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Control System Design for Active Damping of Large-Scale Power Grids

David Schoenwald

Electric Power Systems Research Department

Sandia National Laboratories

The Ohio State University

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Outline of Talk

- Project Overview
- Power System Oscillations
- Wide-Area Measurement Systems
- High Voltage DC Transmission Lines
- Control Design Strategy for Oscillation Damping
- Grid Demonstrations of Control System Operation
- Current and Future Research

Contributors and Acknowledgements

- **Bonneville Power Administration (BPA):**
  - Dmitry Kosterev (Tech. POC)
  - Jisun Kim (PM)
  - Jeff Barton
  - Tony Faris
  - Dan Goodrich
  - Jeff Johnson
  - Gordon Matthews
  - Michael Overeem
  - Sergey Pustovit
  - Greg Stults
  - Mark Yang
- **Sandia:**
  - Dave Schoenwald (PI)
  - Brian Pierre
  - Felipe Wilches-Bernal
  - Ryan Elliott
  - Ray Byrne
  - Jason Neely
- **Montana Tech:**
  - Dan Trudnowski (co-PI)
  - Matt Donnelly

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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:

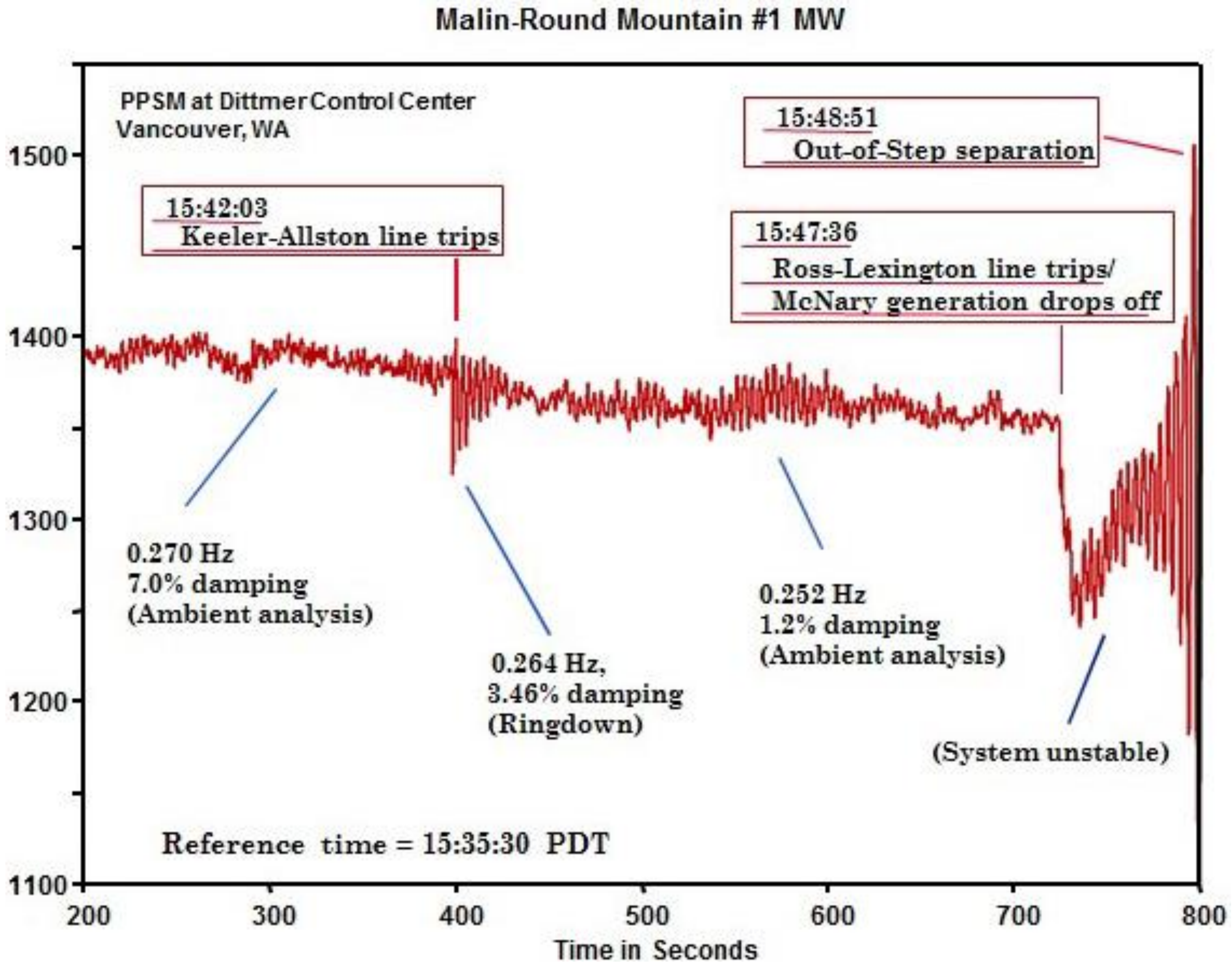
- Construct closed-loop feedback signal using real-time PMU (Phasor Measurement Unit) data: 1st demonstration of this in North America
- Modulate power flow on PDCI (Pacific DC Intertie) up to +/- 125 MW
- Implement a supervisory system to ensure "Do No Harm" to grid and monitor damping effectiveness

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

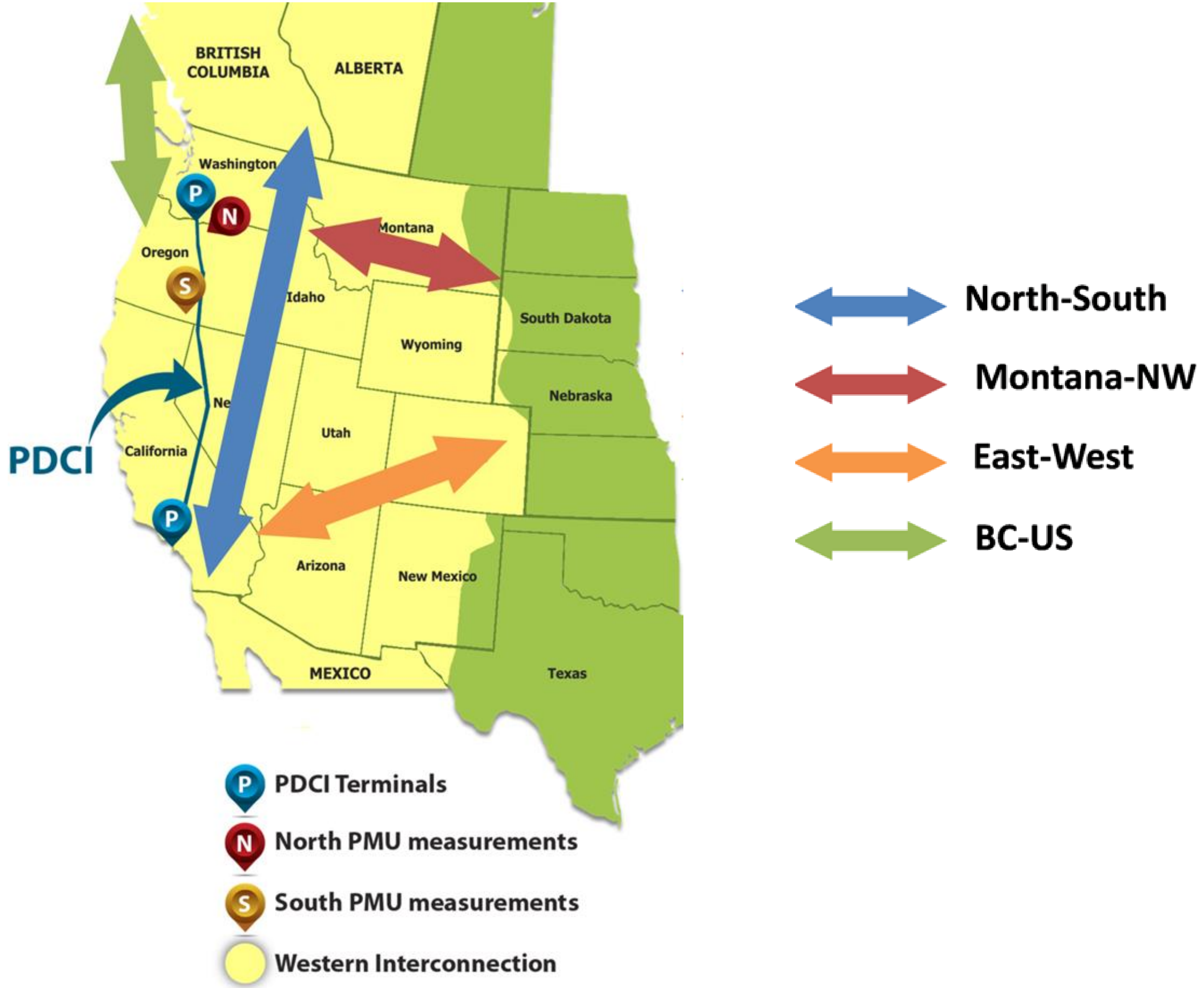


Background

- Based on 1970s BPA experiments [1] later shown to have destabilized BC-US mode
- Revived by BPA with Montana Tech in 2007 – 2012 [2] with advent of GPS time-stamped, high accuracy, high data rate phase angle measurements
- Current project launched in Summer 2013 based on theory developed in [2]
- Principal Goal:
  - Build, install, and demonstrate a damping controller via real-time feedback modulation of PDCI (Pacific DC Intertie) power
  - Control signal based upon wide-area PMU (Phasor Measurement Unit) feedback
- Phase 1 (June 2013 – Sept 2015)
  - Controller design based on extensive simulation studies and eigensystem analysis
  - Open-loop testing – assessment of PMU data quality
- Phase 2 (Oct 2015 – Sept 2017)
  - Actual system install at BPA Celilo Converter Station, The Dalles, Oregon
  - Closed-loop testing on western North American grid using PDCI
  - Documentation and publishing of results (engagement of utility community)
- Phase 3 (Jan 2018 – Sept 2019)
  - Conduct longer-term tests
  - Operationalize controller (cyber security compliance)

1. R. Cresap, W. Mittelstadt, D. Scott, and C. Taylor, “Operating experience with modulation of the Pacific HVDC intertie,” *IEEE Trans. on Power Apparatus and Systems*, vol. PAS-97, no. 4, pp. 1053-1059, July/Aug. 1978.
2. D. Trudnowski, D. Kosterev, and J. Undrill, “PDCI damping control analysis for the western North American power system,” IEEE PES General Meeting, Vancouver BC, July 2013.

Western Interconnection Oscillation Modes



Visualization of Oscillation Mode Shape

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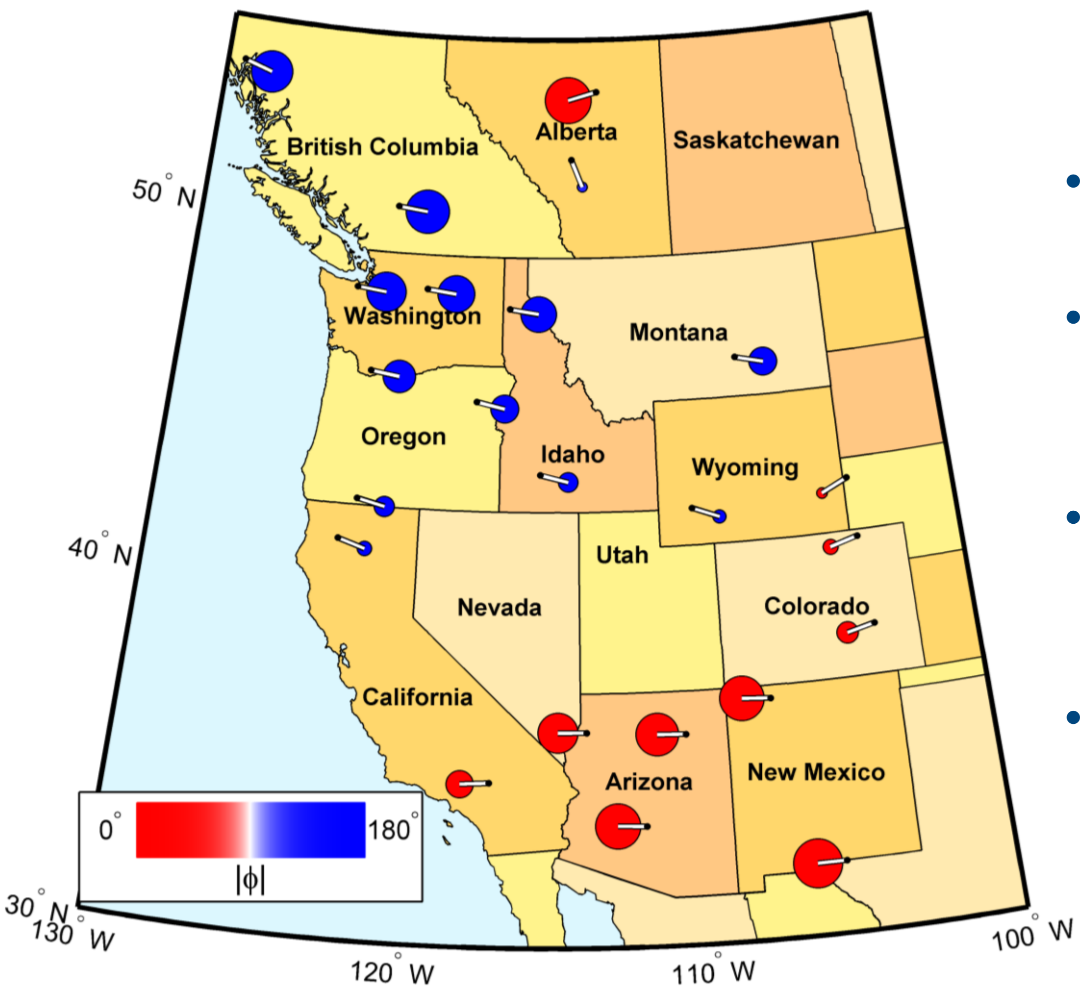
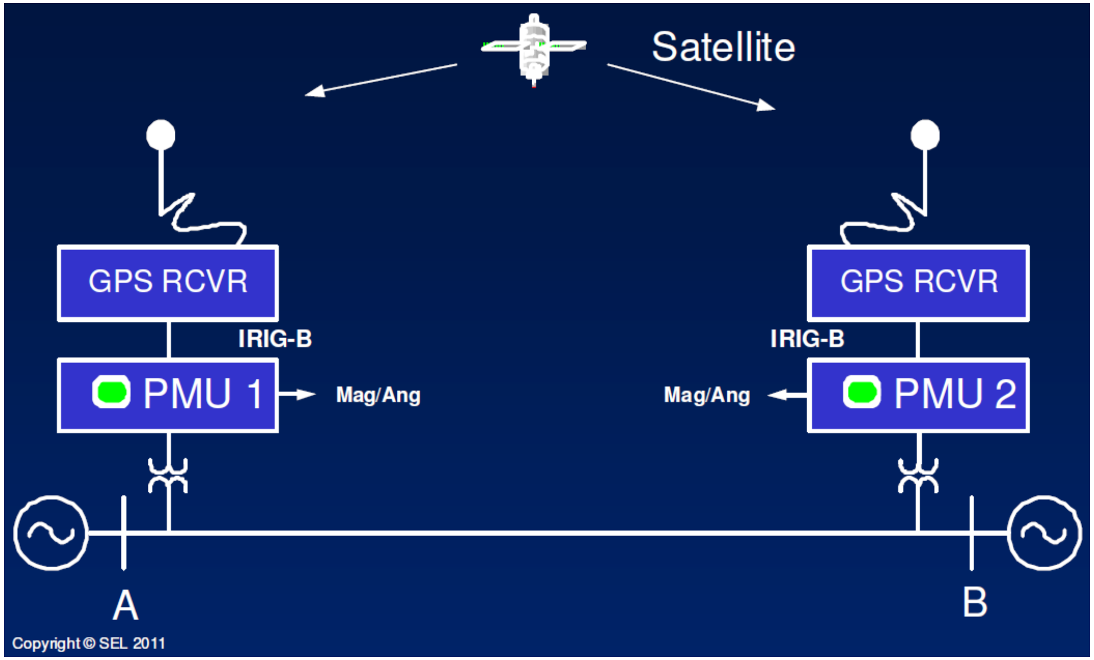
North South Mode
0.36 Hz, 13.7% damping



- Reference site is the location with the largest observed amplitude for that mode.
- Amplitude is proportional to radius of disk
- Color of disk indicates if site was in (red) or out of phase (blue) with reference site.
- Phase angle is indicated by a fixed length arrow in the center of each disk
- Mapping results based upon simulations using 2015 heavy summer base case

Phasor Measurement Units (PMUs)

- PMUs measure voltage & current phasors with respect to an absolute time reference.
- Time synchronization – key for feedback ➔ can determine phase relationships between electrical signals at different locations on the grid (possibly 100s to 1000s of miles apart) that were measured at the same time (+/- 500 ns timing accuracy).
- PMUs record measurement data in packets that are GPS time-stamped and transmitted on a communication network at high data rates, typically 60 Hz.
- History – developed by Profs. Phadke & Thorp at Virginia Tech in 1990s.
- Primarily used for monitoring, alarming, and forensic analysis.
- Challenges – network issues (cost, security, delay, data integrity), GPS dependence, "big data" to analyze & store, costly to use for distribution grid, standards not yet firm.

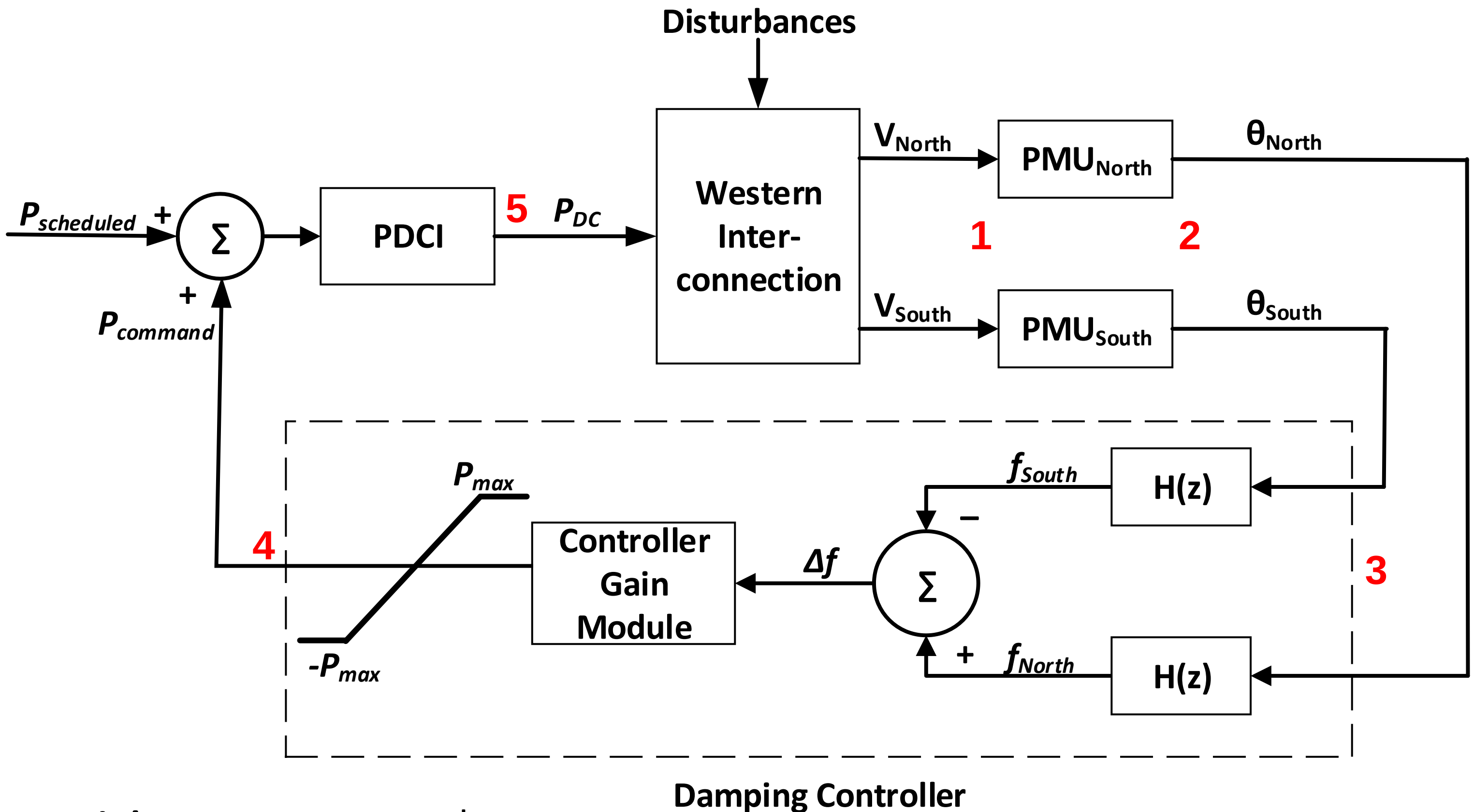


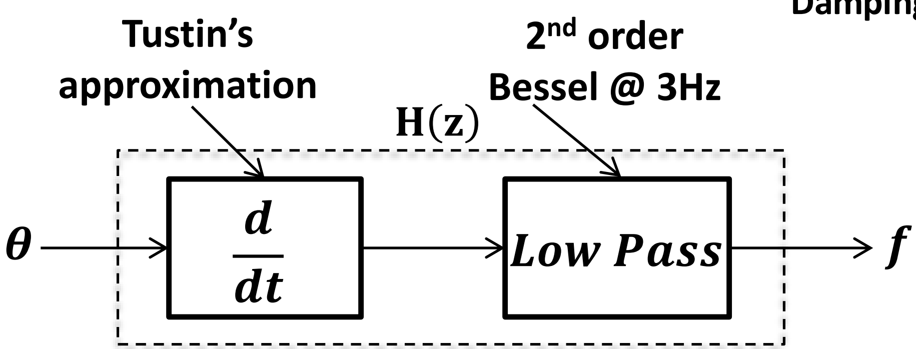
- Project is first in North America to use PMUs in real-time feedback control.
- PMUs are a game changer for damping inter-area oscillations because we can now "time align" phasor measurements taken from different locations giving us a real-time "snapshot" of oscillation behavior in the grid.

Pacific DC Intertie (PDCI)

- High Voltage DC line: +/- 500 kV
- 3220 MW capacity
- 850 miles long – Celilo to Sylmar
- BPA operates Celilo
- LADWP operates Sylmar
- Operational since 1970
- PDCI is annually used for probing tests (since 2008) to identify and better understand inter-area oscillations on the western grid

Damping Controller Strategy





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

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

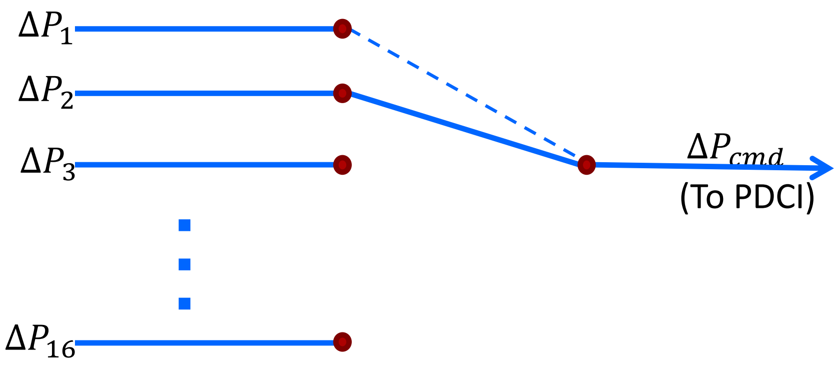
4 Controller sends power command to PDCI

5 PDCI injects power command into grid

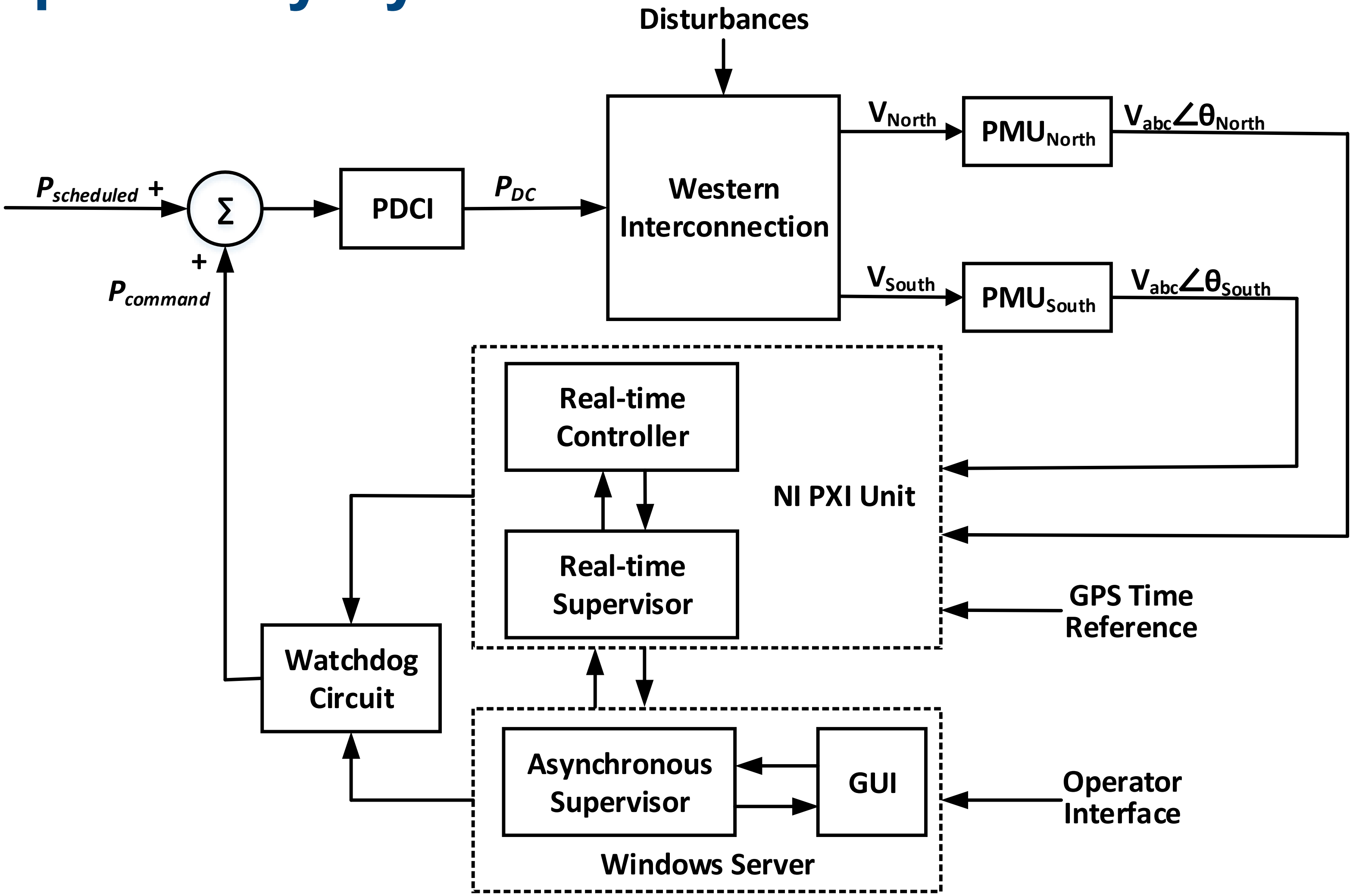
Redundancy and Diversity in PMU Feedback

- **Diversity ≡ Geographic Spread**
  Redundancy ≡ Multiple PMUs/site
- **Controller reads 8 PMUs every update cycle (16.67 ms)**
  - **4 North and 4 South**
  - **16 possible PMU feedback pairs**
- **These 16 real-time feedback pairs, constructed in parallel, are prioritized off-line based on simulation studies.**
- **Controller continuously re-evaluates rankings of all 16 pairs based on observed data quality and measured latencies.**
- **Controller seamlessly switches to a different pair based on the most recent rankings of the 16 pairs.**

Index	North PMU	South PMU
1	North Site 1, PMU 1	South Site 1, PMU 1
2	North Site 1, PMU 1	South Site 1, PMU 2
3	North Site 1, PMU 2	South Site 1, PMU 1
⋮	⋮	⋮
16	North Site 2, PMU 2	South Site 3, PMU 1



Supervisory System Ensures “Do No Harm”



Watchdog Circuit: Detects hardware failures, ensures smooth state transitions, handles E-stop functions.

Real-time Supervisor: Monitors latencies and data quality, switching to other PMU sites if needed.

Asynchronous Supervisor: Estimates gain/phase margin, PDCI health, slower-than-real-time tasks.

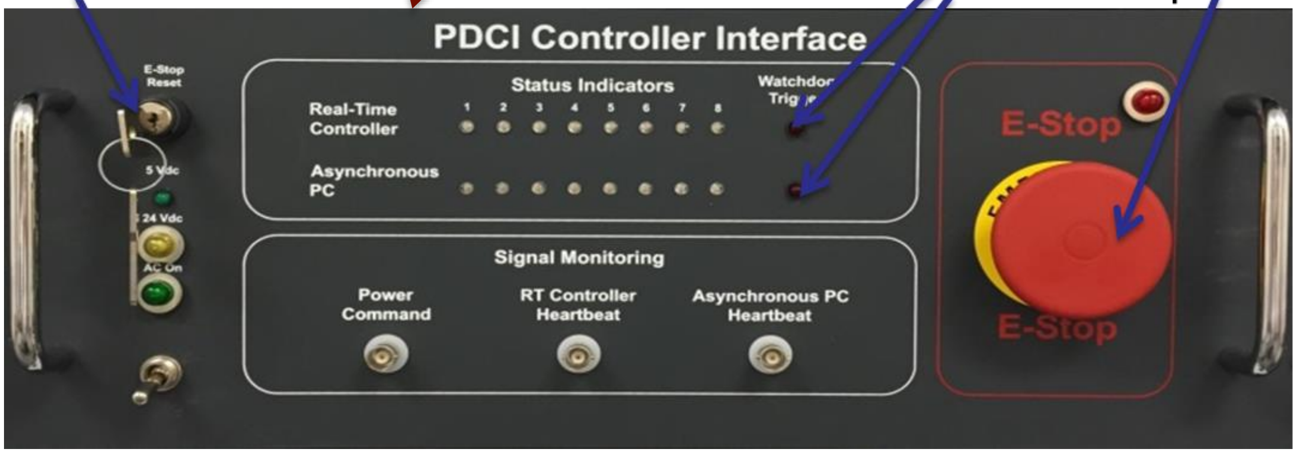
Damping Controller Hardware

Watchdog circuit module

Key switch

Heartbeat indicators

E-Stop button

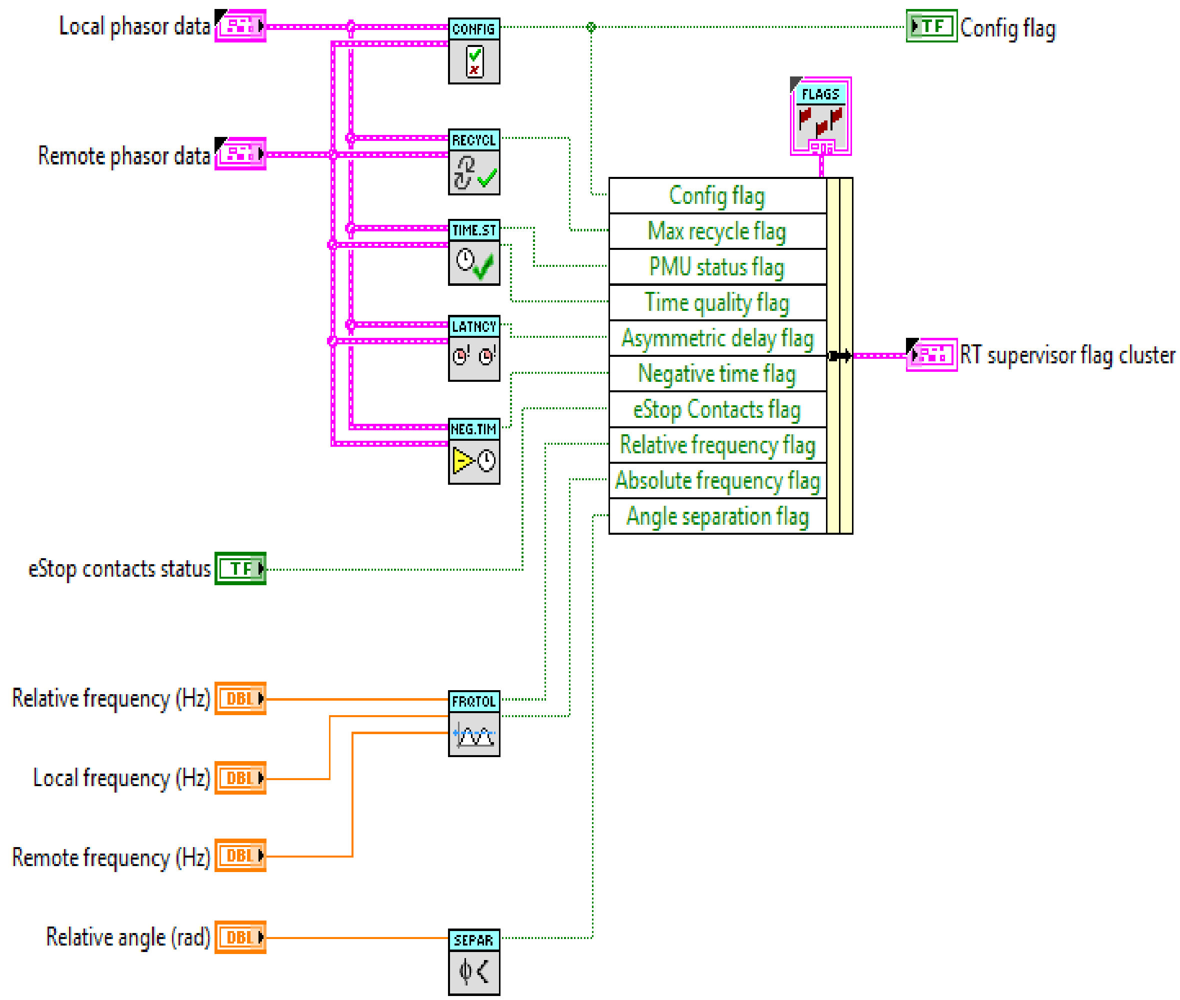


Server for select supervisory functions

Real-time Control platform

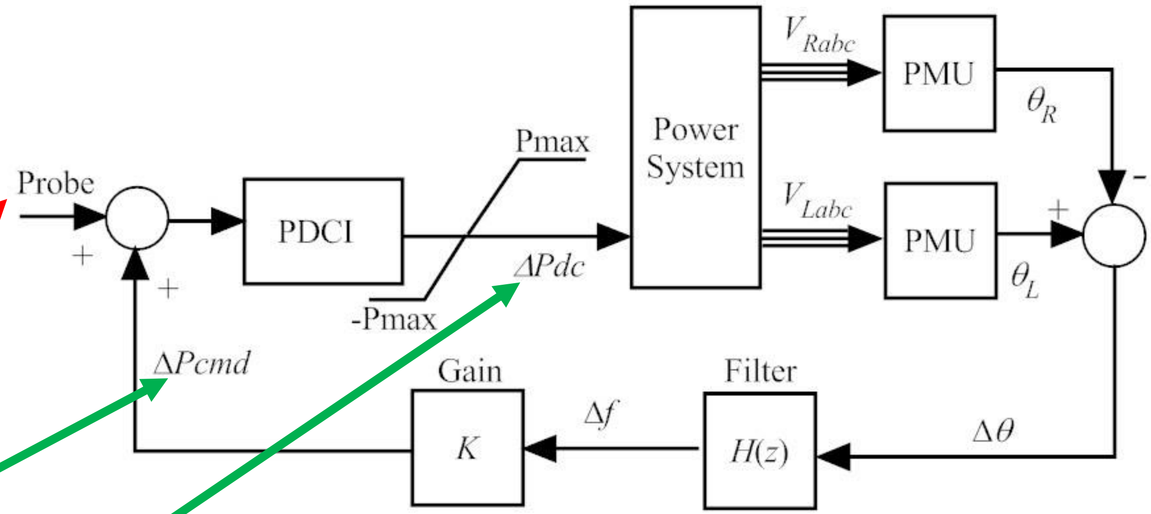
Real-Time Supervisory Checks

- **Immediately disarms controller if any abnormal condition is detected**
- **Oscillation detection**
  - Disarm controller if out-of-band oscillations are detected in feedback signal or on PDCI
- **Islanding detection**
  - Disarm controller if islanding between local and remote signal locations is detected
  - Uses local, remote, relative frequencies, and relative angle tolerances to detect islanding
- **PMU validity and time latency management**
  - Bumpless switching between feedback pairs
  - Disarm controller if no pairs available
- **Emergency stop**



Asynchronous Supervisor

- **Gain/Phase margin monitoring**
  - Assures controller is **NOT** destabilizing any modes
  - Requires periodic low-level probing
- **PDCI monitoring**
  - Makes sure commanded modulation is entering PDCI system



All Planned Experiments on the Grid were Extensively Simulated

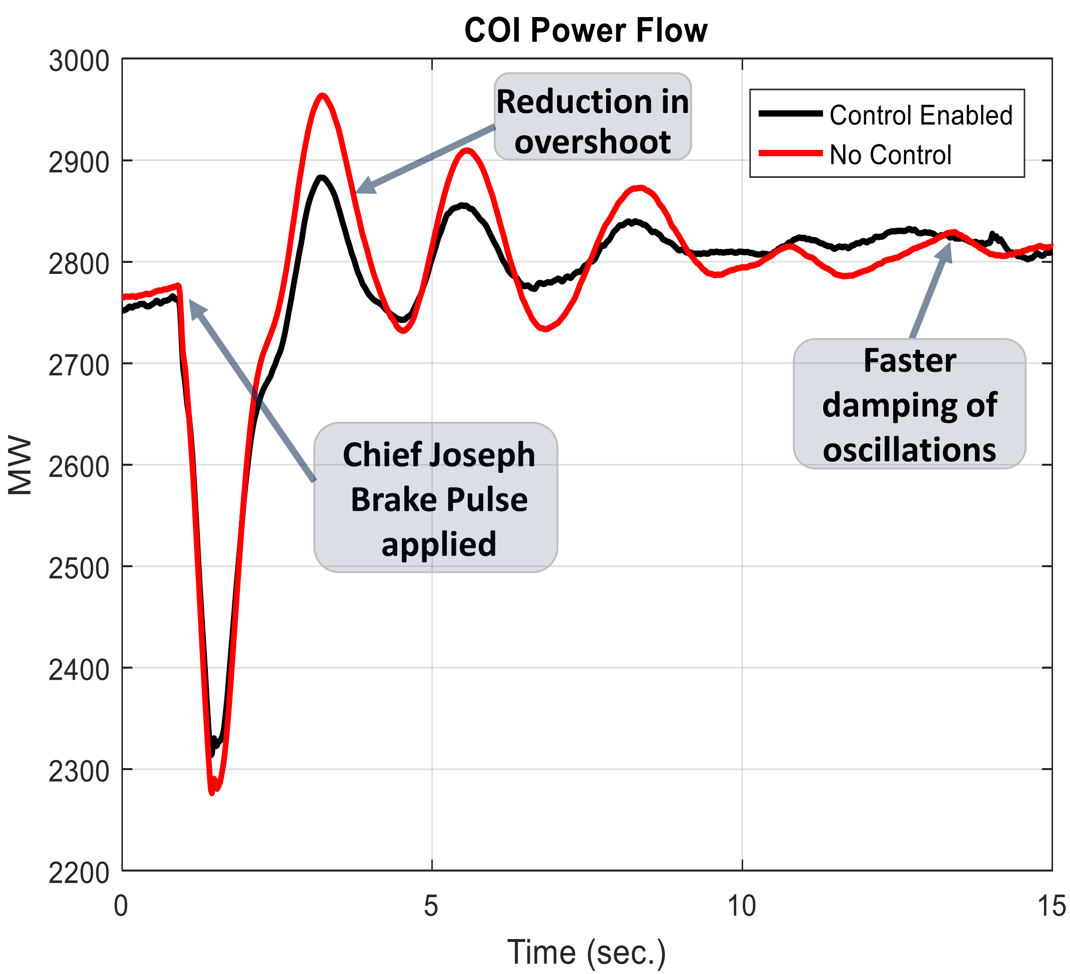
- Three base cases, Heavy Summer 2016, Light Summer 2016, Dual Export 2014 were used to simulate controller performance in four test sequences:
  1. Negative Gain Testing
  2. Controller Limits with Large Gain Values
  3. Chief Joseph Brake Duration Comparison
  4. Forced Oscillations (30 MW probing at wide range of frequencies)
- Rare events were added to the studies for analysis of worst case scenarios:
  1. Double Palo Verde Trip
  2. BC-US Separation
  3. BC-Alberta Separation
  4. Chief Joseph Brake Pulse added to each of the above 3 events
- Simulation studies created confidence that tests would be safe & successful
- Test results confirmed the simulations, which helps validate the models

Chief Joseph Dynamic Braking Resistor

- Purpose – Transient Stability: Remedial Action Scheme (RAS) to handle large faults in western grid
- Can dissipate 1400 MW for 0.5 – 1.0 sec
- Side Benefit – Ideal as an impulse response to the grid ➔ Aids system identification and control system testing
- History – Built in early 1970s
- Owned & operated by BPA
- Described in M. Shelton et al., “Bonneville Power Administration 1400-MW braking resistor,” IEEE Trans. Power Apparatus & Syst., vol. 94, no. 2, pp. 606-611, 1975.

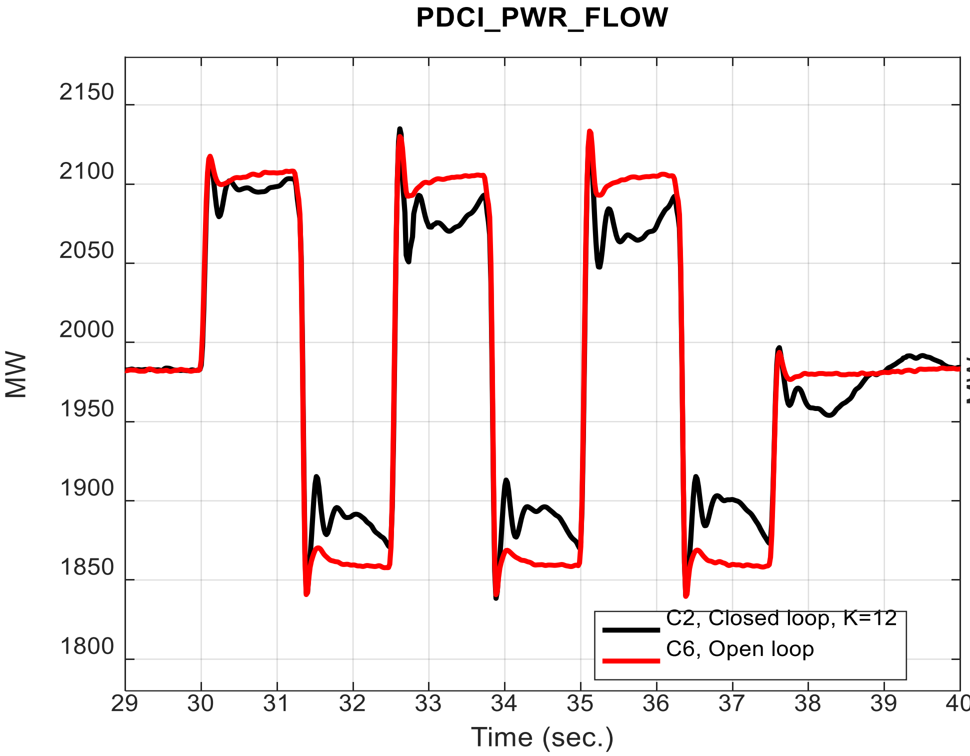
Grid Demonstrations Showed Significant Improvements in Damping with Controller Operational

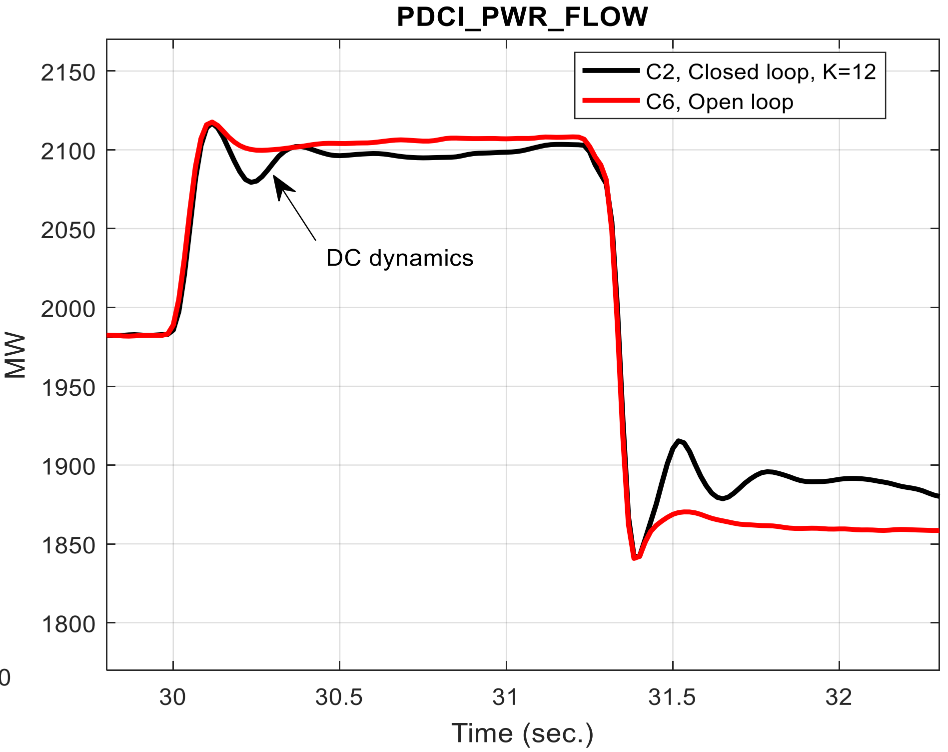
Experiments conducted at Celilo Converter Station Sept 2016, May & June 2017



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.

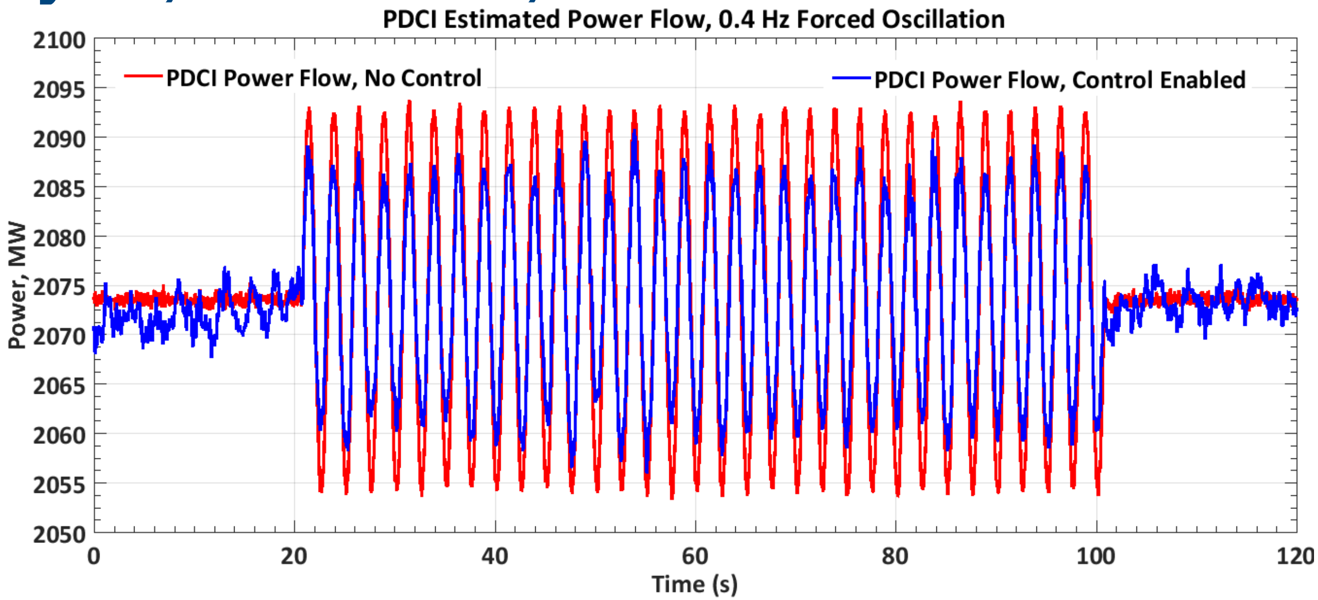
May 16, 2017 Tests, Square Wave Response, Gain = 12 MW/mHz

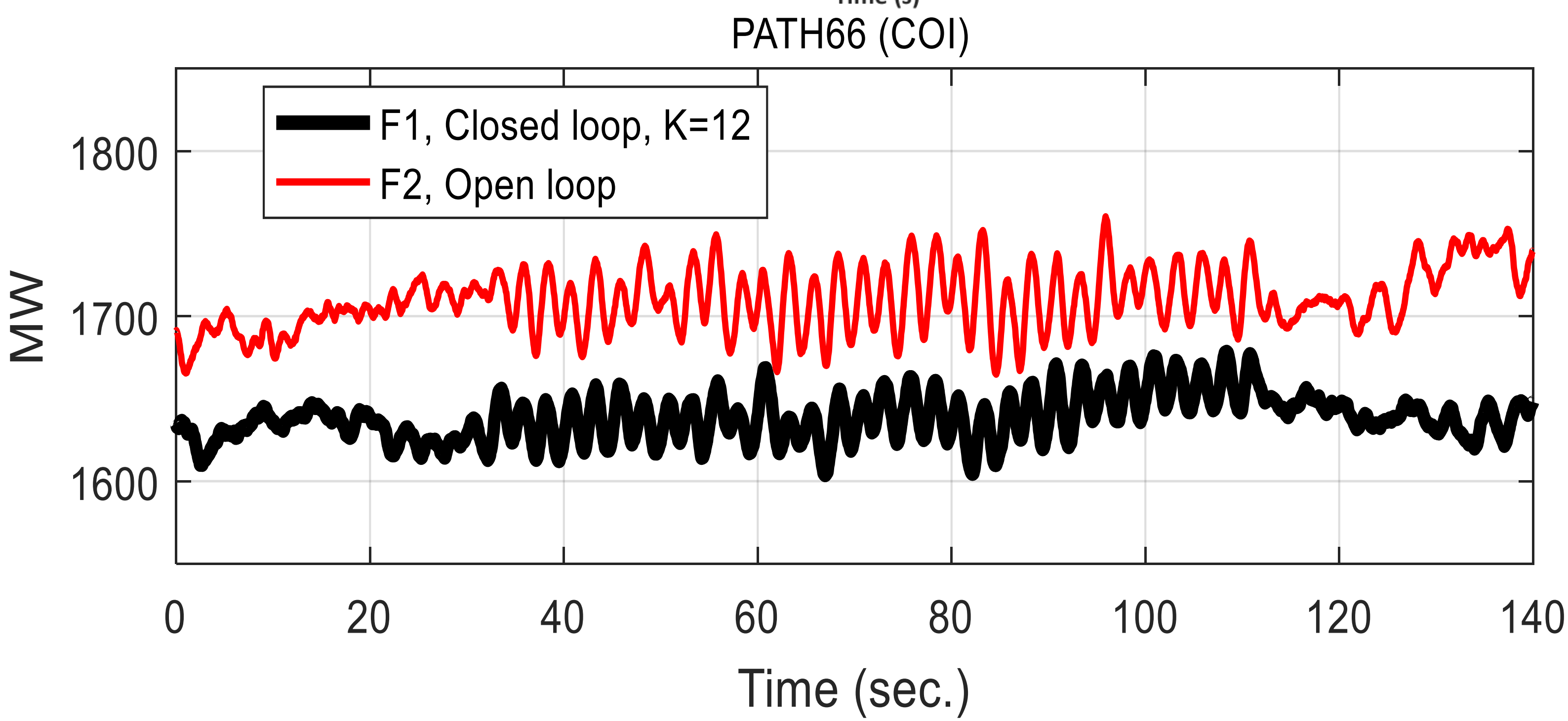




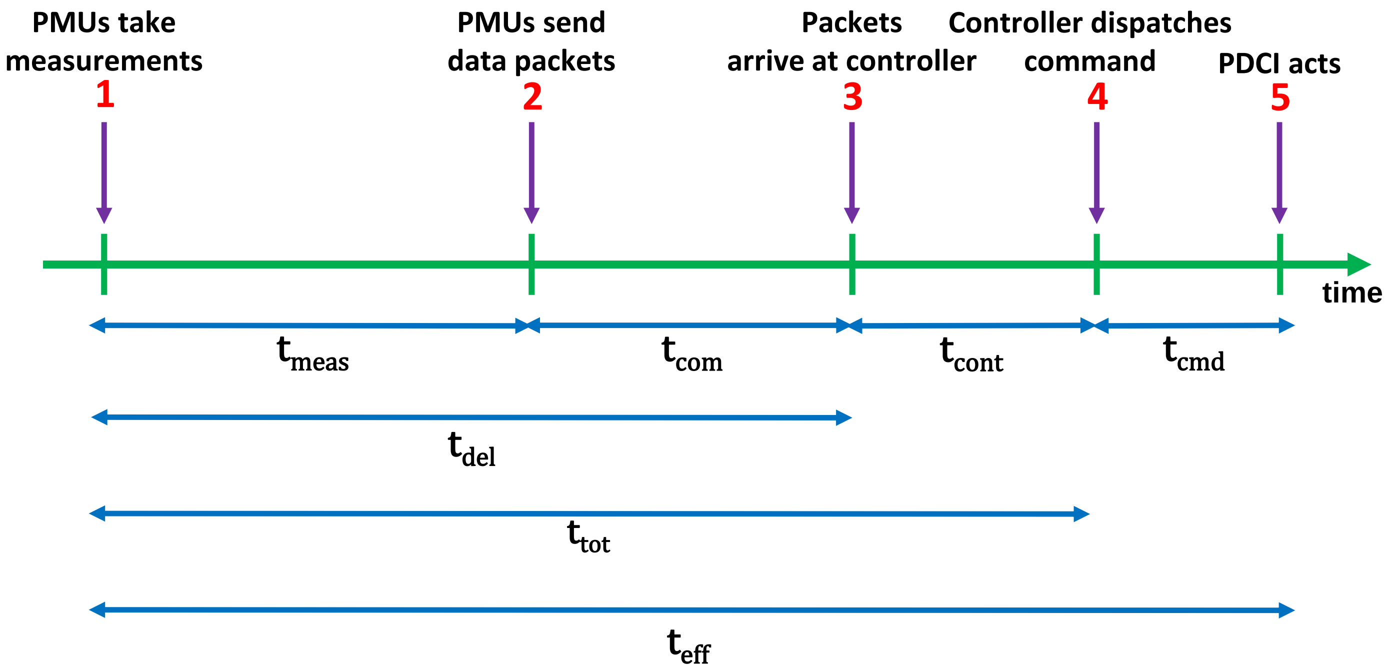
Dynamics of DC system are a factor in selecting controller gain

May 16, 2017 Tests, 0.4 Hz Forced Oscillation





Time Delays in PDCI Damping Control



Symbol	Name	Mean	Range	Distribution
t_{meas}	PMU Delay	50 ms	Assumed fixed at 50 ms	N. A.
t_{com}	Communications Delay	10 ms	[5,38]	Heavy Tail Normal
t_{del}	Signal Delay	60 ms	[55,88]	Heavy Tail Normal
t_{cont}	Control Processing Delay	11 ms	[3,17]	Bimodal Normal with peaks at 8 & 15 ms
t_{tot}	Total Controller Delay	71 ms	[58,102]	Bimodal Normal with peaks at 66 & 73 ms
t_{cmd}	Command Delay	Estimated at 11 ms	Assumed fixed at 11 ms	N. A.
t_{eff}	Effective Delay	82 ms	[69,113]	Bimodal Normal with peaks at 77 & 84 ms

Conclusion: Round trip time delays < 100 ms ➔ well within bounds for robust closed-loop control

Summary of Project Accomplishments

- First successful demonstration of wide-area control using real-time PMU feedback in North America ➔ Design expertise in using PMUs for control can be leveraged by other applications.
- Experience gained in networked controls will advance control design using other network-enabled assets, such as energy storage, smart inverters, and demand response.
- Supervisory system architecture and design can be applied to future real-time grid control systems to ensure “Do No Harm”.
- 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.

2017 R&D 100 Award Winner

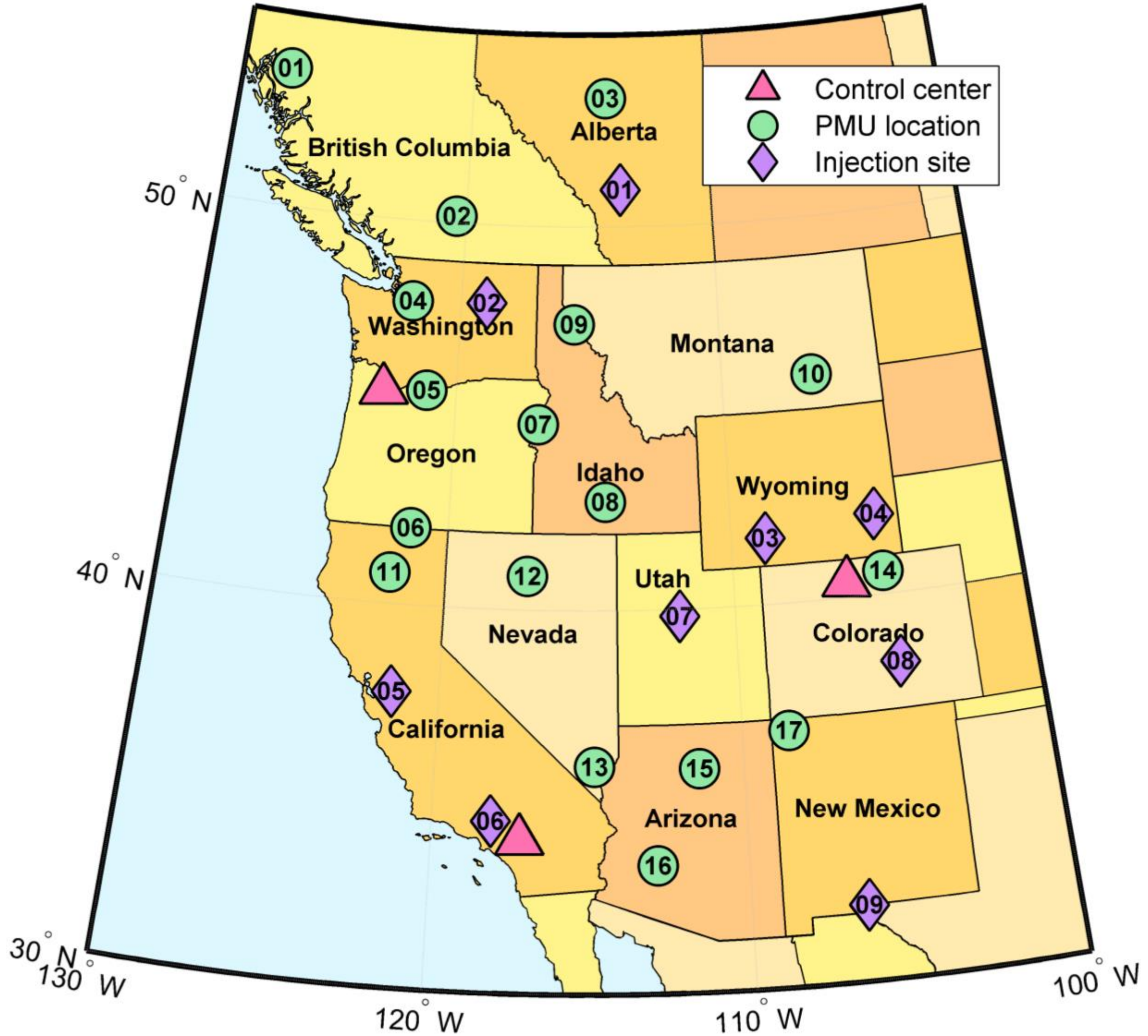
Ongoing & Future Research

- Distributed controls – leverage large #'s of assets (sensors and actuators) over a wide area to improve performance of grid control systems.
- Networked controls – improve performance of grid control systems through the use of sensors and actuators connected by communication networks.
- Scalable, modular architectures – create reusable and reconfigurable architectures to standardize design and grid integration of distributed controls.
- Cyber security – the reliance on communication networks for feedback information must be robust to delays, lost or corrupted data, natural disasters, malicious attacks (spoofing, denial of service), etc.

Multi-Node Distributed Control

Advantages:

- Robust to single points of failure
- Controllability of multiple modes
- Size/location of a single site not as critical as more distributed energy resources are deployed

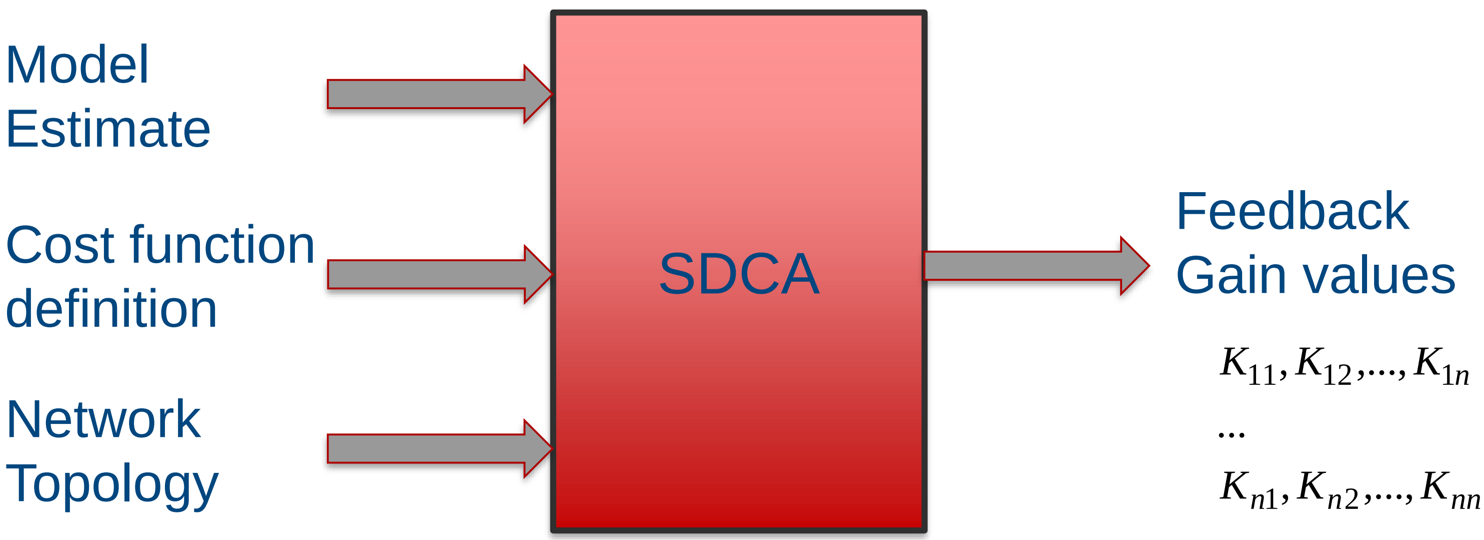


Multi-Node Distributed Damping

- Multi-node damping provides redundancy and improved controllability of multiple modes
  - Work is underway to develop a scalable *N*-node damping control scheme based on distributed energy storage with “Tailored Gains”
  - Each node modulates power based on local PMU and multiple remote PMU measurements

$$\Delta P_i = -\sum_{j=1}^{n} K_{d,ij} f_i$$

- Gains are computed using a Structured Damping Control Algorithm (SDCA)



An Optimization Problem is Formulated

- To attain the control law $u_d = -K_d y$

$$\underset{K_d}{\text{minimize}} \quad J = \int_0^{T_f} \left(x^T Q x + u_d^T R u_d \right) d\tau$$

$$\text{subject to:}$$

$$(1)\ \dot{x}(t) = Ax(t) + B_q q(t) + B_d u_d(t)$$

$$(2)\ y(t) = \begin{bmatrix} \Delta\omega_1 & \Delta\omega_2 & \cdots & \Delta\omega_m \end{bmatrix}^T$$

$$(3)\ u_d(t) = -K_d y(t)$$

$$(4)\ Q \geq 0, R > 0$$

- The above optimization problem must be solved iteratively
- For solution details, see the recent journal paper:

J. Neely, J. Johnson, R. Byrne, and R. 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*, vol. 11, no. 1, pp. 69-94, 2015.

Example using Distributed Energy Storage

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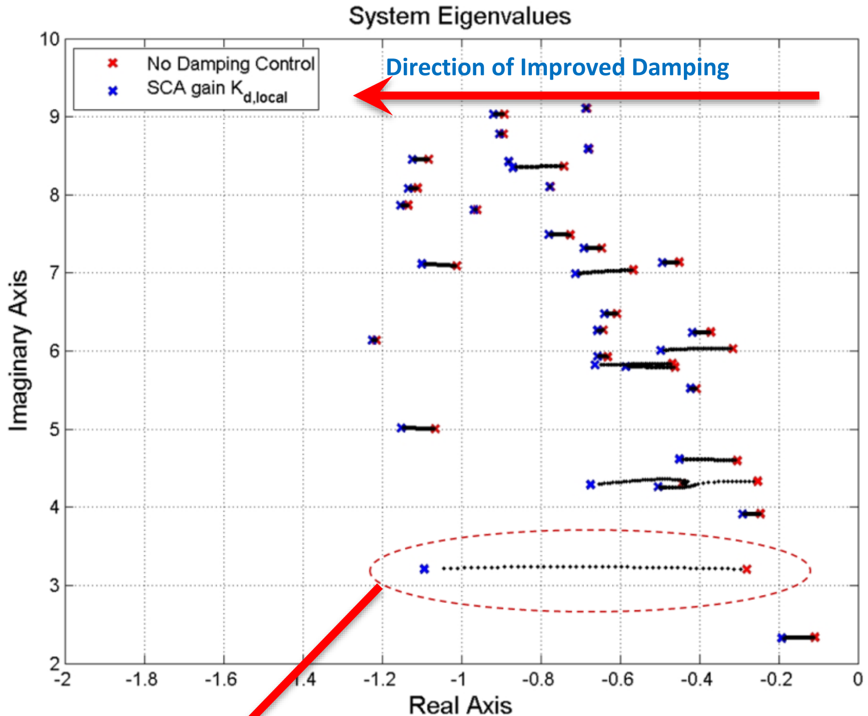
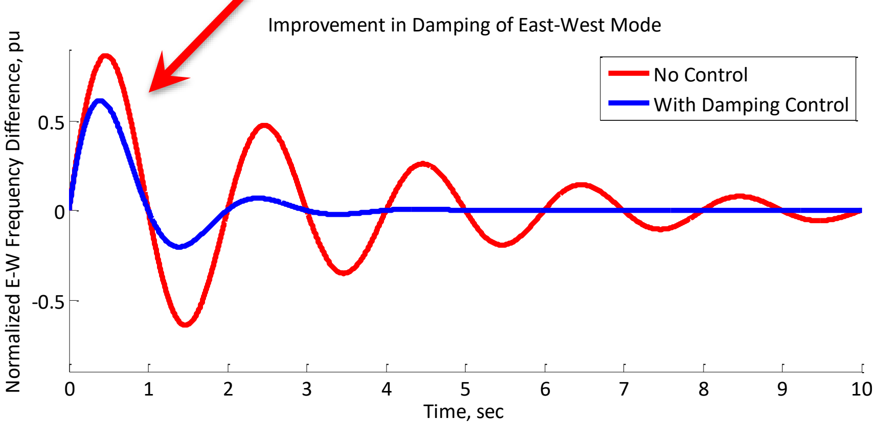
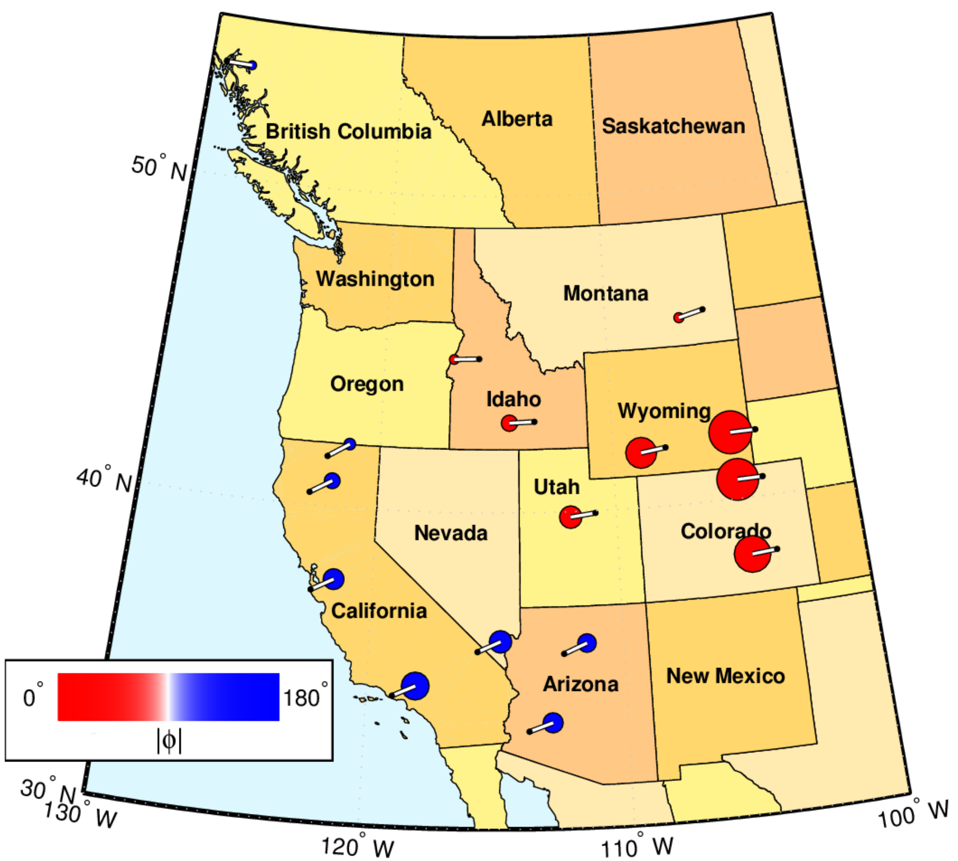
- Total real power capacity on order of 20 – 50 MW is sufficient
- With 10s of sites deployed, individual resource capacity ≤ 1 MW will work

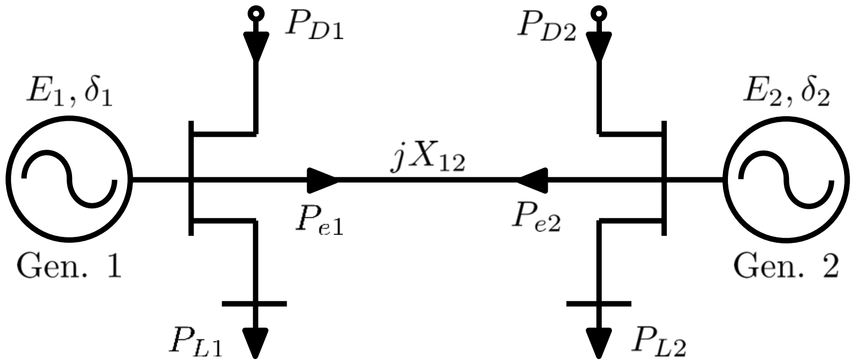




East-West Mode



Impact of Network Delays on Stability of Oscillations in a Two-Area Power System



Dynamics:

$$\dot{\delta}_i = \omega_i$$

$$2H_i\dot{\omega}_i = P_{mi} - P_{ei} - \frac{D_i}{R_i}\omega_i - P_{Li} + P_{Di}$$

Controlled injections:

$$P_{D1}(t) = -k_d\big(\omega_1(t-\tau_1) - \omega_2(t-\tau_2)\big)$$

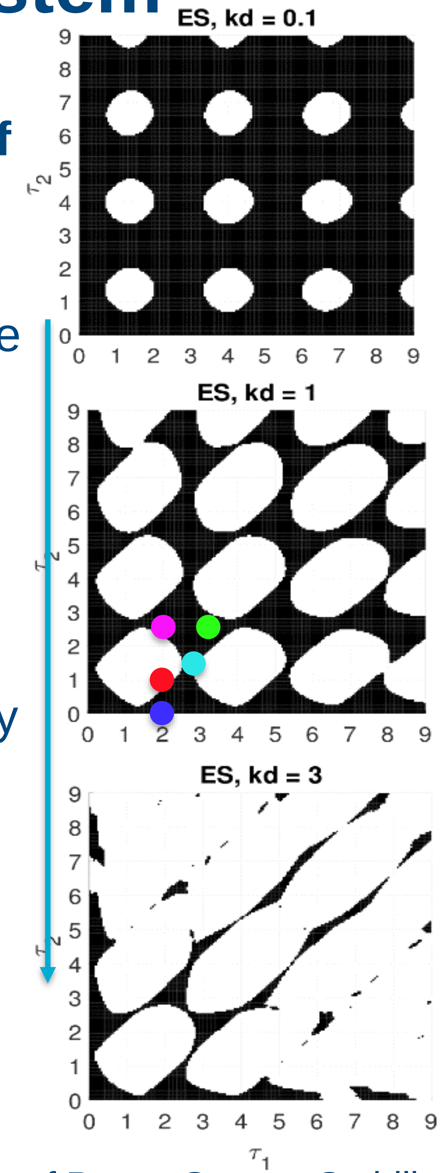
$$P_{D2}(t) = k_d\big(\omega_1(t-\tau_2) - \omega_2(t-\tau_1)\big)$$

Regions of Stability

Black: Stable

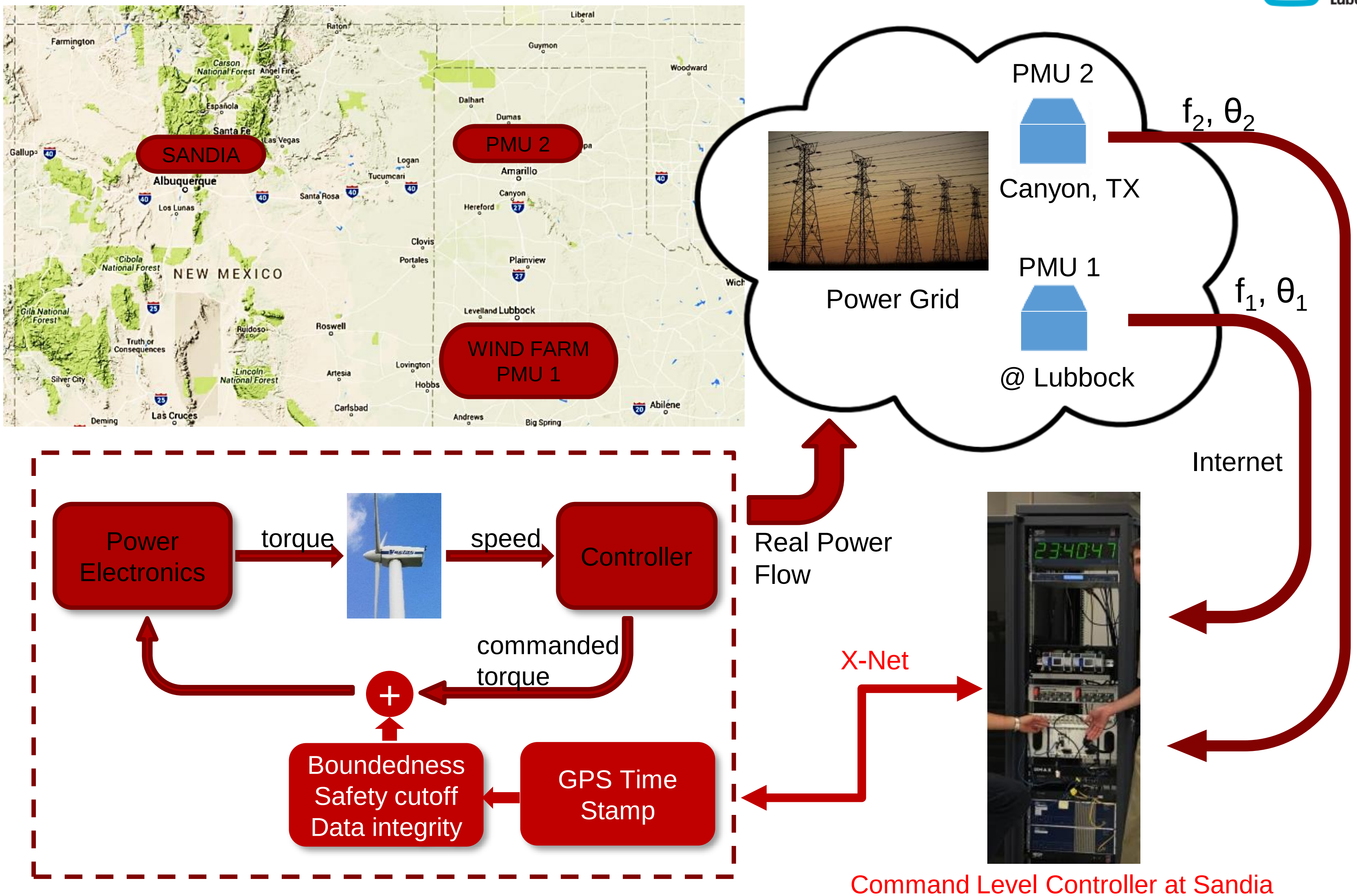
White: Unstable

In the presence of delays, increasing damping may lead to instability.



D.A. Copp, F. Wilches-Bernal, I. Gravagne, D.A. Schoenwald. Time-Domain Analysis of Power System Stability with Damping Control and Asymmetric Feedback Delays. *49th North American Power Symposium*, 2017.

Network-Based Modulation of Power in Wind Turbines



- Modulation of wind power implemented in turbine nacelle at wind farm in Lubbock, TX.
- Command level controller implemented at Sandia in Albuquerque, NM.
- Successful demonstration of coordinated control strategy on Sept. 28, 2017.
- Outcome is scalable, giving wind operators the opportunity to provide valuable grid services.