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Real-Time Damping of Power Grid Oscillations Using Synchrophasor Feedback

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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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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:

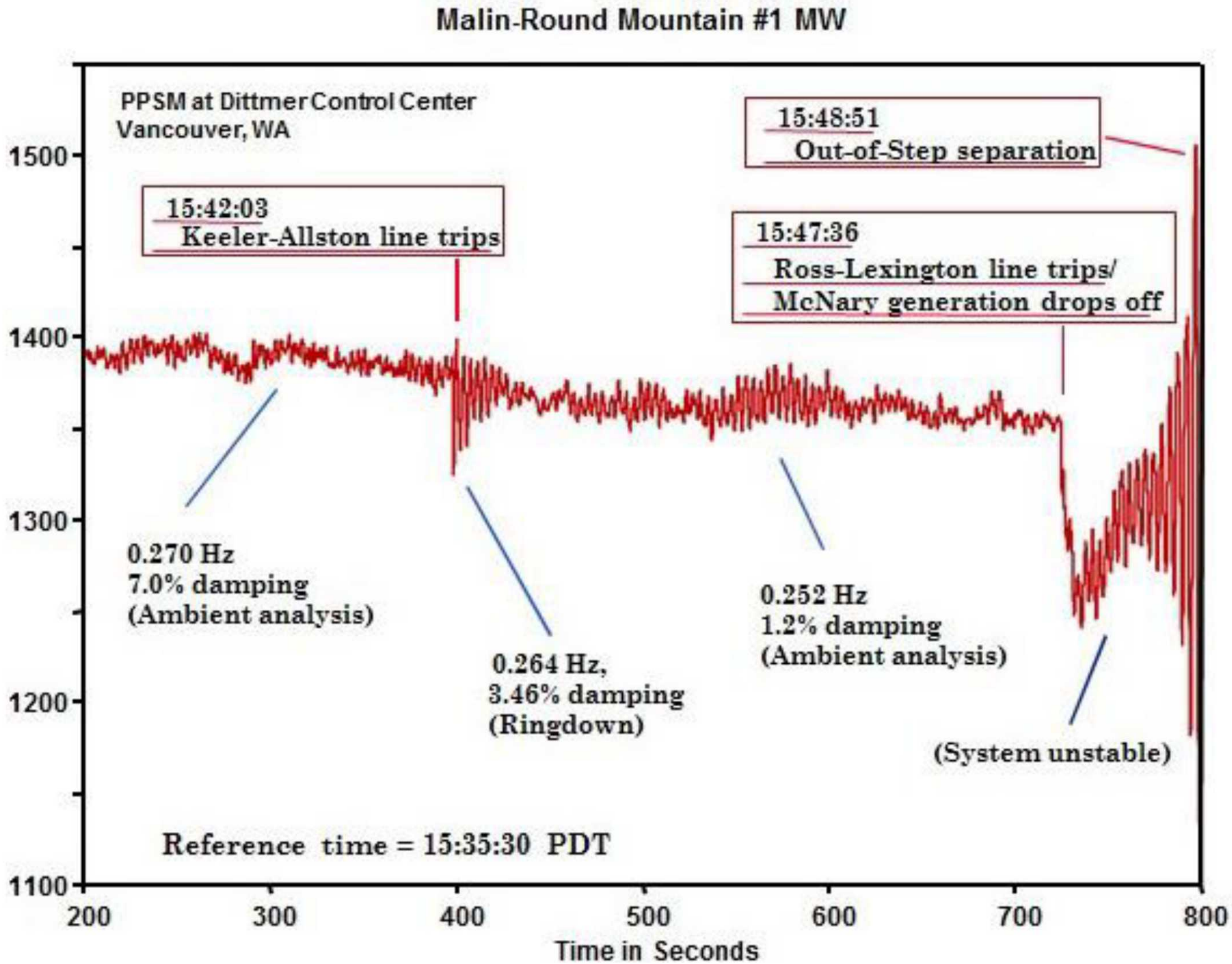
- Construct closed-loop feedback signal using real-time PMU (Phasor Measurement Unit) data: 1st demonstration of this in North America
- Modulate power flow on PDCI (Pacific DC Intertie) up to +/- 125 MW
- Implement a supervisory system to ensure "Do No Harm" to grid and monitor damping effectiveness

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

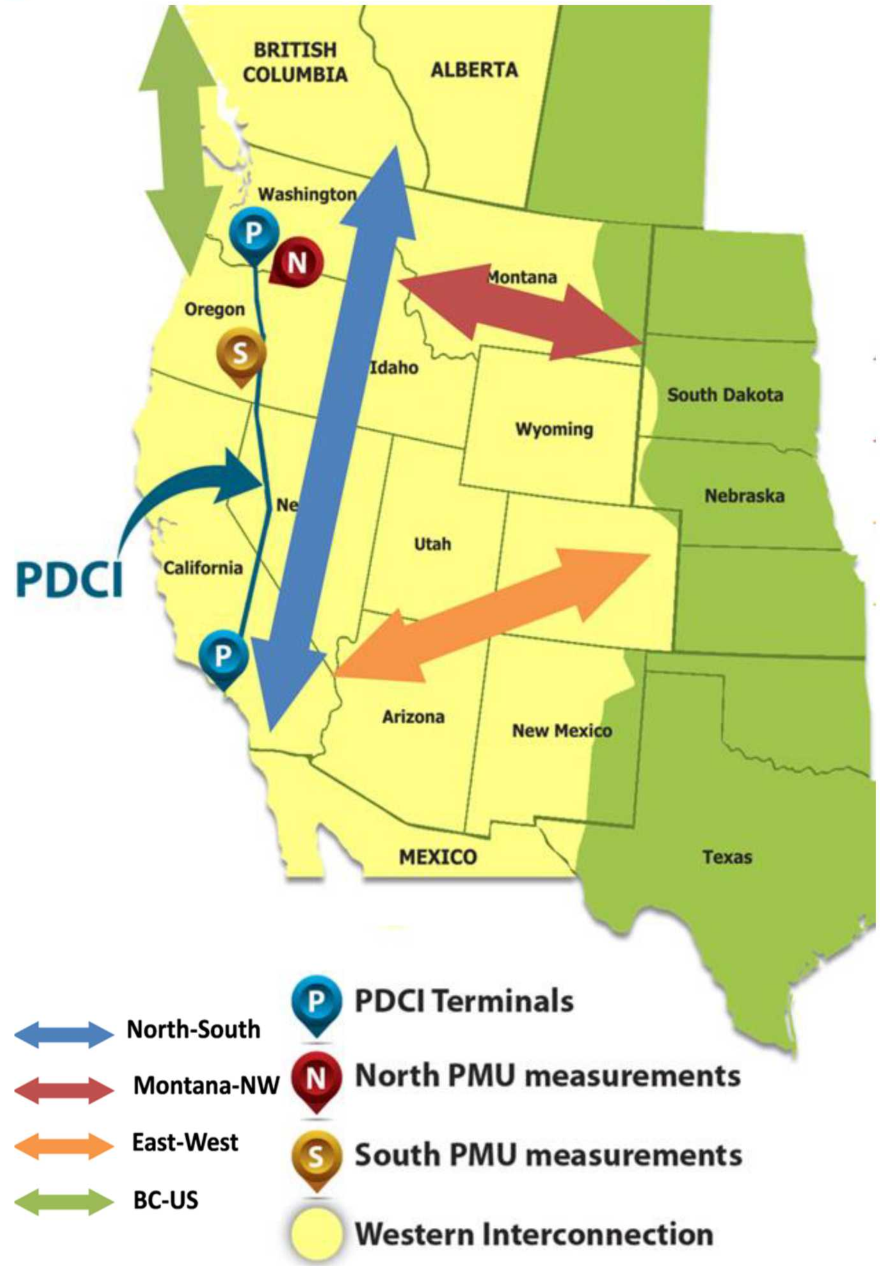
Inter-Area Oscillations Jeopardize Grid Stability

Western Power System Breakup on August 10, 1996

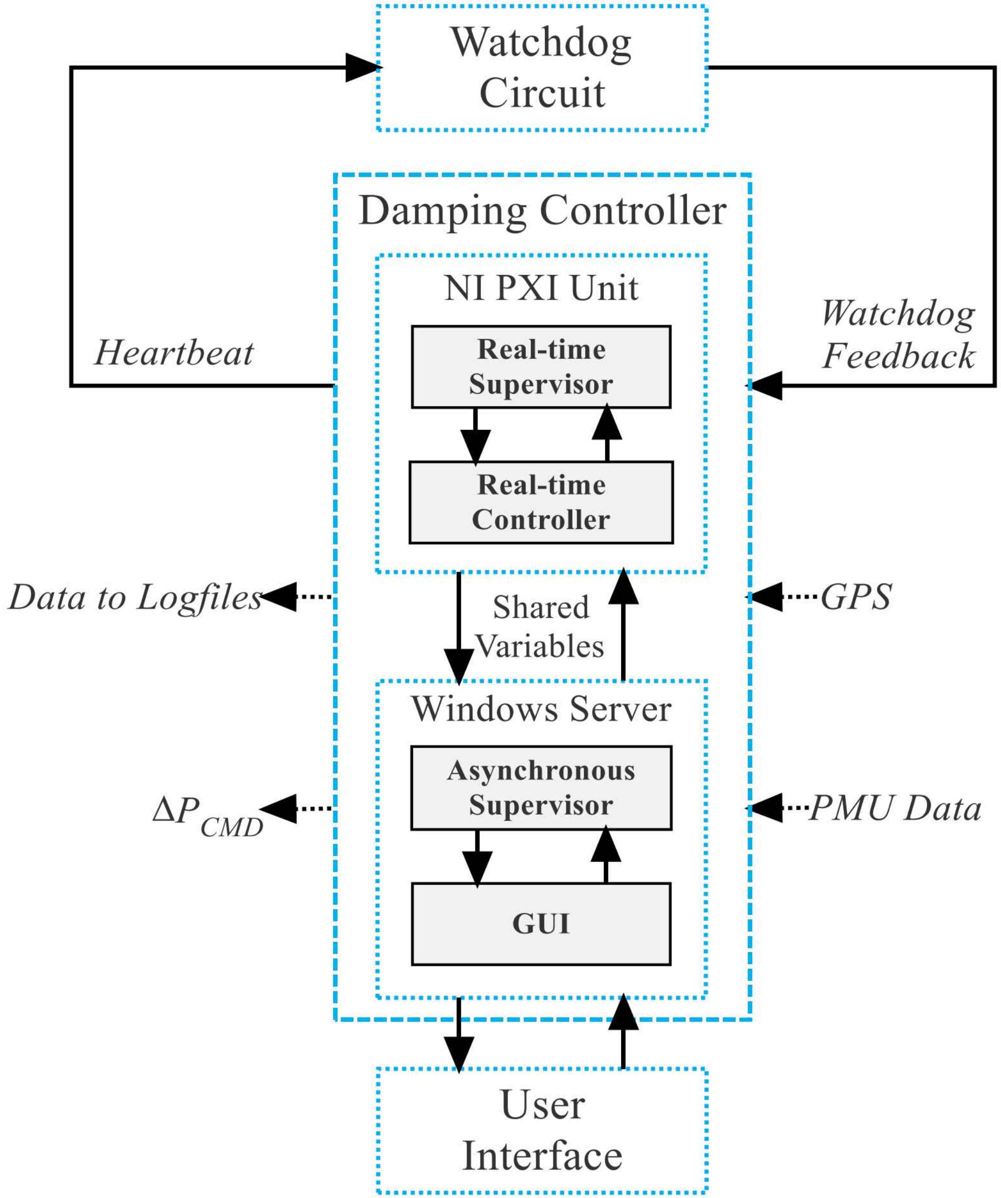


Project Background

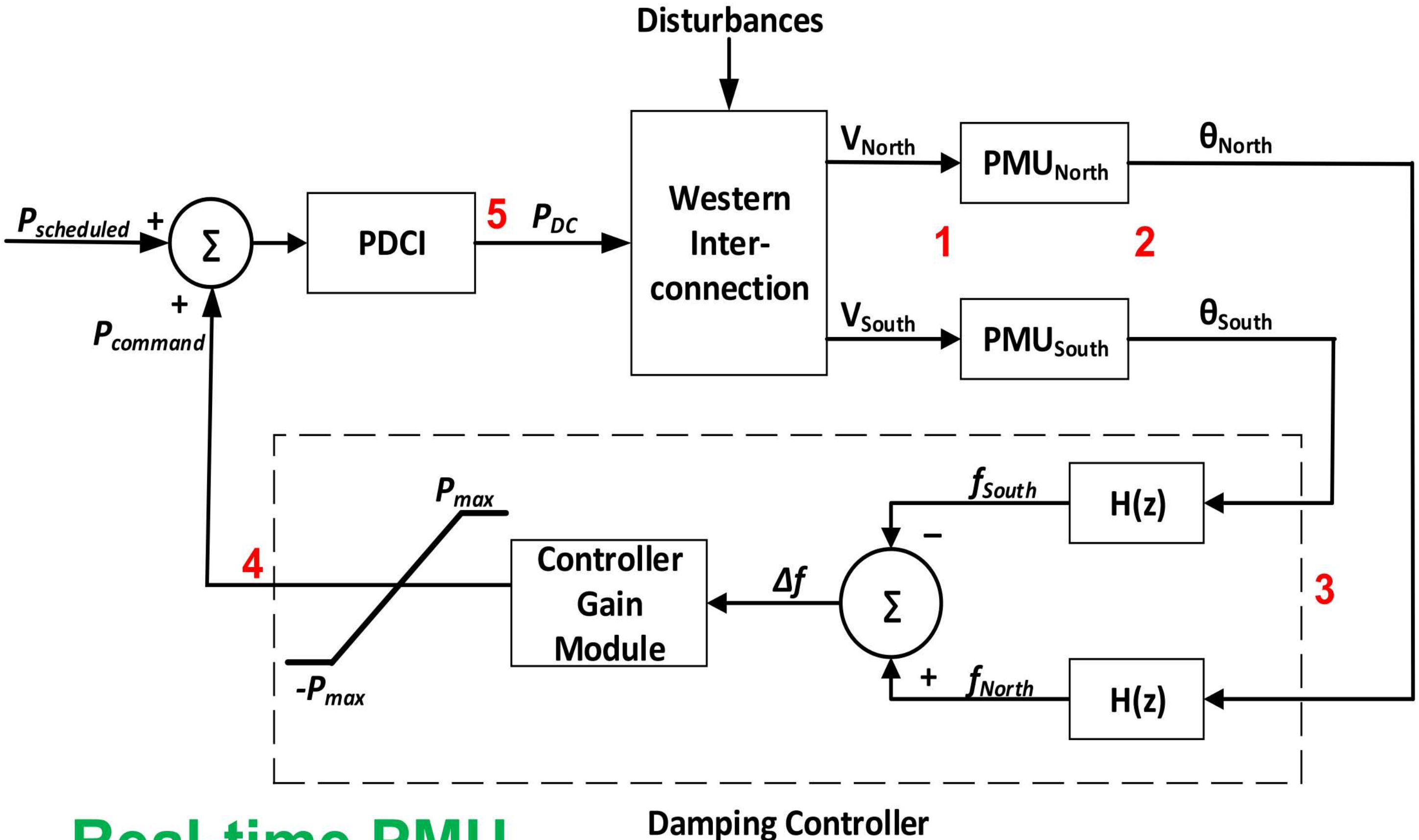
- Based on 1970s BPA experiments on PDCI later shown to have destabilized BC-US mode
- Revived in 2007 – 2012 by BPA with Montana Tech leveraging PMU deployments in WECC
- Current project launched in June 2013 as a collaboration of SNL, MT, BPA, and DOE to develop and demonstrate damping control
- Phase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



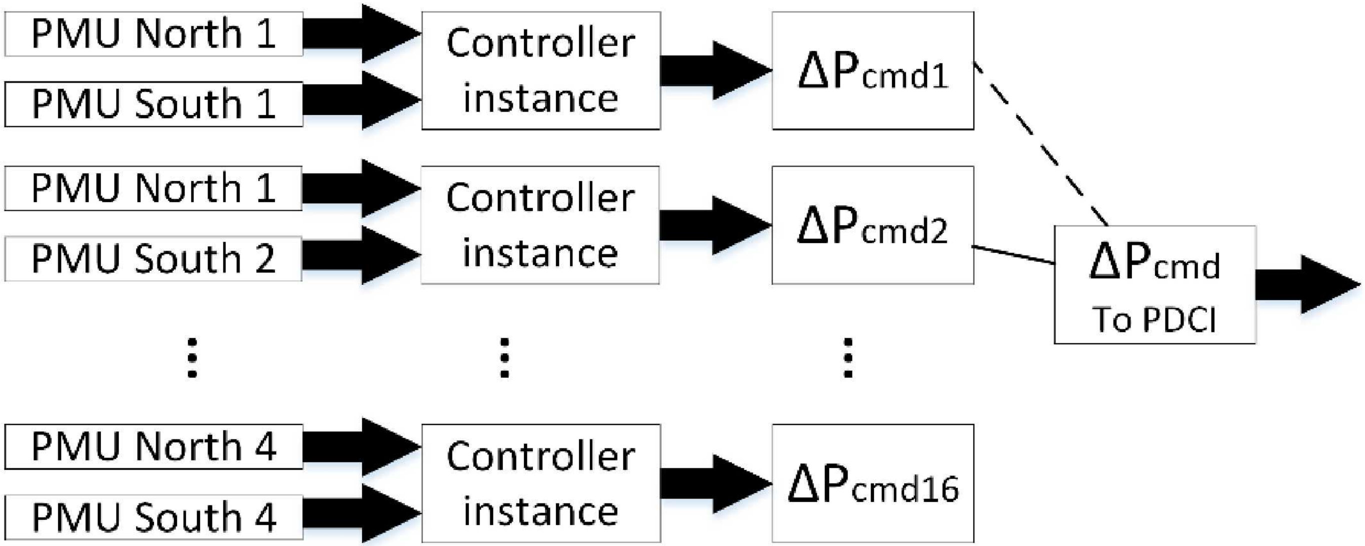
Real-time PMU feedback is the key to stable control

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

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

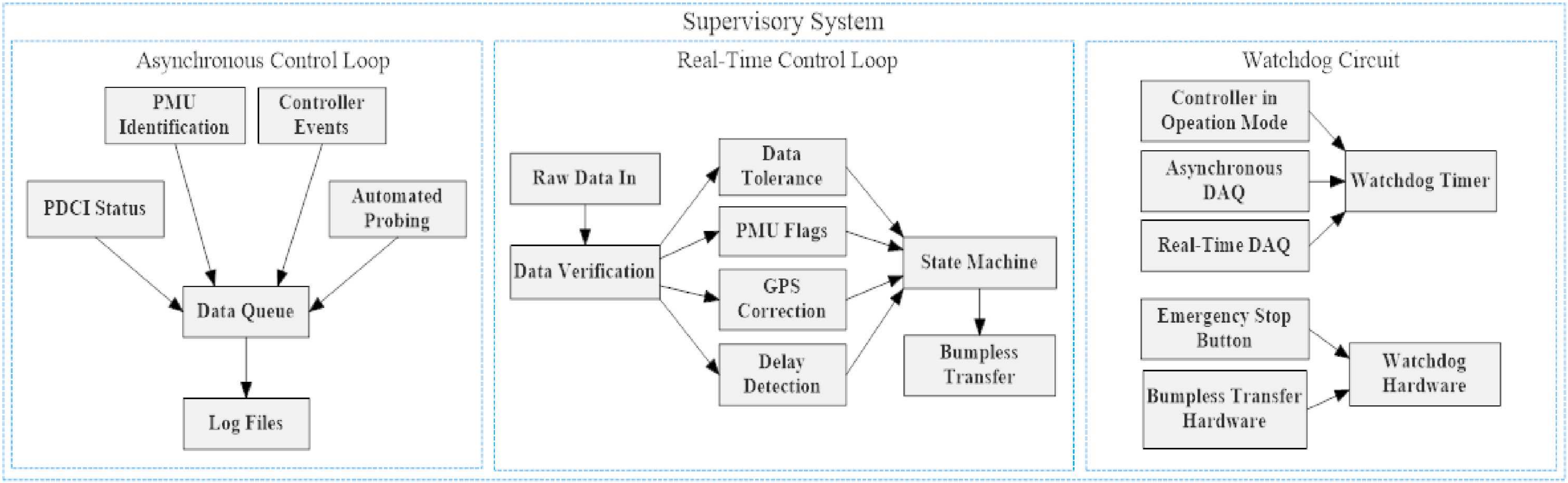
Controller Employs Diversity and Redundancy in Feedback



- **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



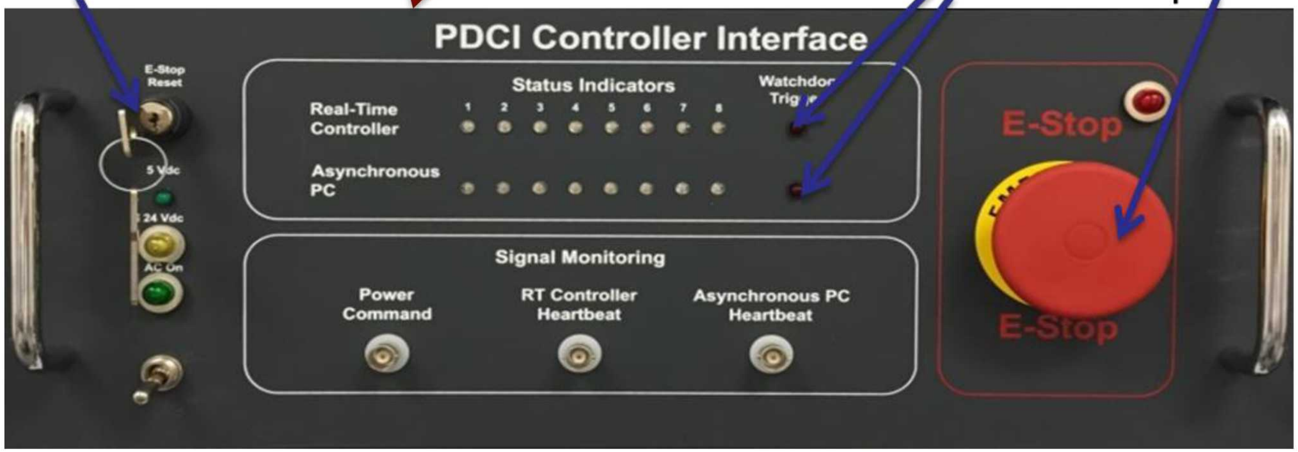
Damping Controller Hardware

Watchdog circuit module

Key switch

Heartbeat indicators

E-Stop button

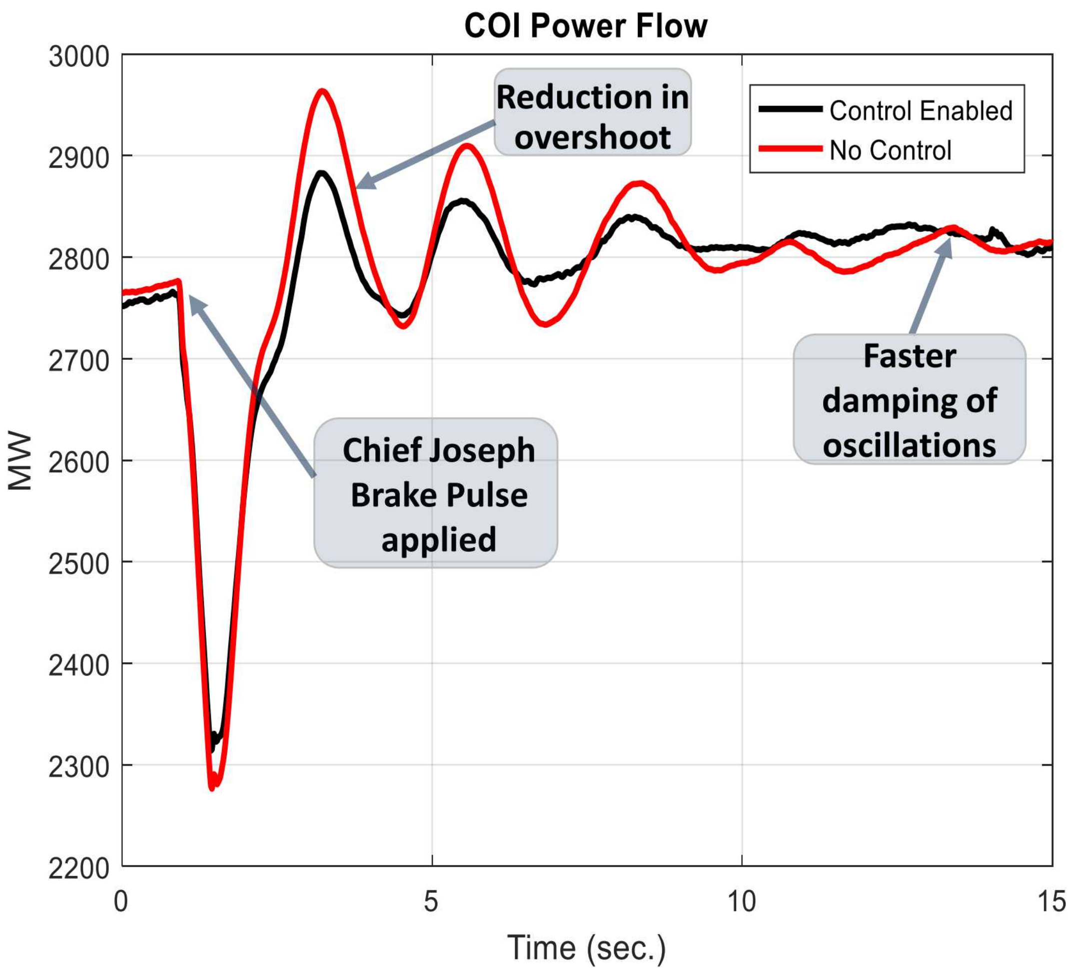


Server for select supervisory functions ("Do No Harm")

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

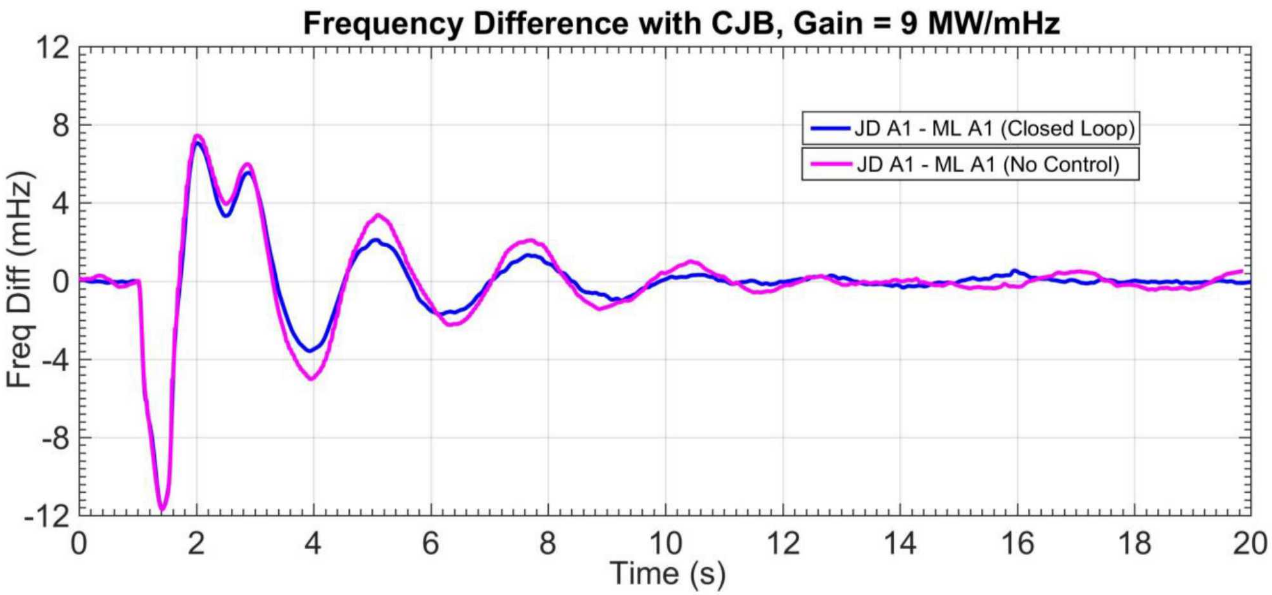


Chief Joseph brake test	Damping of North-South B Mode improved 4.5 percentage points (11.5% to 16.0%) in closed-loop vs. open-loop operation.
Square wave pulse test	Damping controller significantly reduces amplitude of North-South B mode oscillations in 15 seconds vs. 23 seconds in open-loop tests for 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)

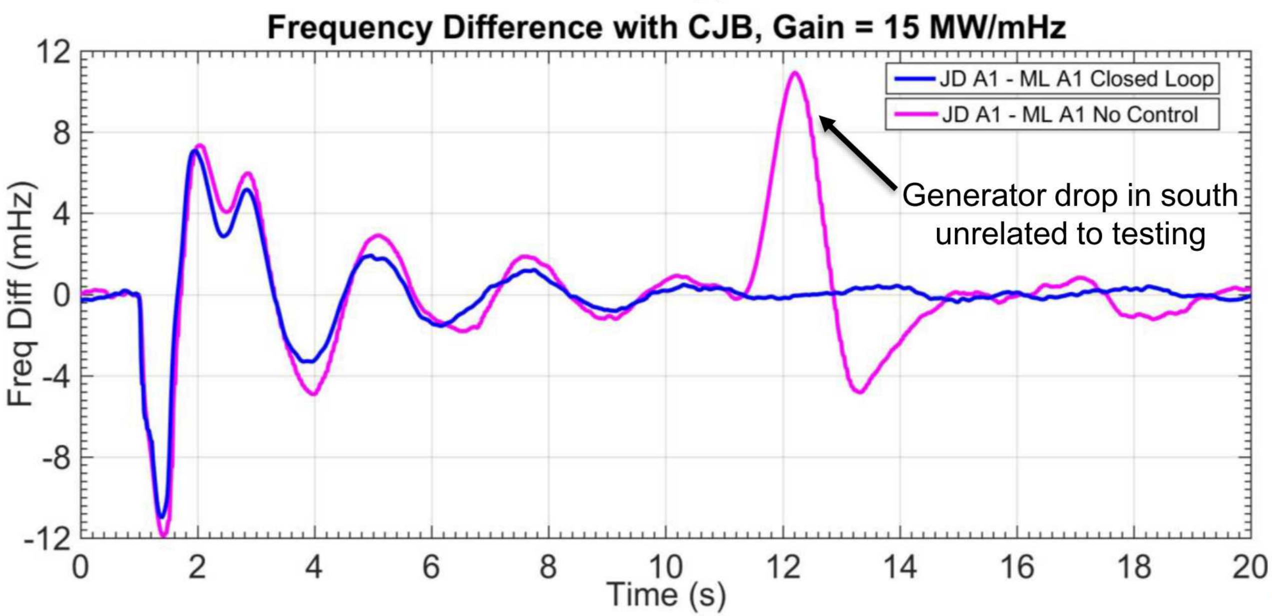
Chief Joseph brake test

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

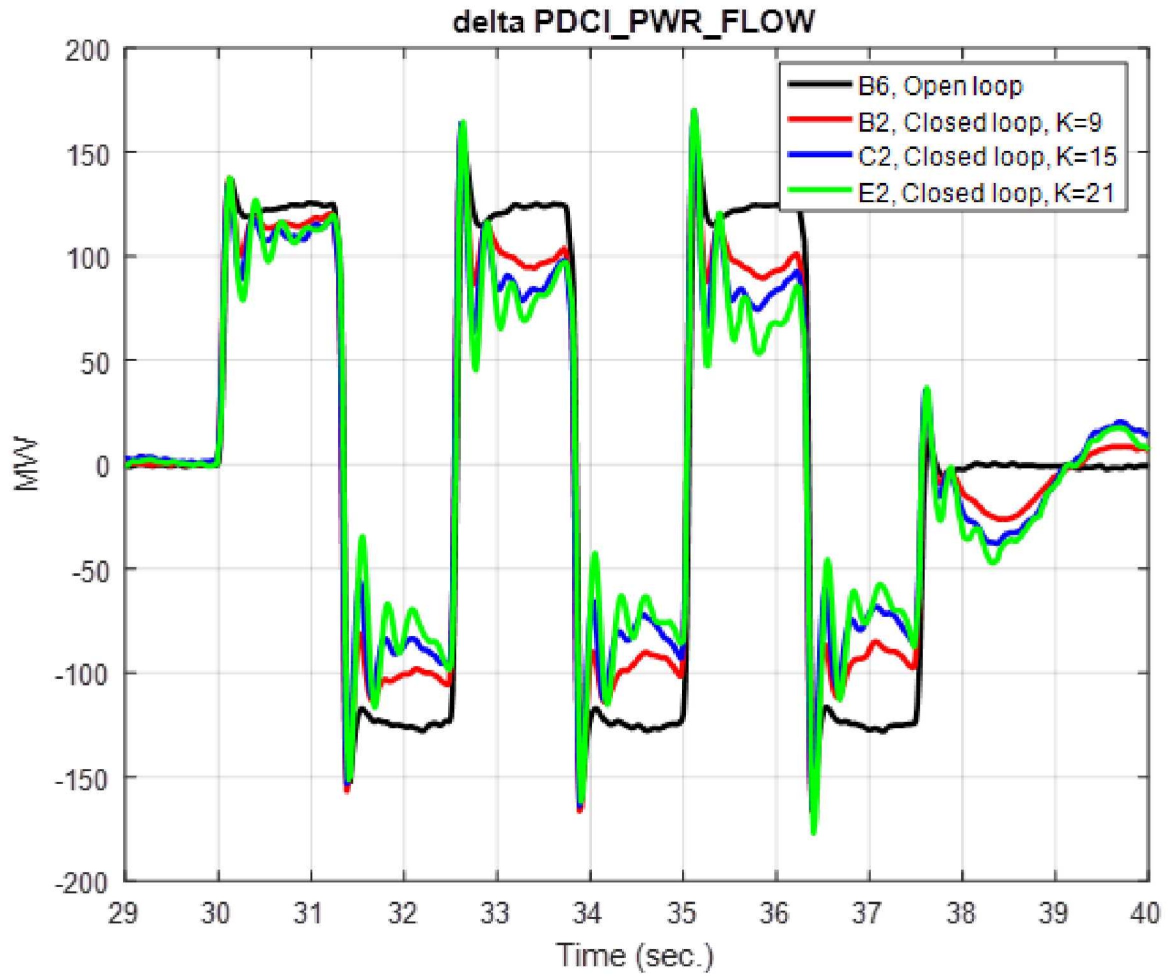


Chief Joseph brake test

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

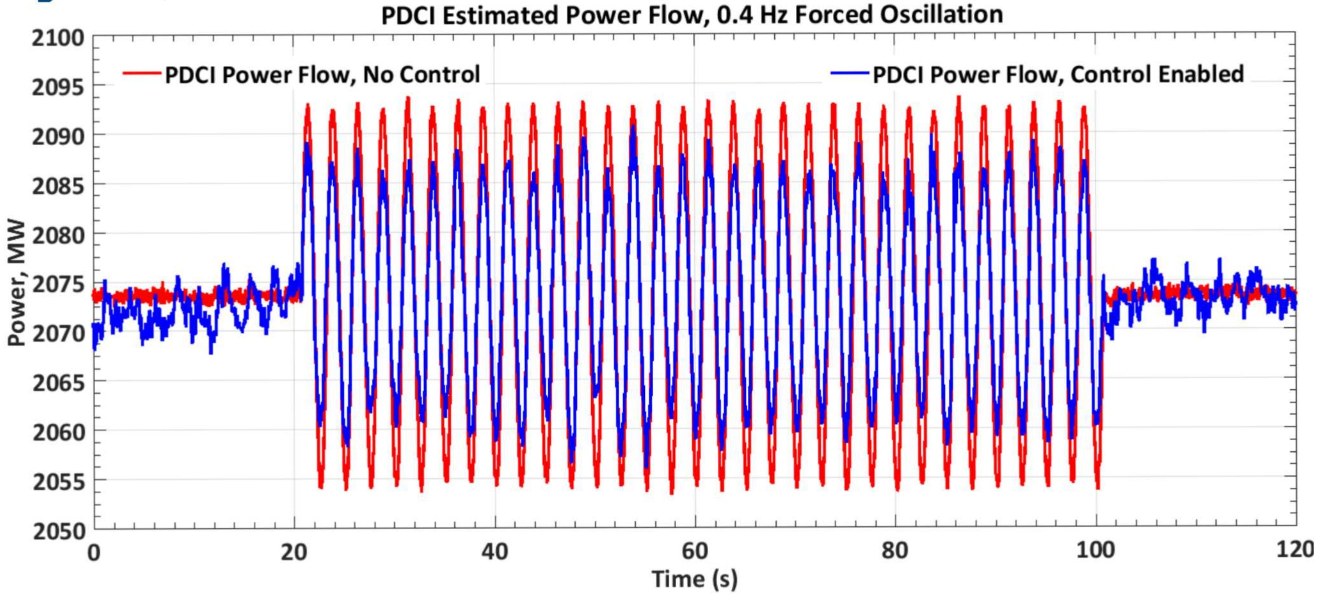


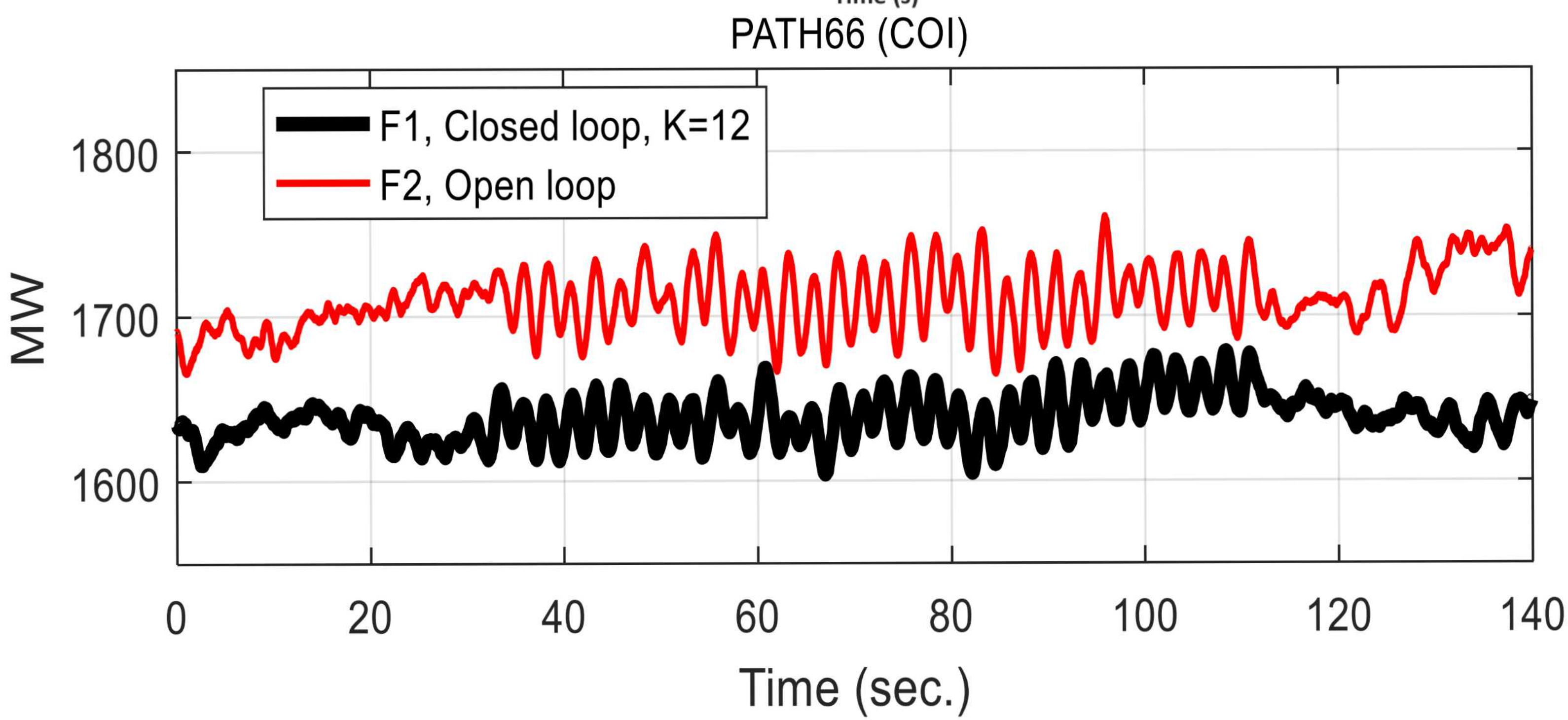
Gain Tuning was Informed by Square Wave Pulses
(Tests conducted at Celilo on May 23, 2018)



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

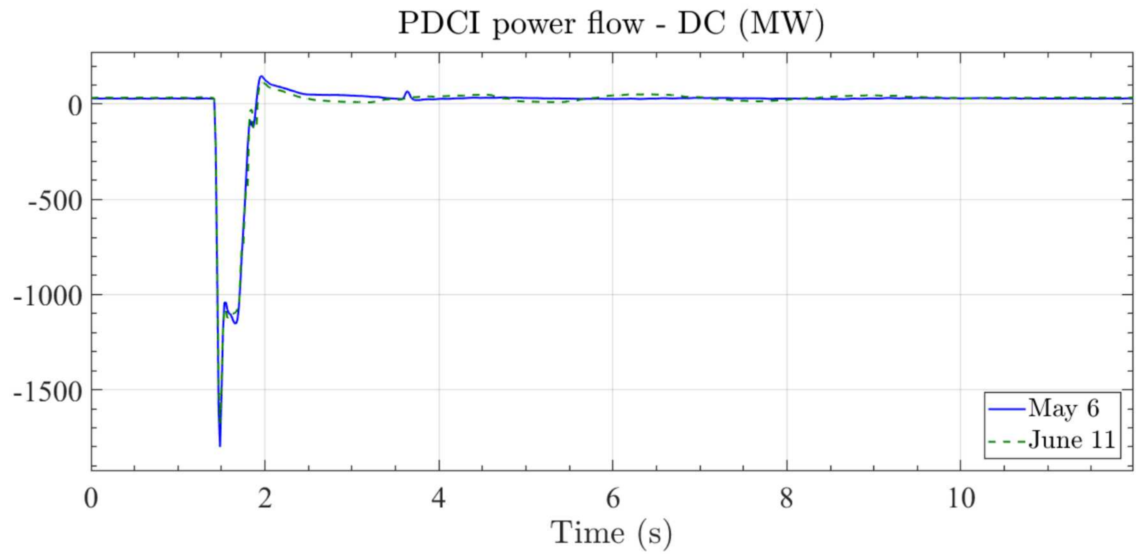
May 16, 2017 Tests, 0.4 Hz Forced Oscillation



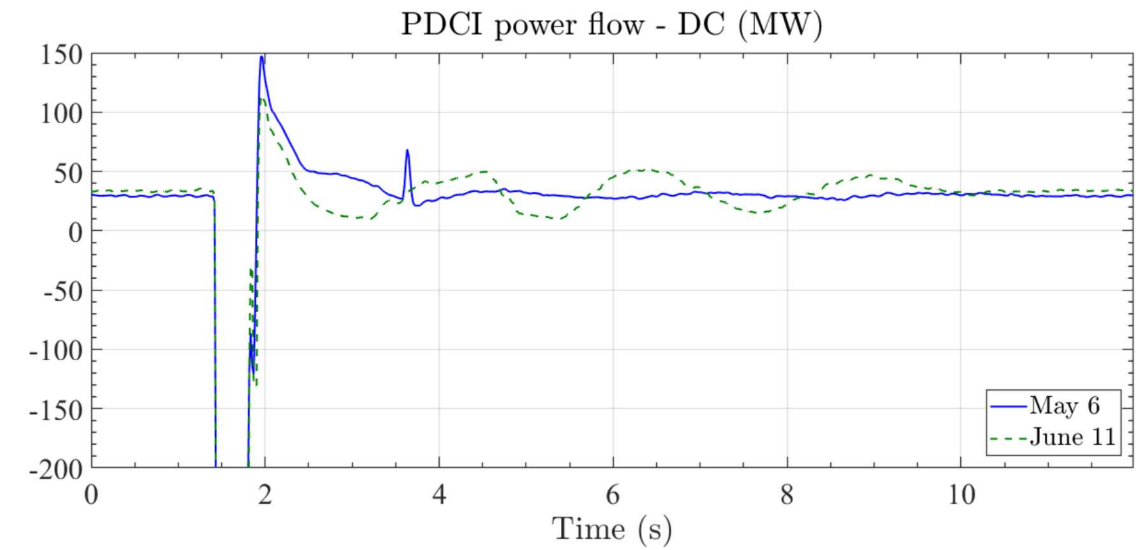


Events on the DC Side Provide a Good Basis of Comparison for Controller Performance

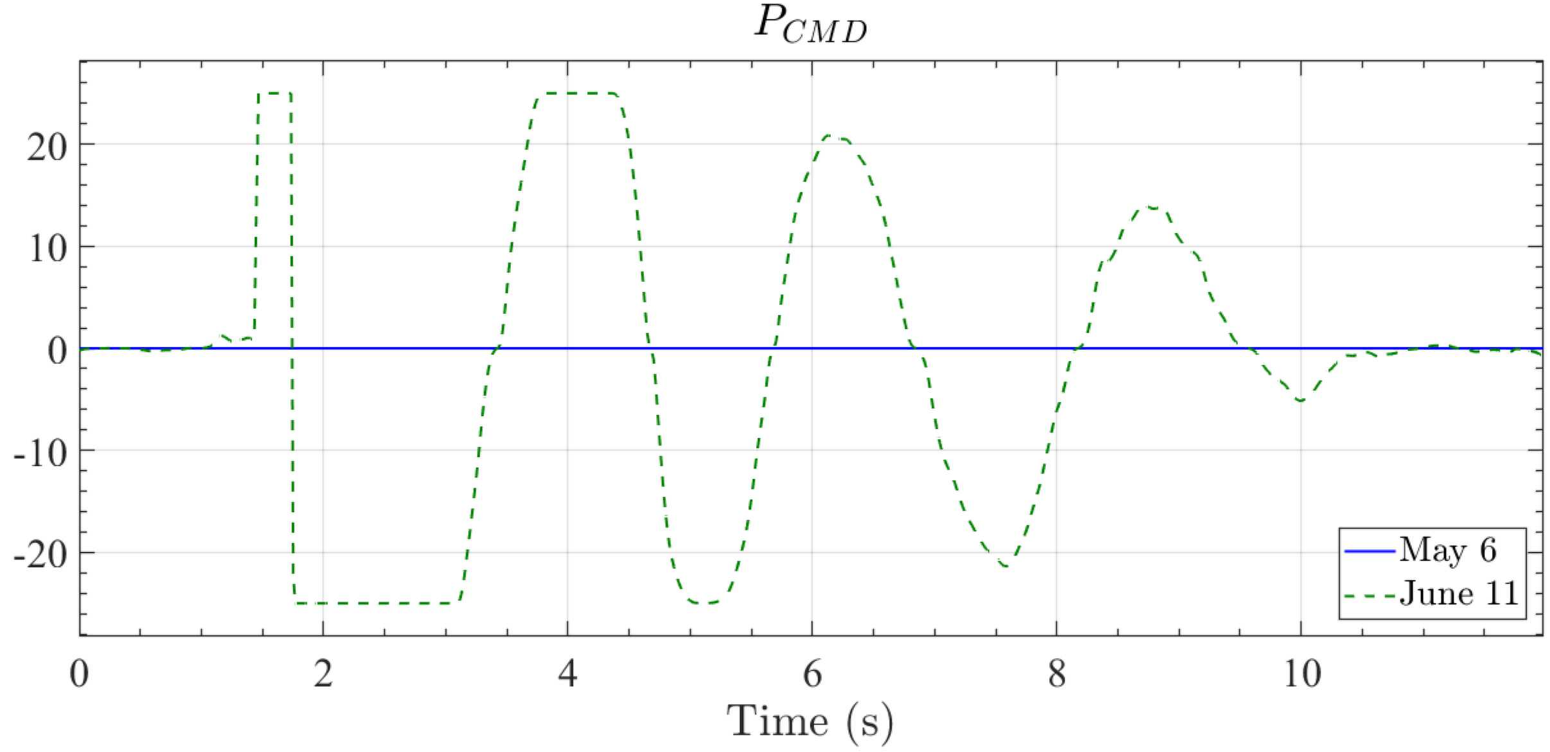
Two very similar events are captured. May 6 – controller was not connected. June 11 – controller was in closed-loop operation.



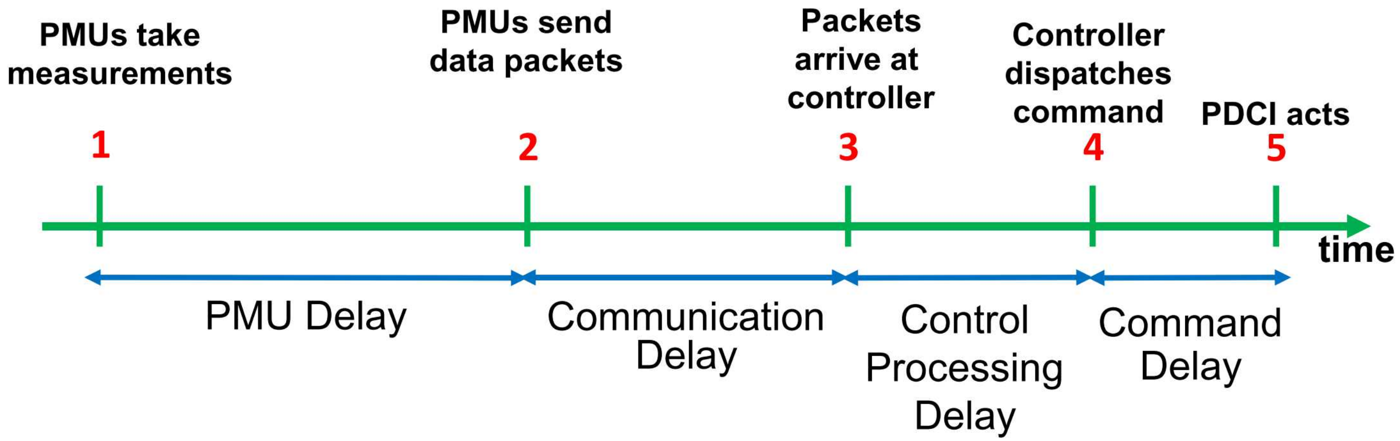
This plot zooms in on the y-axis to show controller modulation (June 11 curve).



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



Communication and Delays

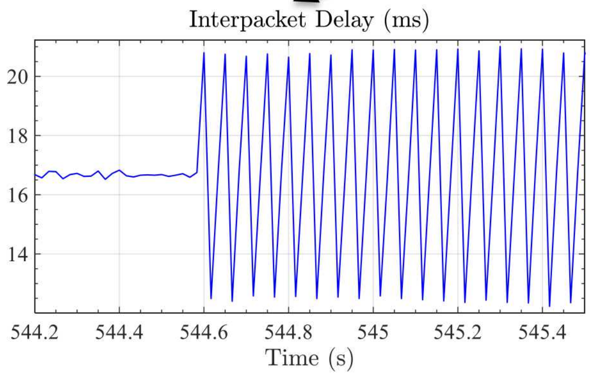


Name	Mean	Range	Note
PMU Delay	44	40 – 48	Dependent on PMU settings. Normal distribution.
Communication Delay	16	15 – 40	Heavy tail
Control Processing Delay	11	2 – 17	Normal around 9 ms, but a peak at 16 ms due to control windows when no data arrives (inconsistent data arrival)
Command Delay	11	11	Tests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

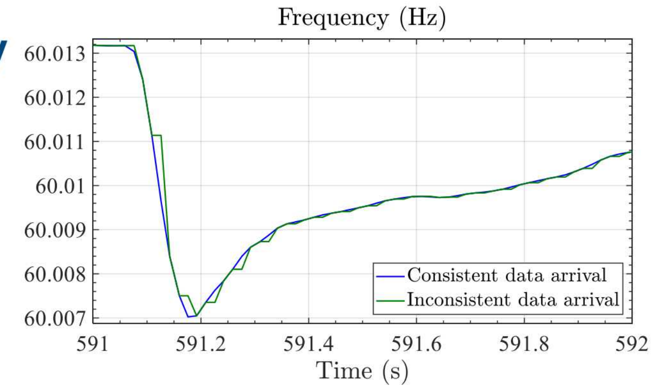
Total time delays are well within our tolerances (<< 150 ms)

PMU Data Considerations

- **PMUs have inconsistent interpacket delays**

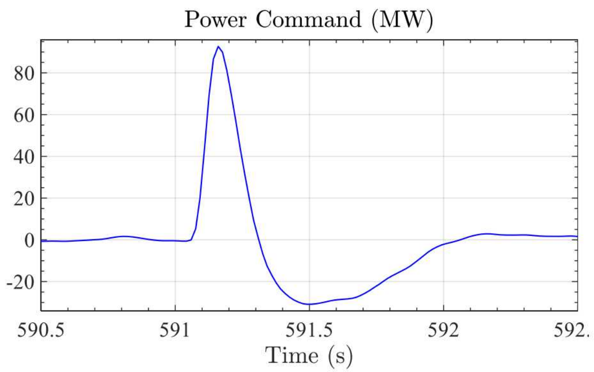


Delay inconsistency affects frequency estimation

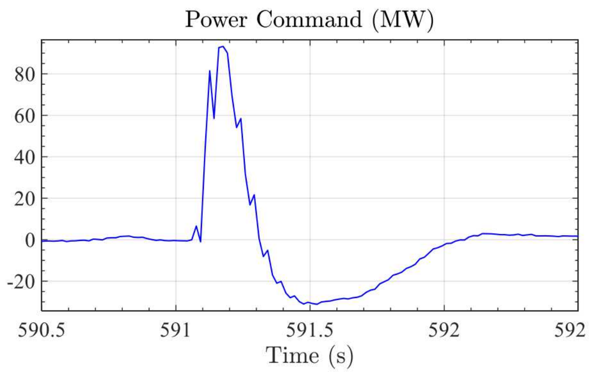


- **Delay inconsistency also affects the power command**

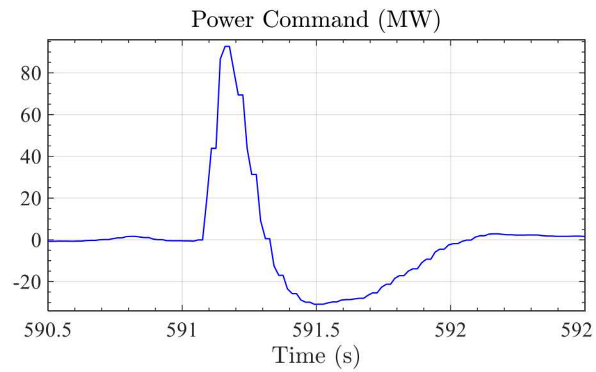
Ideal case



Delay inconsistency with NO time alignment



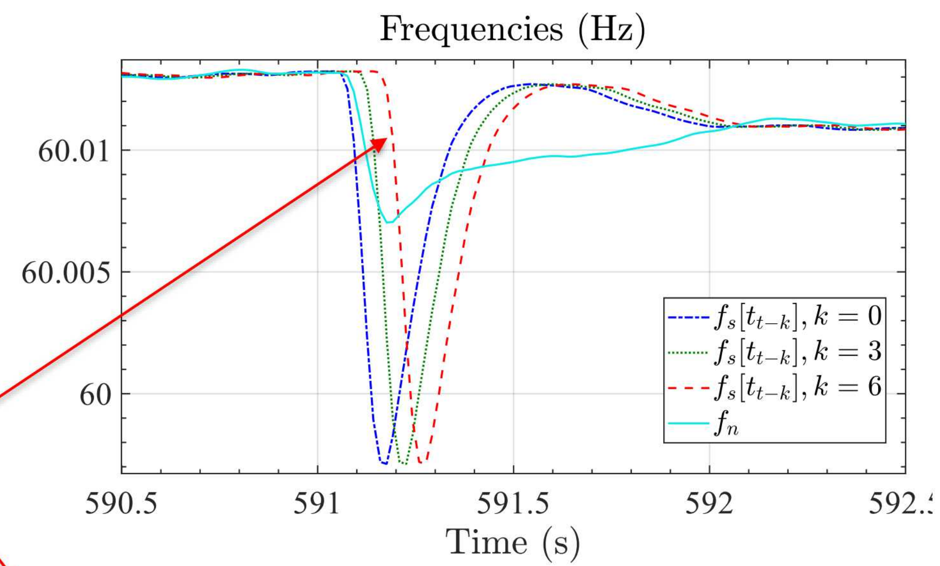
Delay inconsistency with time alignment

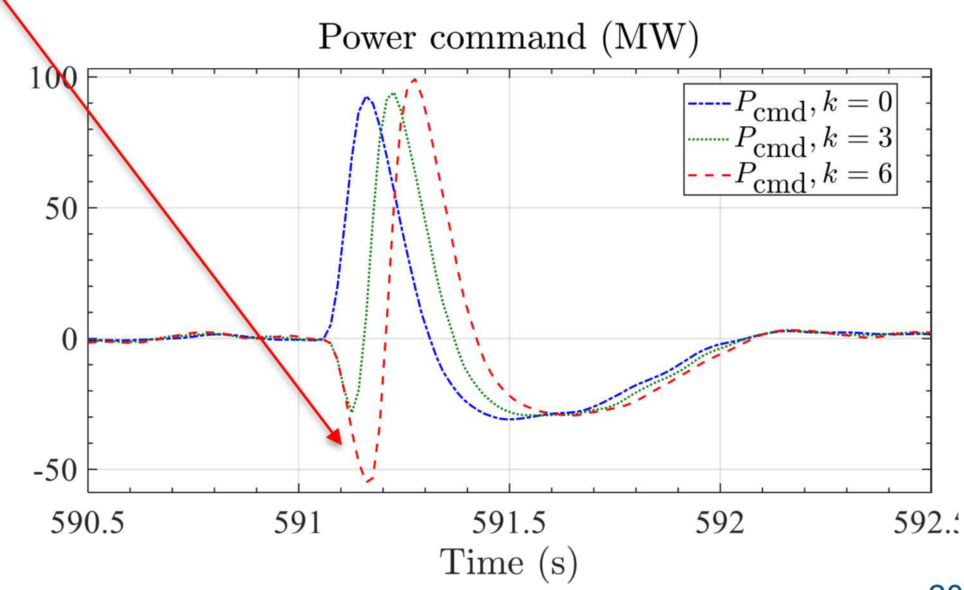


PMU Data Considerations

- **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)





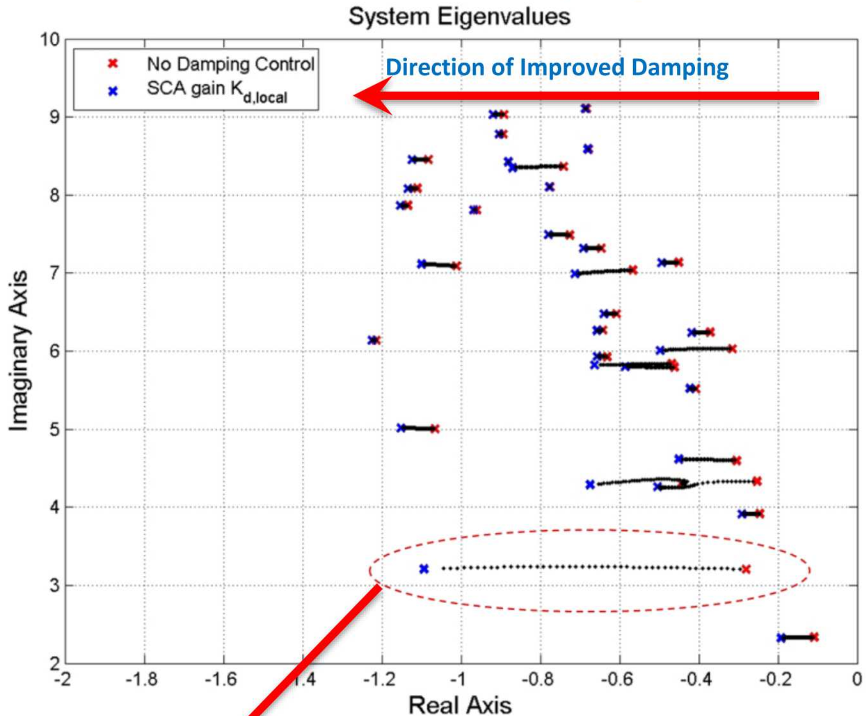
Damping Control Using Distributed Energy Resources

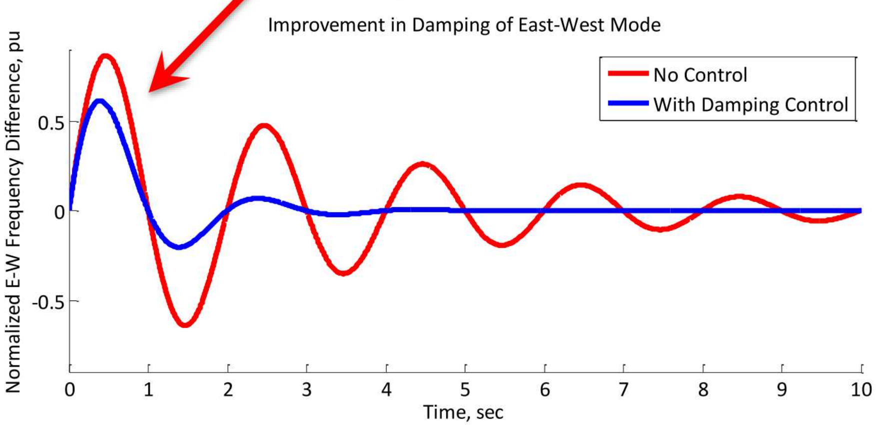
Advantages:

- 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

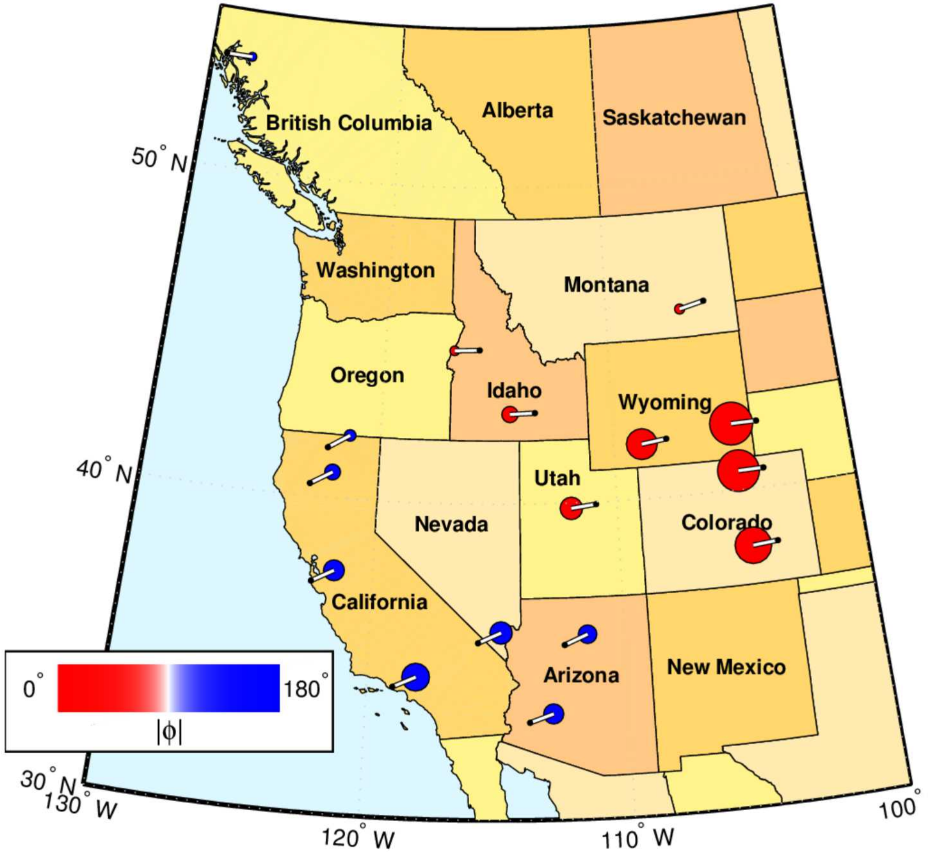
Example using Distributed Energy Storage

- 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

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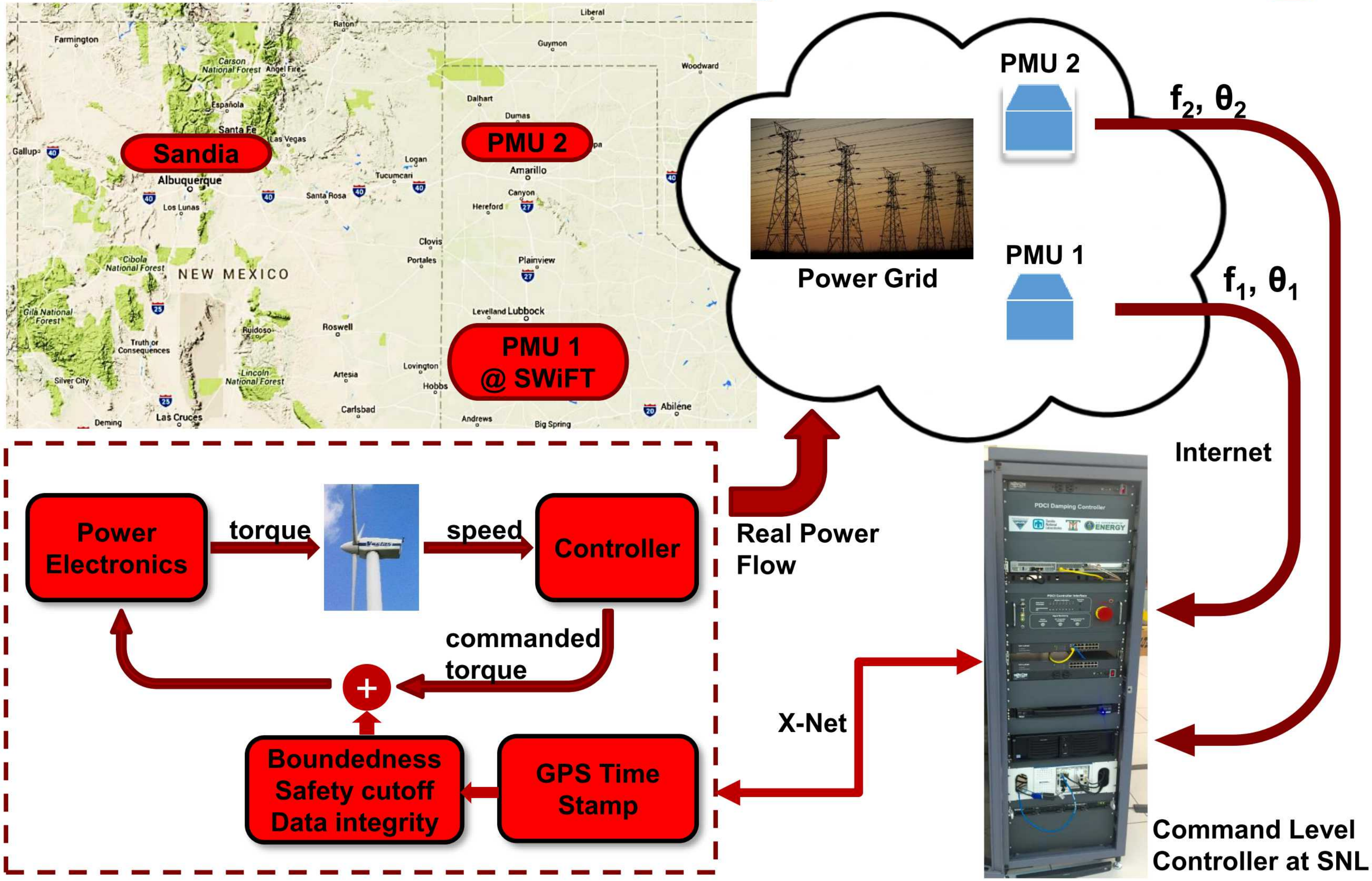

- PDCI damping controller was modified to modulate the torque command of a wind turbine at Sandia wind facility (SWiFT)
- Actuator (wind turbine) is remote – not co-located with the controller
- Communication channel used the public internet

Key Takeaways from Project

- 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