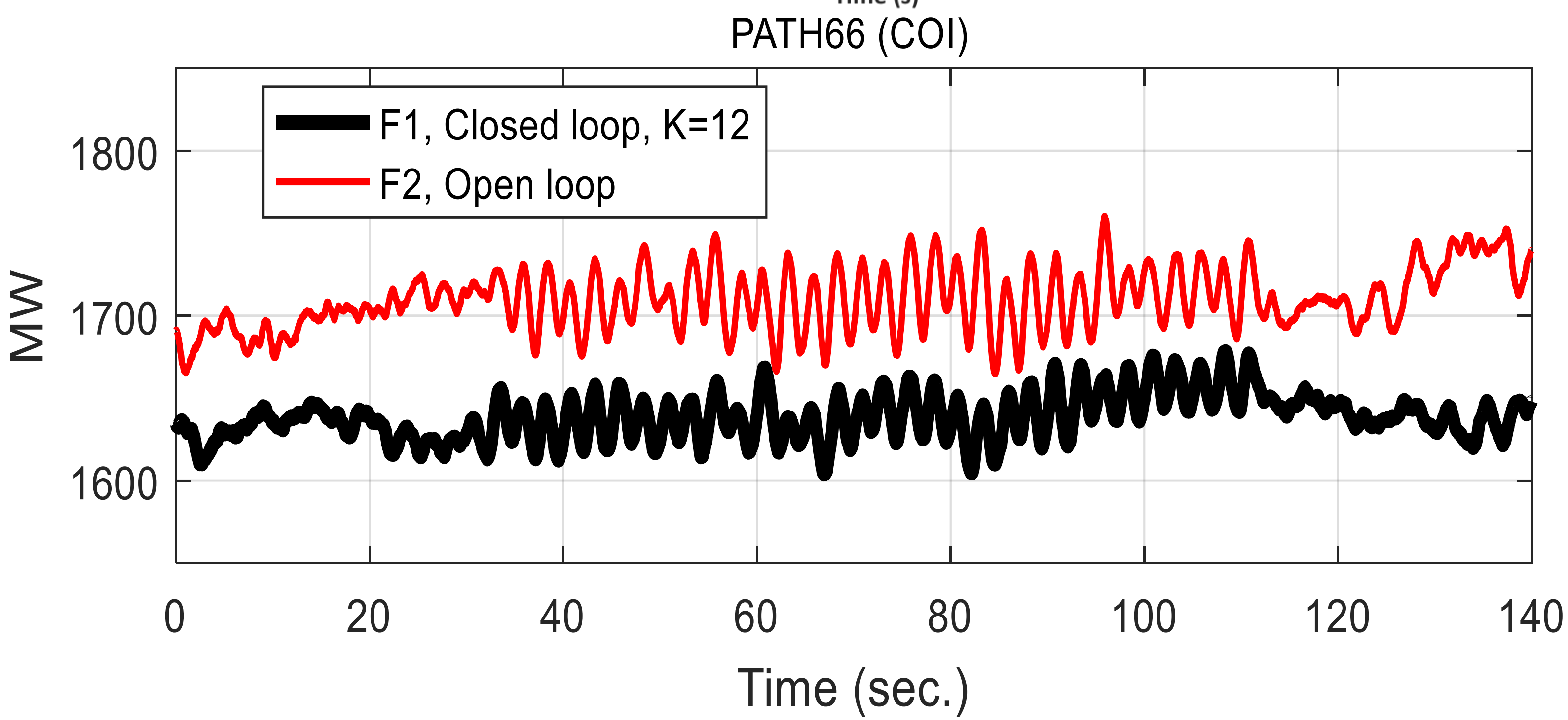
Gain Tuning was Informed by Square Wave Pulses
(Tests conducted at Celilo on May 23, 2018)



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

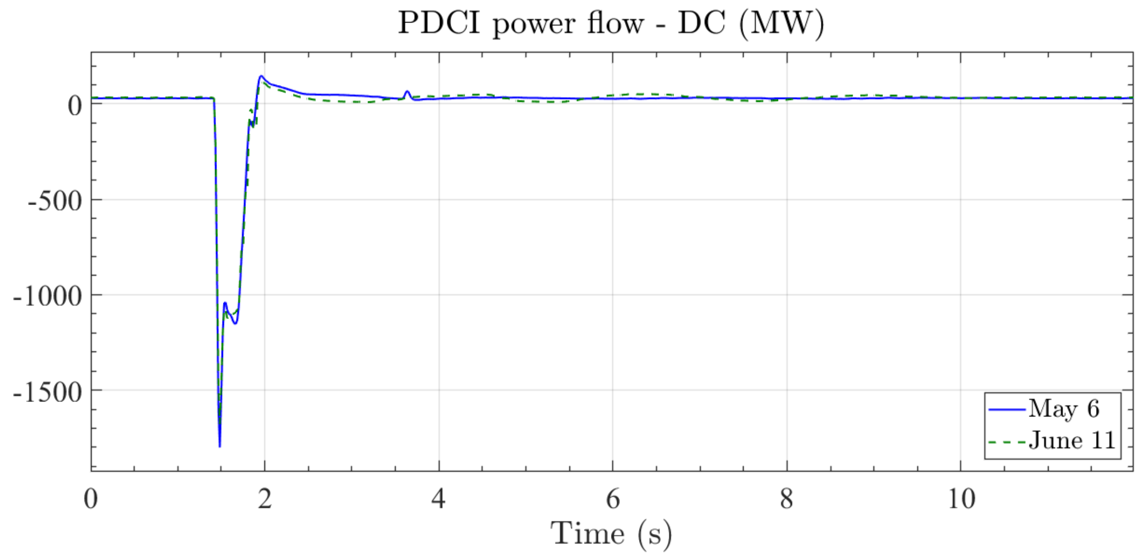
May 16, 2017 Tests, 0.4 Hz Forced Oscillation



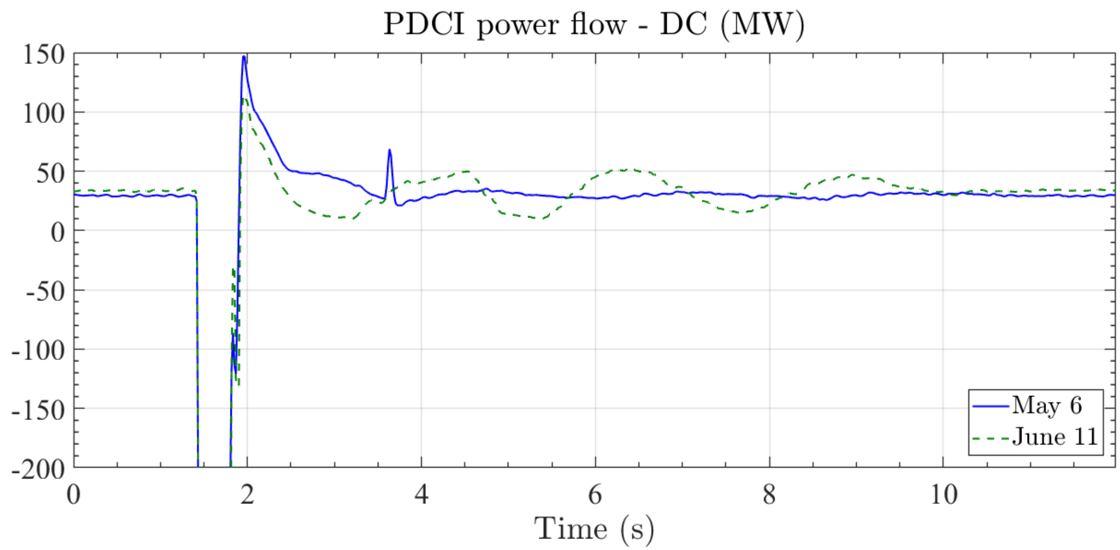


Events on the DC Side Provide a Good Basis of Comparison for Controller Performance

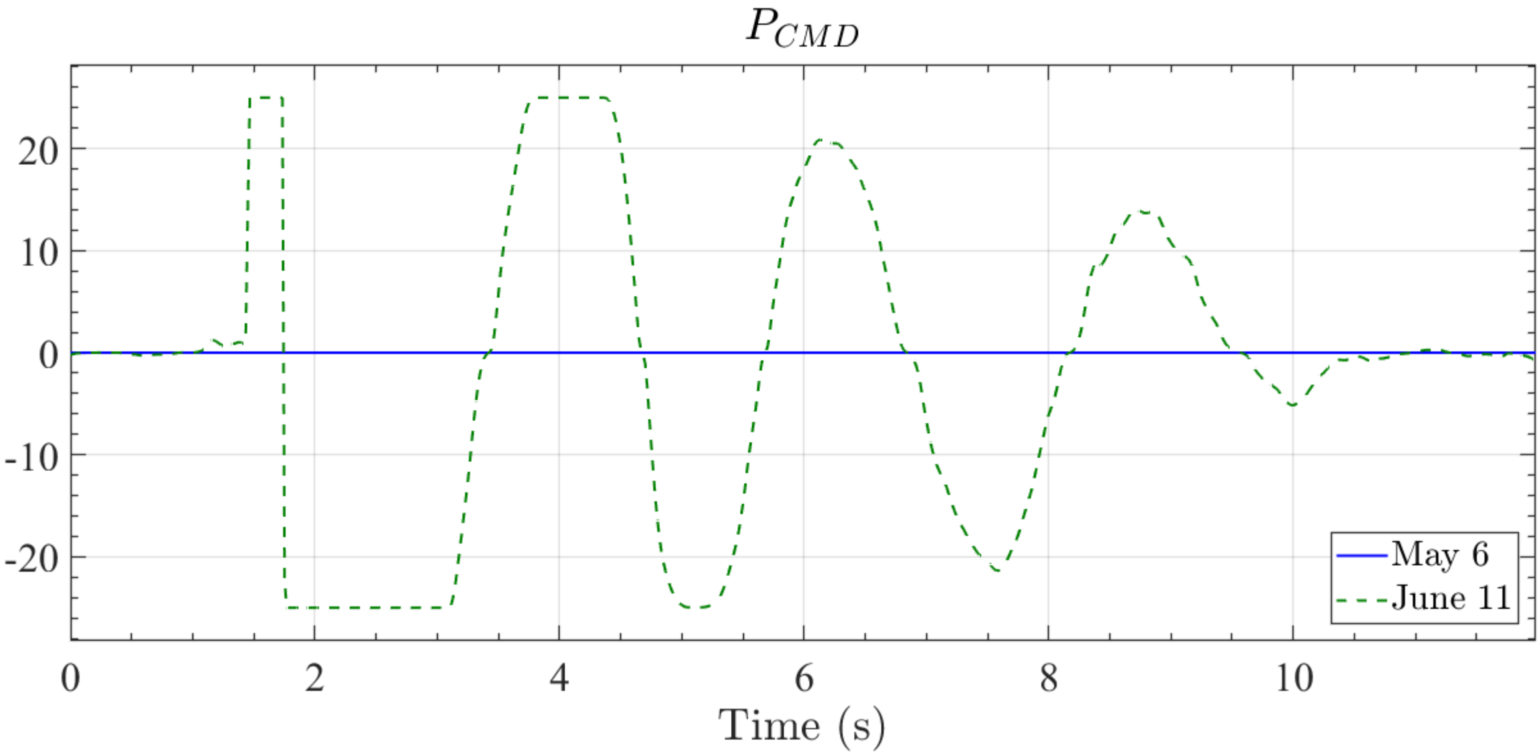
Two very similar events are captured. May 6 – controller was not connected. June 11 – controller was in closed-loop operation.



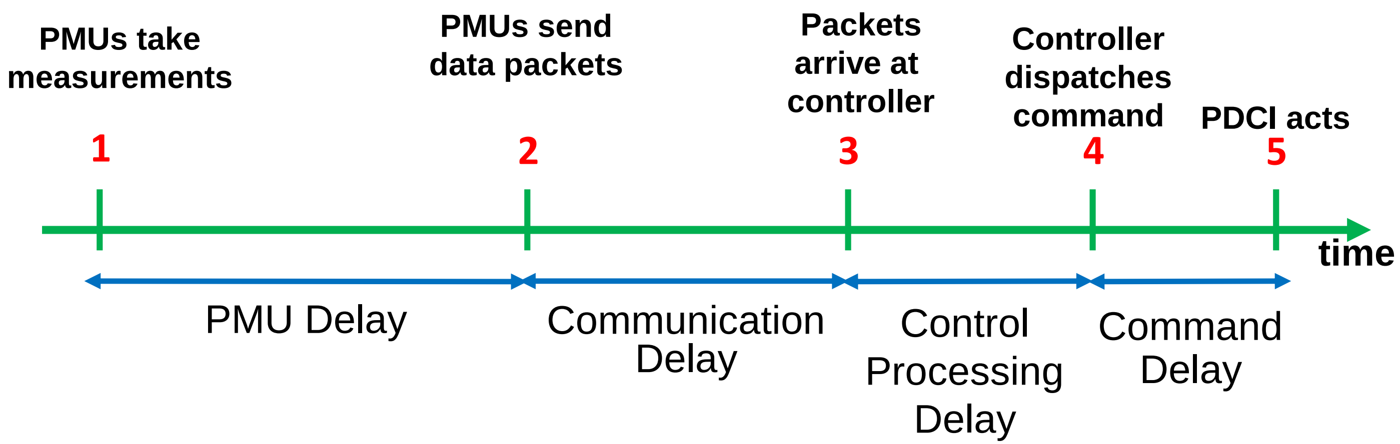
This plot zooms in on the y-axis to show controller modulation (June 11 curve).



Damping controller performs as expected in response to a trip on the DC side



Communication and Delays

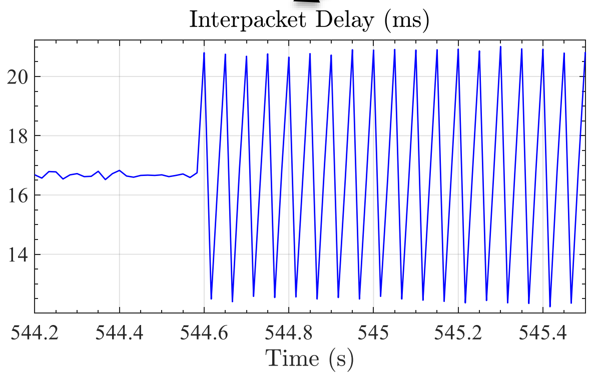


Name	Mean	Range	Note
PMU Delay	44	40 – 48	Dependent on PMU settings. Normal distribution.
Communication Delay	16	15 – 40	Heavy tail
Control Processing Delay	11	2 – 17	Normal around 9 ms, but a peak at 16 ms due to control windows when no data arrives (inconsistent data arrival)
Command Delay	11	11	Tests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

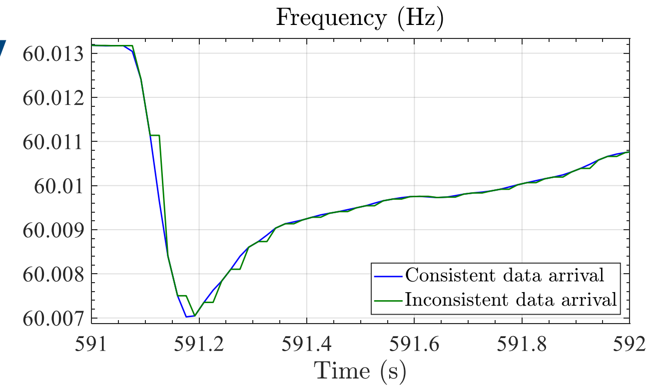
Total time delays are well within our tolerances (<< 150 ms)

PMU Data Considerations

- **PMUs have inconsistent interpacket delays**

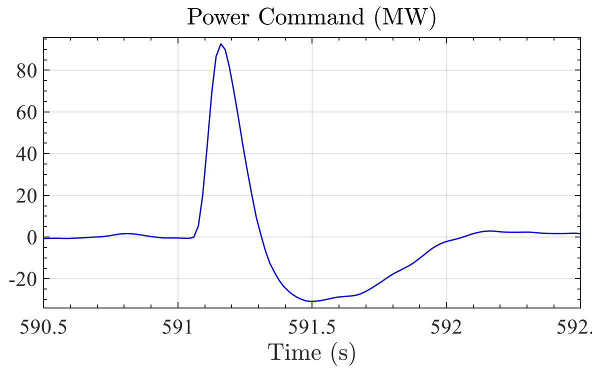


Delay inconsistency affects frequency estimation

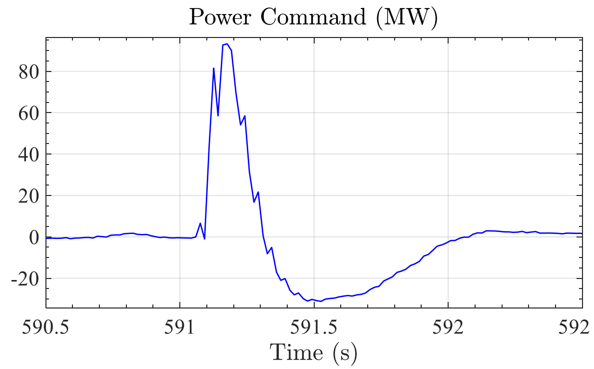


- **Delay inconsistency also affects the power command**

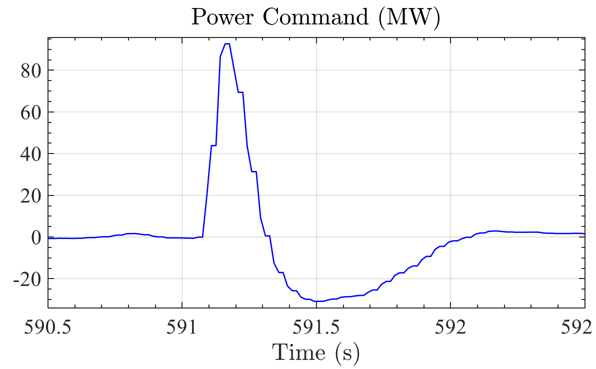
Ideal case



Delay inconsistency with <u>NO</u> time alignment

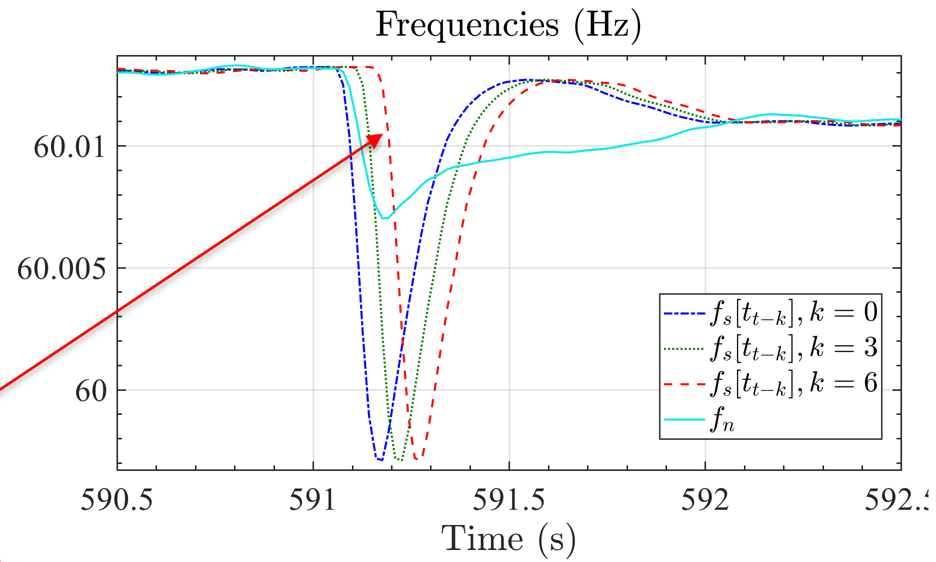


Delay inconsistency with time alignment

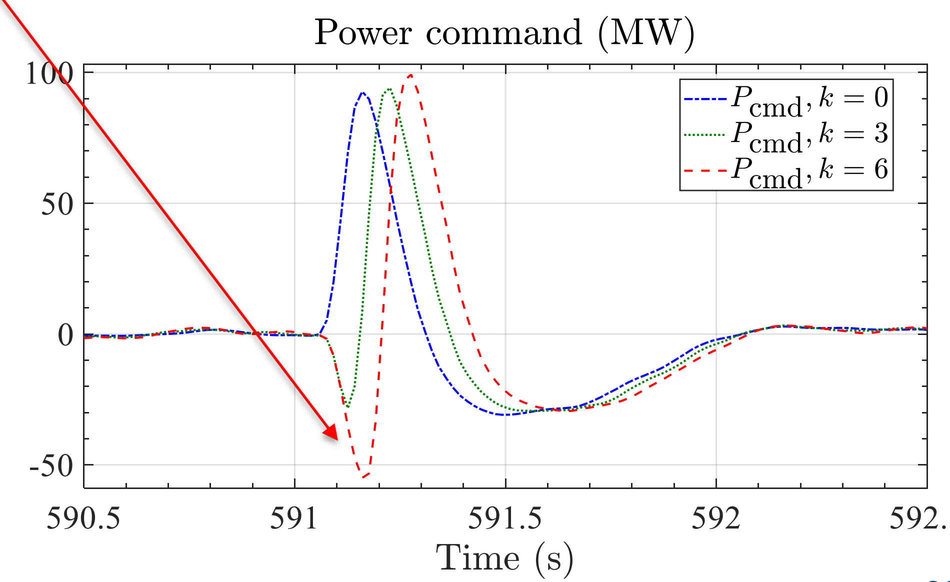


PMU Data Considerations

- **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**



- **Other PMU data issues**
  - **Data dropout:**
    Supervisory system catches data dropouts and disables that controller instance
  - **Corrupted data:**
    Supervisory system flags irregular data (e.g. repeated values, missing time stamps)



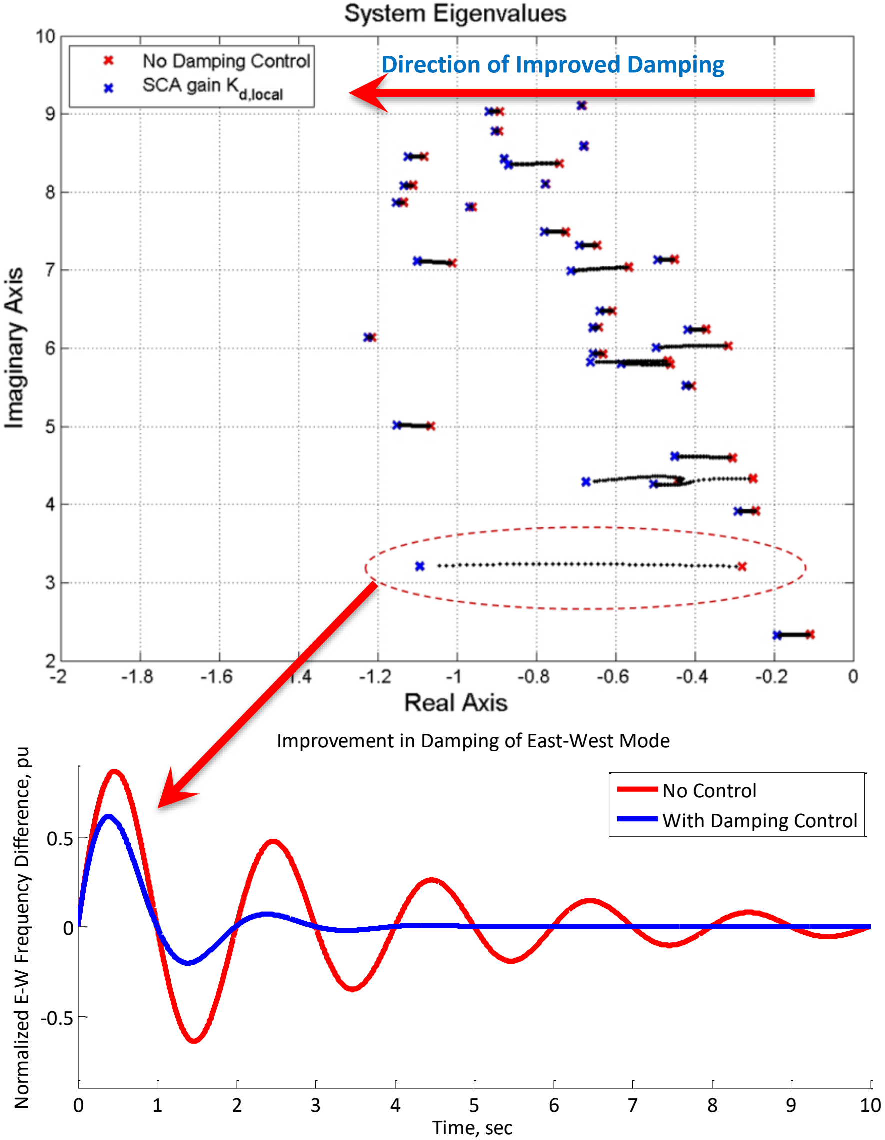
Damping Control Using Distributed Energy Resources

Advantages:

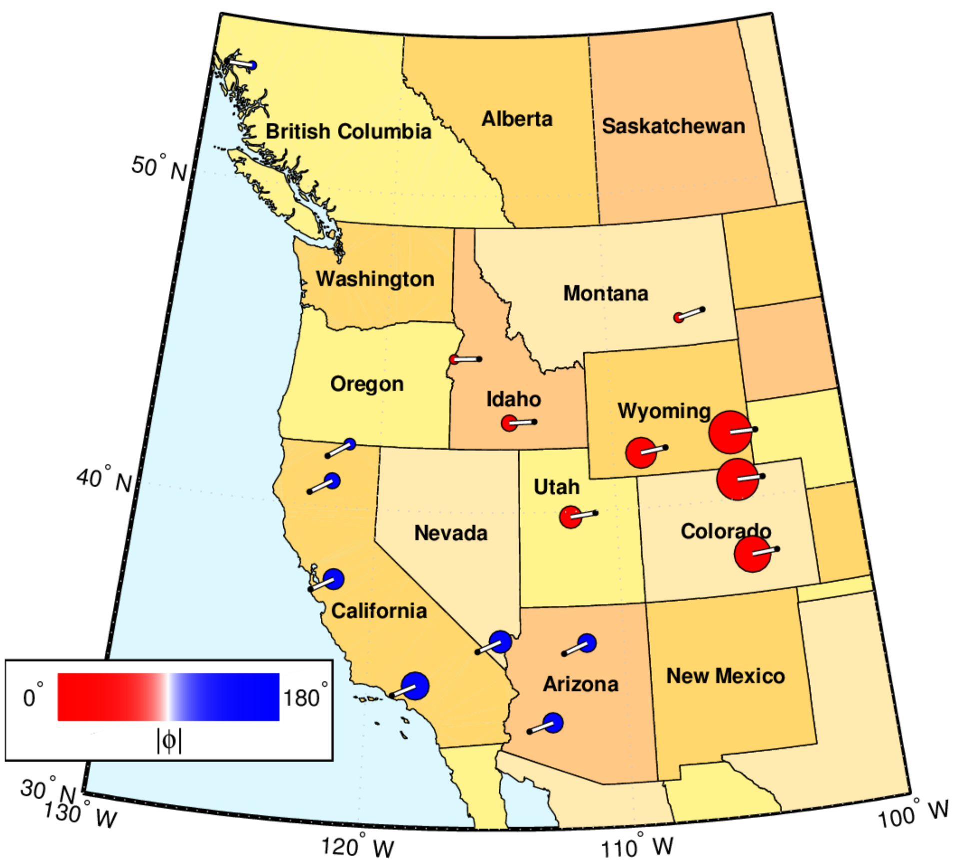
- Robust to single points of failure
- Controllability of multiple modes
- Size/location of a single site not critical as more distributed energy resources are deployed on grid
- With 10s of sites engaged, single site power capability ≈ 1 MW can provide improved damping
- Control signal is energy neutral and short in time duration ➔ sites can perform other applications

Example using Distributed Energy Storage

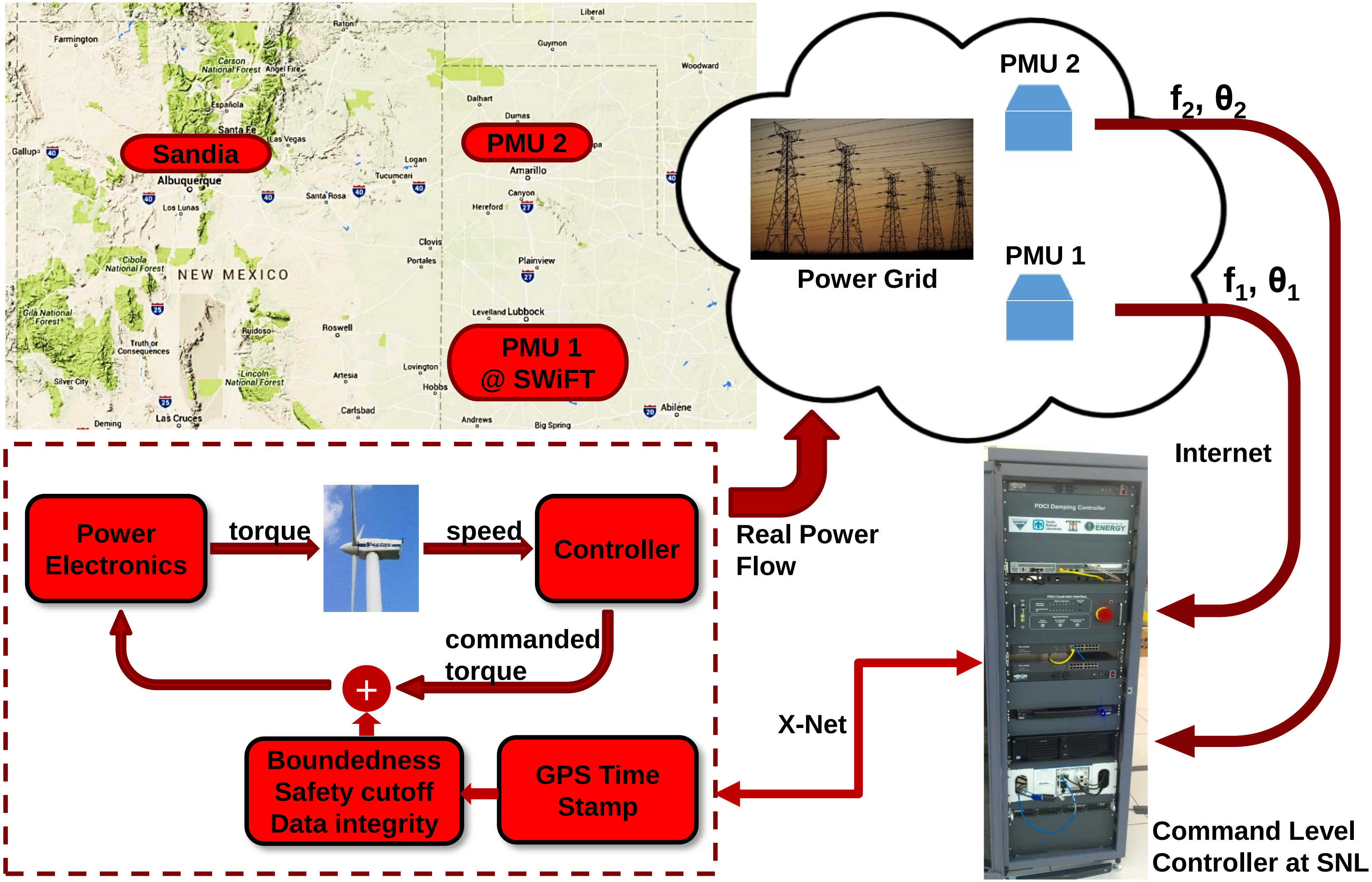
- Total real power capacity on order of 20 – 50 MW is sufficient
- With 10s of sites deployed, individual resource capacity ≤ 1 MW will work



East-West Mode



Damping Control Using Wind Turbines



- **PDCI damping controller was modified to modulate the torque command of a wind turbine at Sandia wind facility (SWiFT)**
- **Actuator (wind turbine) is remote – not co-located with the controller**
- **Communication channel used the public internet**

Key Takeaways from Project

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

Project Recognition

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

Current Status

- We are teaming with a software firm to "harden" the software to be operational in a substation environment
- We are leveraging the actuator "agnosticism" to widen the potential commercial market beyond the initial high voltage DC application with BPA
- We are enabling the "modularization" of the damping controller to be easily adaptable to other environments (energy storage, wind, large PV plants, etc.)
- Interested vendors include ABB and Schweitzer Engineering Labs

Future Research Recommendations

- ➢ Control designs to improve transient stability and voltage stability on transmission grids
- ➢ Assessment & mitigation of forced oscillations on transmission grids (both AC and HVDC)
- ➢ Enhancements to improve resilience of transmission grids
  - Design of control architectures that are more robust to single points of failure (e.g. decentralized control)
  - Control designs that leverage large #'s of distributed assets (e.g. power sources, measurement systems) to improve performance and reliability of transmission grids
- ➢ Analytics to improve transmission reliability
  - 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?

    Potential techniques include machine learning