DOE/OE Transmission Reliability Program

Wide-Area Damping Control Proof-of-Concept Demonstration

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Project Team

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  - DOE-OE Energy Storage Program – PM: Imre Gyuk
  - BPA Office of Technology Innovation – CTO: Terry Oliver

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PDCI Damping Controller Overview

Problem:

- Poorly damped inter-area oscillations jeopardize grid stability and can lead to widespread outages during stressed grid conditions
- Oscillation stability limits constrain power flows well below transmission capacity: Inefficient use of expensive infrastructure investments

Solution:

- Construct closed-loop feedback signal using real-time PMU data: 1st demonstration of this in North America
- Modulate power flow on PDCI (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

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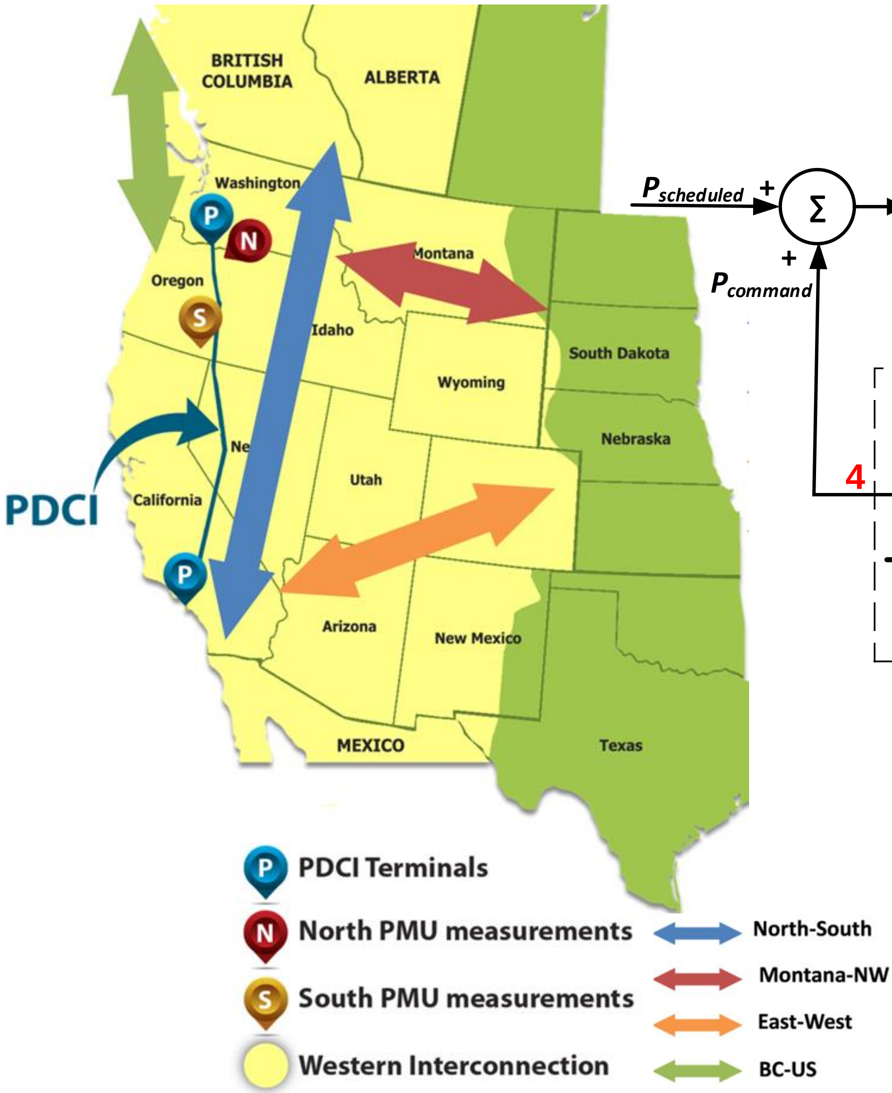
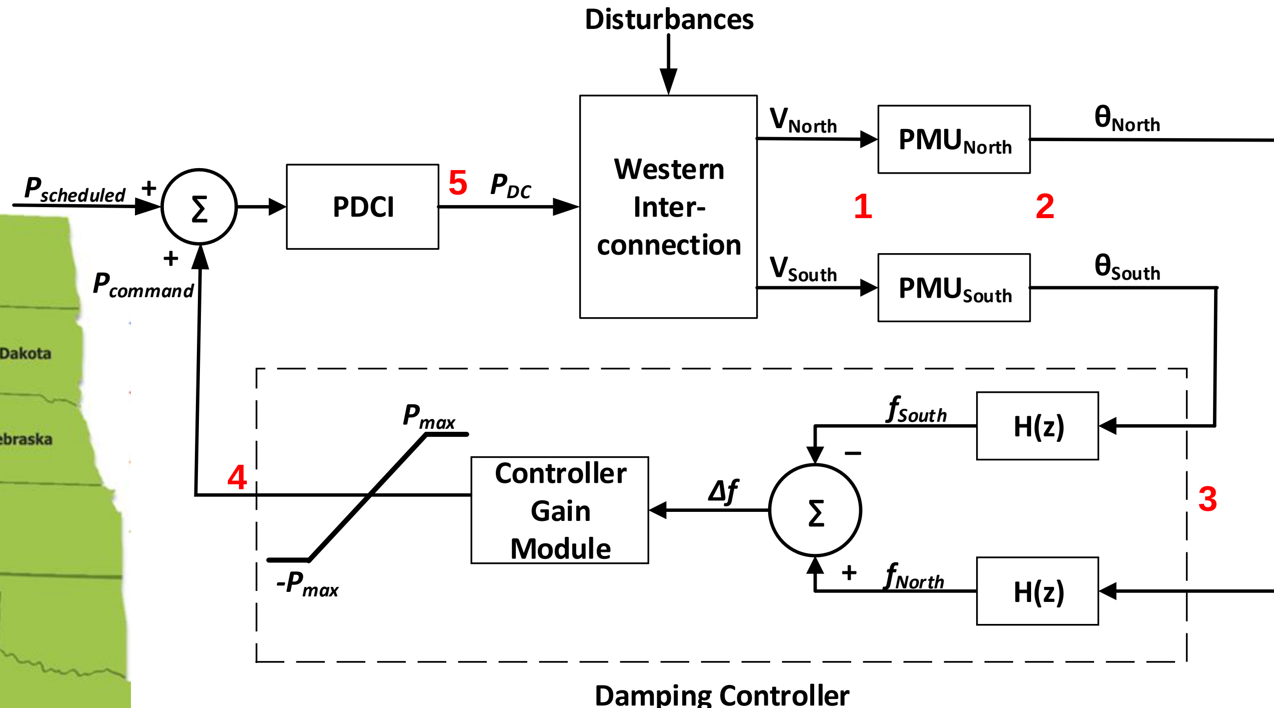
Damping Controller Strategy





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

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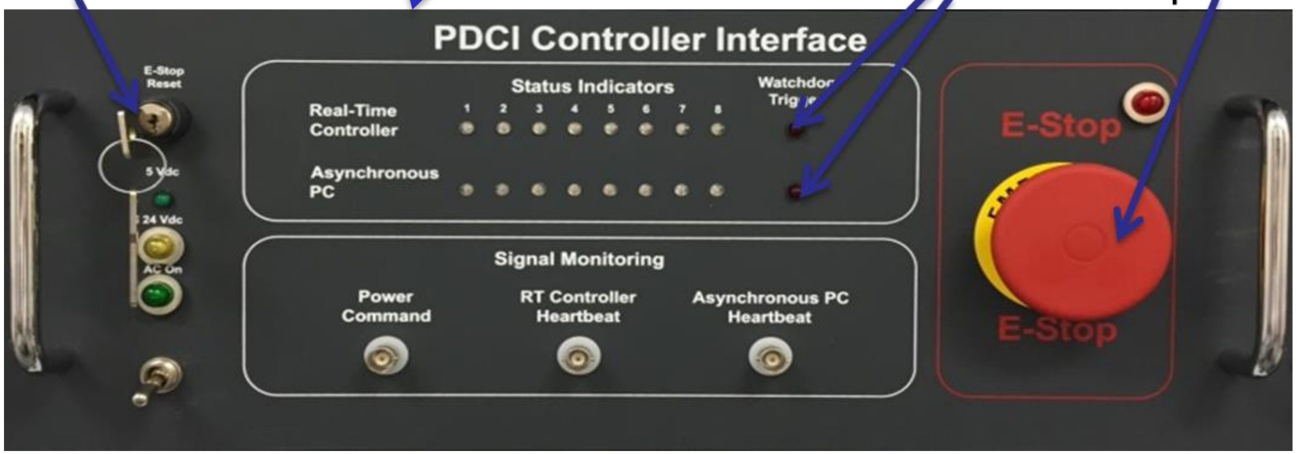
Damping Controller Hardware

Watchdog circuit module

Key switch

Heartbeat indicators

E-Stop button



Server for select supervisory functions

Real-time Control platform

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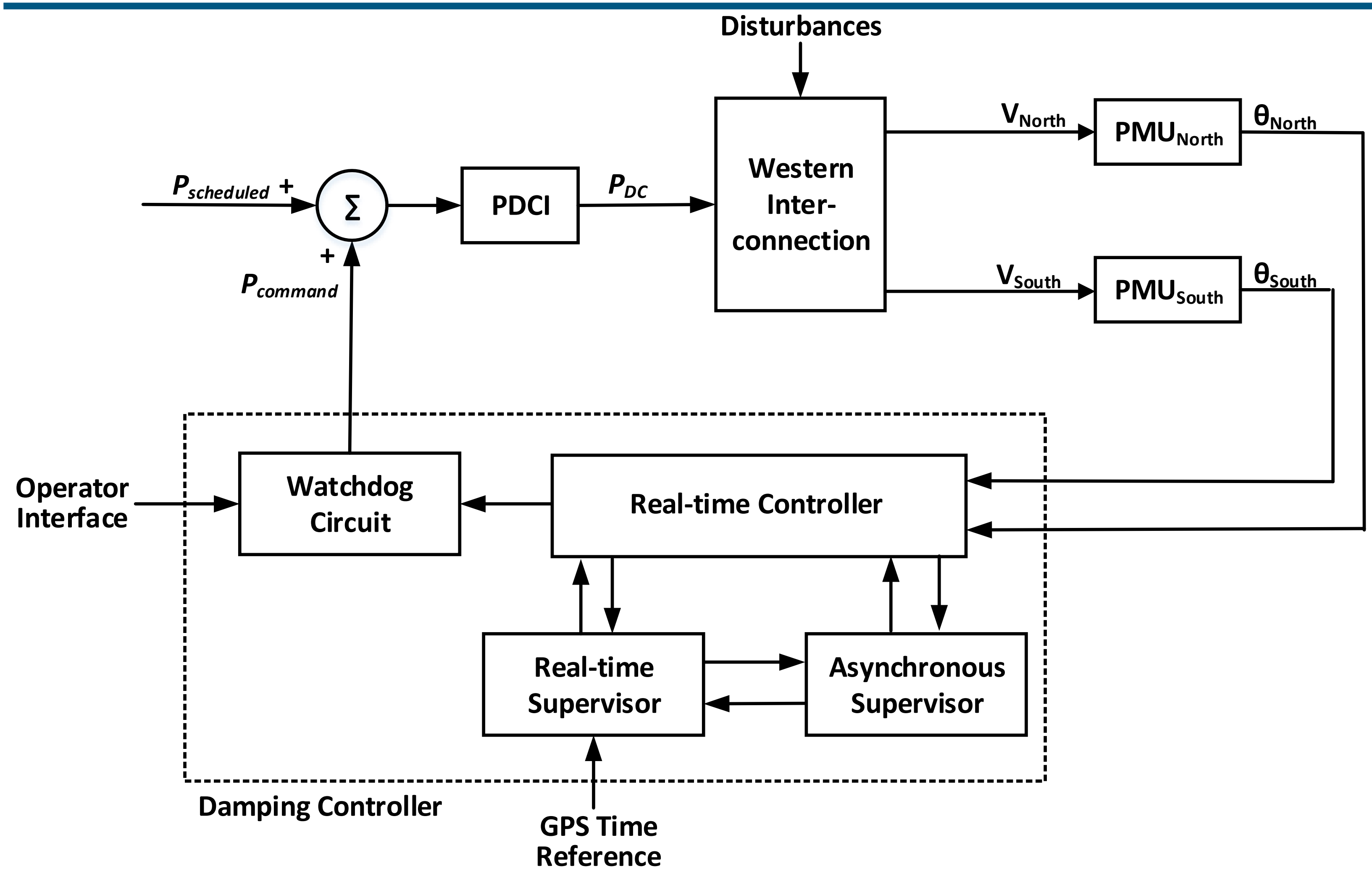
Supervisory System Ensures "Do No Harm"



Watchdog Circuit: Detects hardware failures, ensures smooth state transitions, and 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, and slower-than-real-time tasks.

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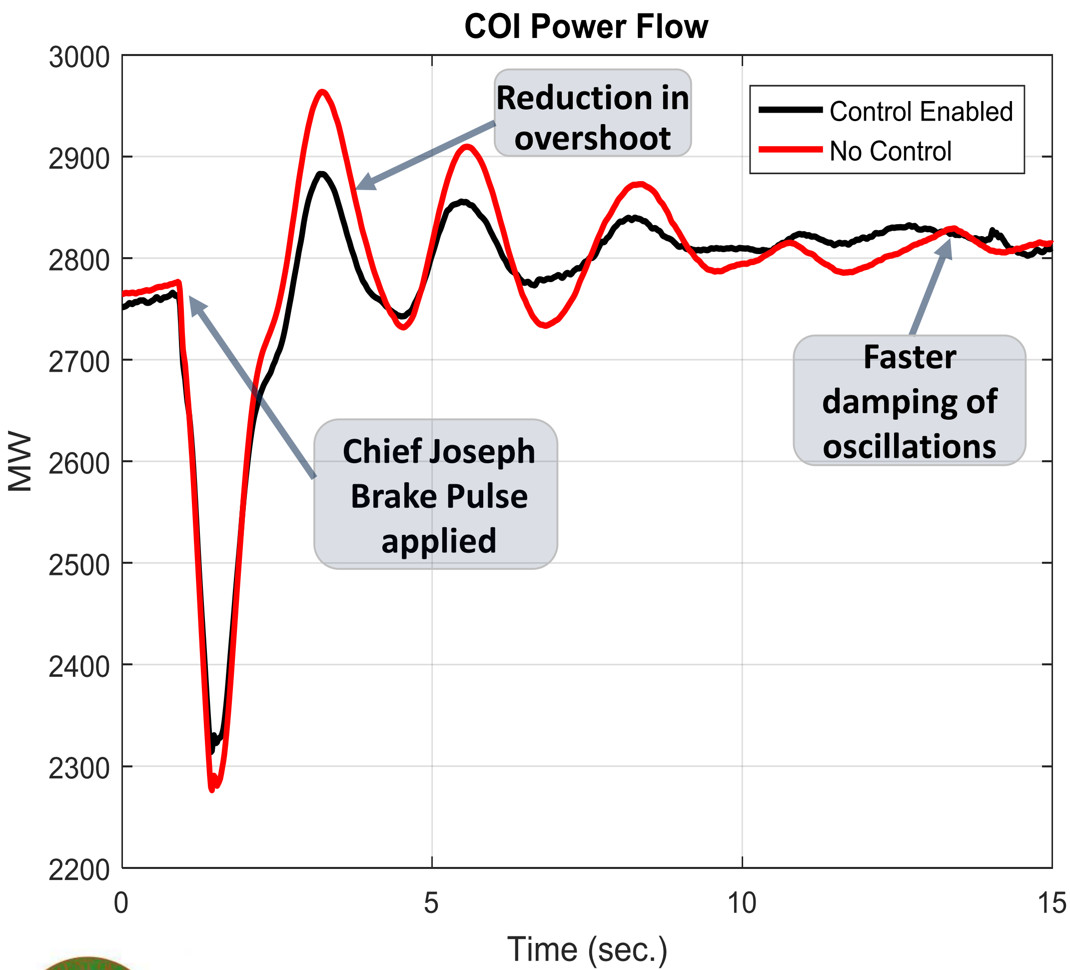
2016 Closed-Loop Tests Showed Significant Damping Improvements

Tests conducted at Celilo Converter Station on September 28-29, 2016



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.

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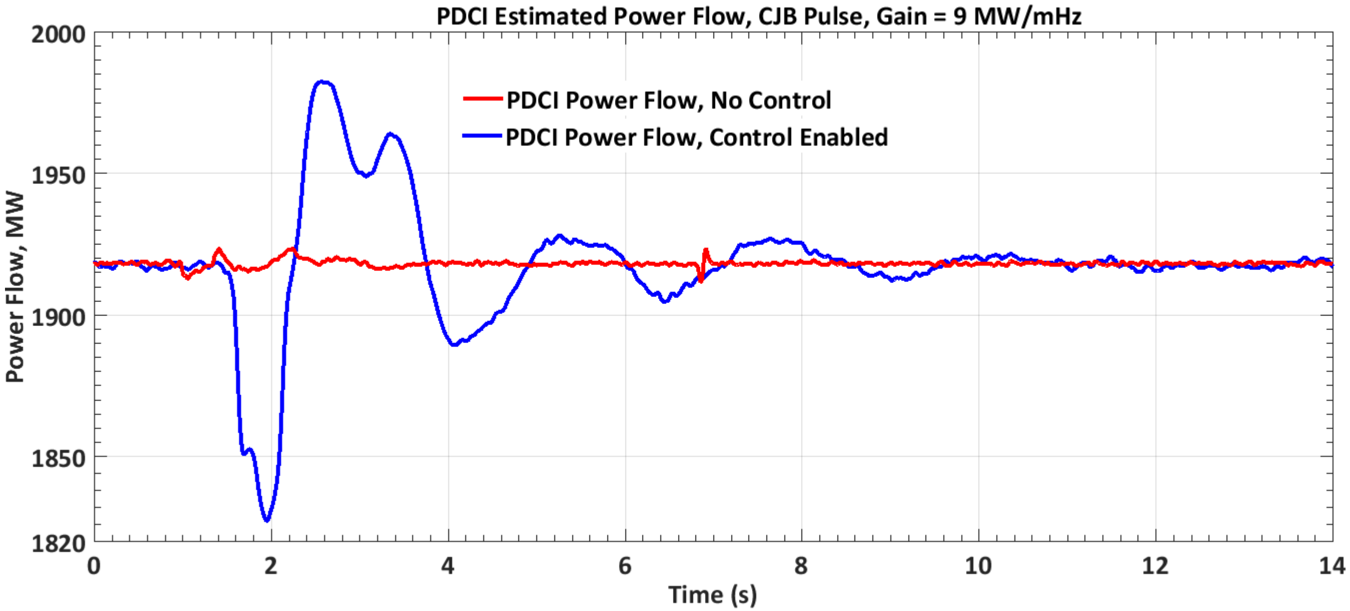
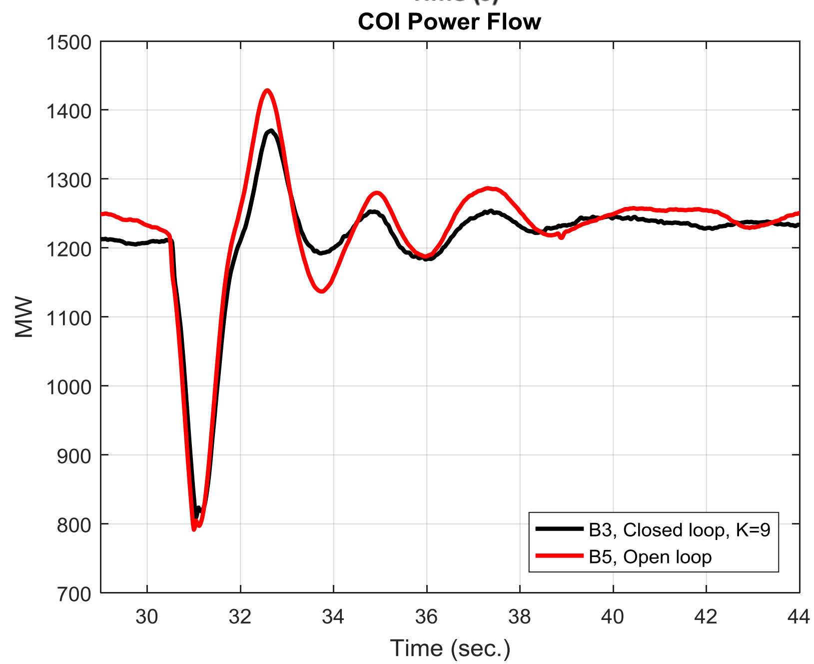
May 16, 2017 Tests, CJB Pulse, Gain = 9 MW/mHz





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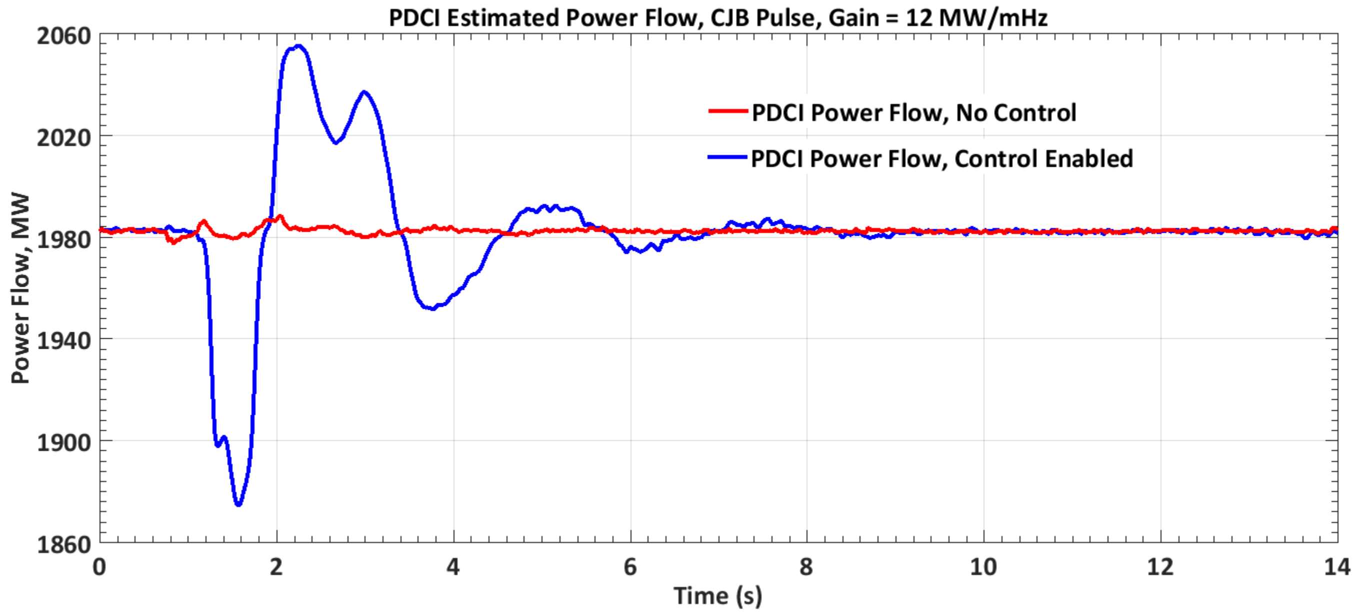
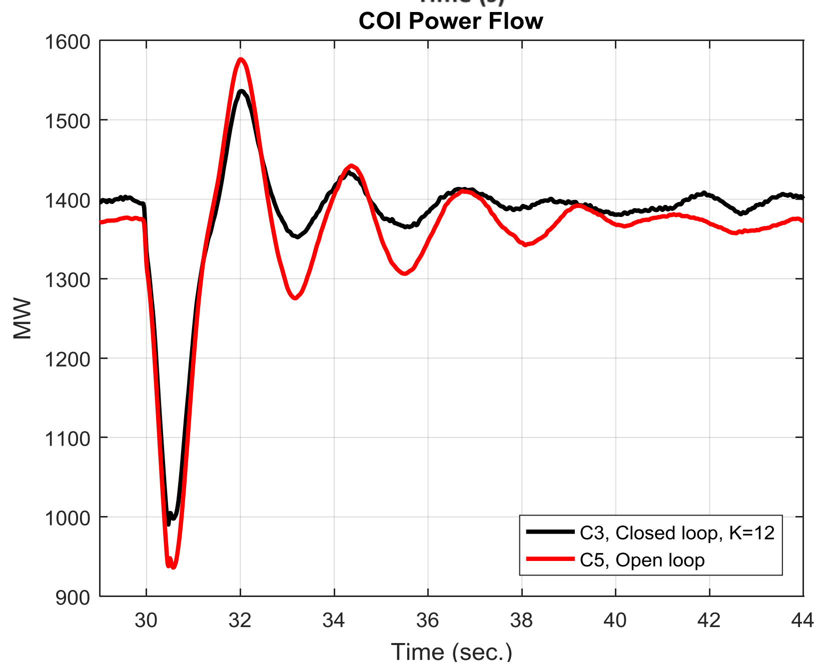
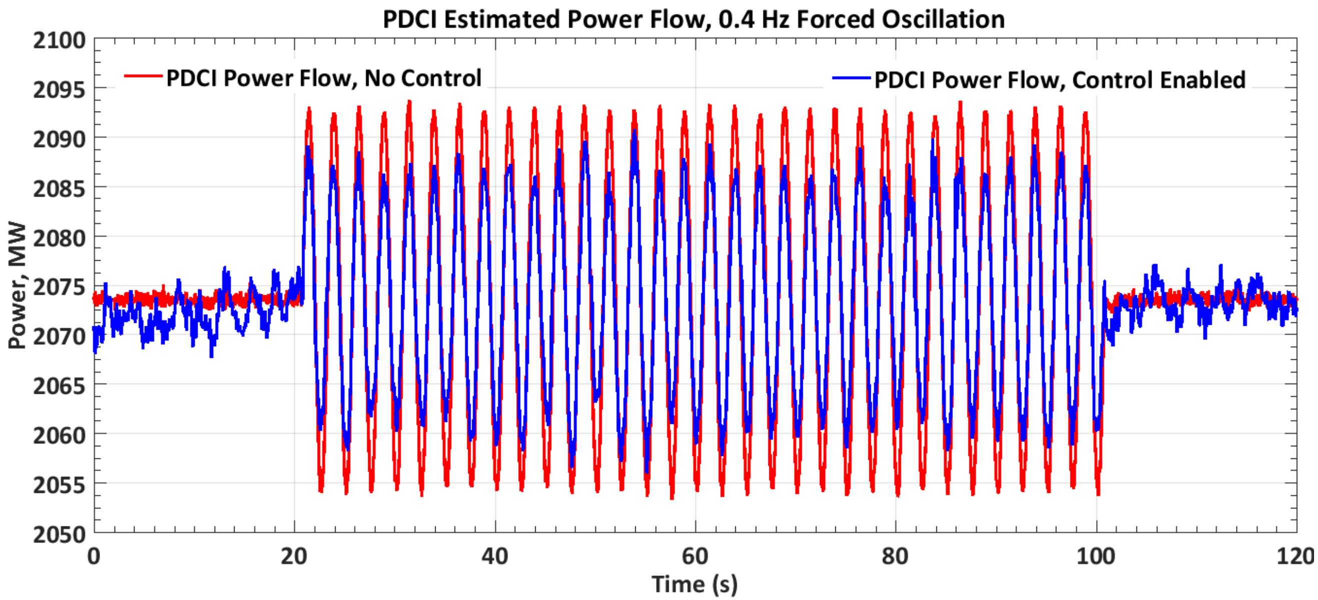
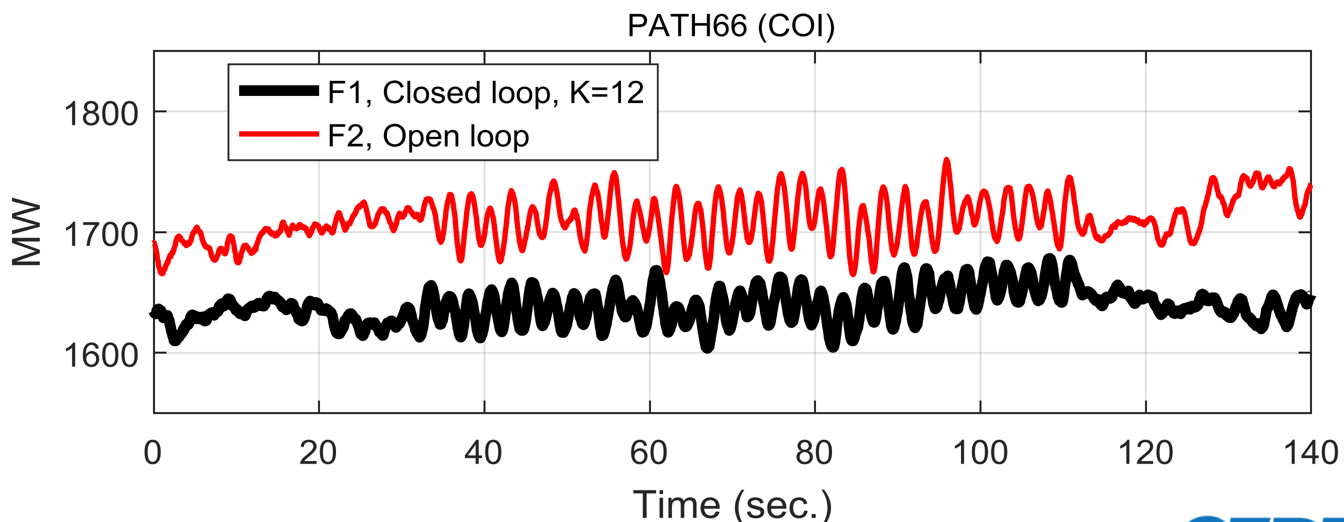
May 16, 2017 Tests, CJB Pulse, Gain = 12 MW/mHz





May 16, 2017 Tests, 0.4 Hz Forced Oscillation





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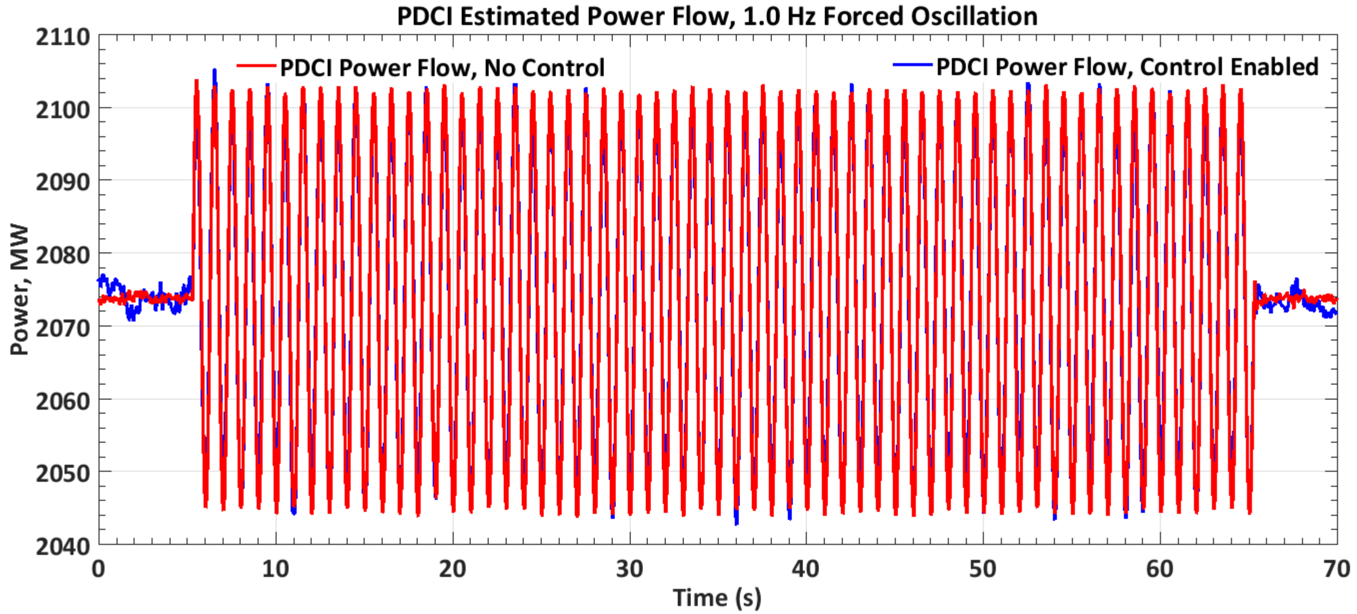
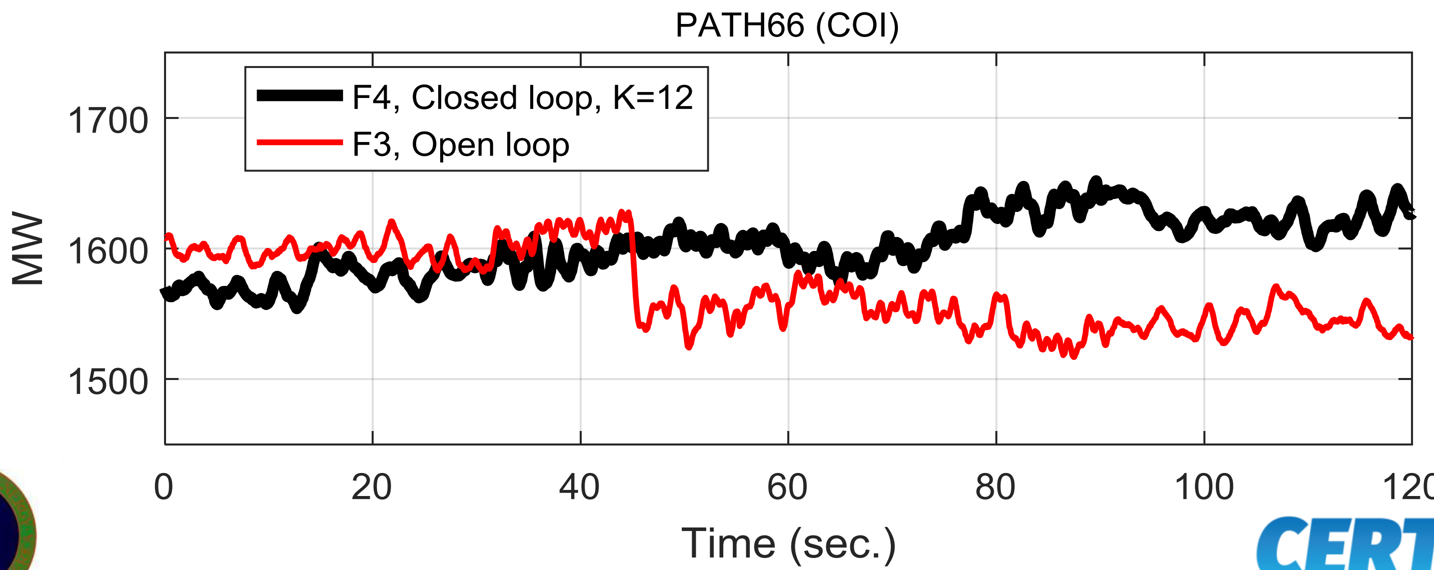
May 16, 2017 Tests, 1.0 Hz Forced Oscillation





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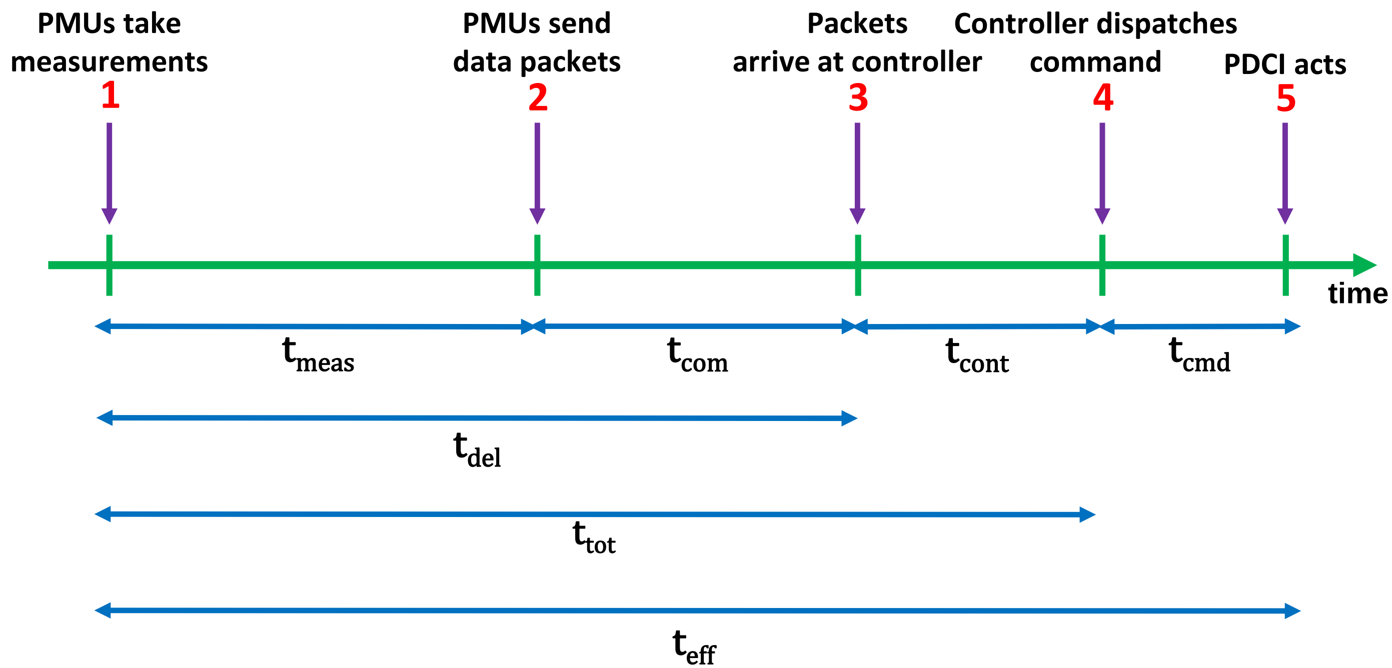
Time Delays in PDCI Damping Control



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 delays < 100 ms → well within tolerances for robust feedback control

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All Planned Tests Have Been Extensively Simulated

- Three WECC PSLF base cases: **Heavy Summer 2016, Light Summer 2016, Dual Export 2014** are 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** are added to the simulations for the negative gain and controller limits tests:
  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

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2017 PDCI Testing Schedule

Phase 1: Active Short-Term Open & Closed-Loop Tests

- **Completed on Tuesday, May 16, 2017**

Phase 2: Active Medium-Term Closed-Loop Test

- **Started on Tuesday, June 6, 2017, 10:33 a.m. PDT**
- **Ended on Wednesday, June 7, 2017, 12:00 p.m. PDT**

Phase 3: Similar to Phase 1 to be Conducted Later in Season

- **Scheduled Dates: TBD** – Later in summer season preferably to coincide when Alberta is disconnected
- Phase 3 is very similar to Phase 1 except forced oscillations are induced from BPA-connected generators

Phase 4: Active Long-Term Closed-Loop Test

- **Scheduled Dates: TBD** – This will be a longer test than Phase 2 (several weeks in length)

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Takeaways from PDCI Tests Conducted Thus Far

- Three phases of tests conducted on PDCI (Sept 2016, May 2017, and June 2017) have shown significant improvements in N-S B mode damping
- Test results have shown no degradations in damping of peripheral modes
- Test results have shown improved damping for forced oscillations < 1 Hz without worsening damping at > 1 Hz
- Test results have consistently confirmed the findings of simulation studies
- Time delays have been well within tolerances
- Supervisory system has performed exactly as expected

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R&D Tasks Needed to "Operationalize" Controller

- **Testing & Network Characterization**
  - Long-term performance testing and analysis of results
  - Network latency characterization and mitigation strategies for bad data
- **Cyber Security**
  - Follow process used by RAS systems
  - Investigate time synchronization
- **Test Automation Unit**
  - Stand-alone unit to fully check out controller modes of operation
  - Needed for RAS consideration
- **Operation under PDCI Constraints**
  - Control design for PDCI flows at limits
  - Design for current limits (AC-VDCOL)
- **RTDS Studies**
  - Exercise controller for scenarios on DC side to analyze PDCI dynamics
  - Support studies of PDCI operation
- **Model Development**
  - Models needed to support wNAPS utilities and regulatory compliance
  - Pursue WECC approvals
- **Monitoring System**
  - Operator interface conveying current status, recent events, and other pertinent information
  - Incorporates ability to quickly retrieve more detailed information

Project Publications & Presentations in FY17

1. Schoenwald et al., "Design and Implementation of a Wide-Area Damping Controller Using High Voltage DC Modulation & Synchrophasor Feedback," IFAC World Congress, Toulouse, France, July 2017.
2. Wilches-Bernal et al., "Effect of Time Delay Asymmetries in Power System Damping Control," IEEE Power & Energy Society General Meeting, Chicago, IL, July 2017.
3. ***Wilches-Bernal et al., "Time Delay Definitions and Characterizations in the Pacific DC Intertie Wide Area Damping Controller," IEEE Power & Energy Society General Meeting, Chicago, IL, July 2017.**
4. Trudnowski et al., "Initial Closed-Loop Testing Results for the Pacific DC Intertie Wide Area Damping Controller," IEEE Power & Energy Society General Meeting, Chicago, IL, July 2017.
5. Pierre et al., "Simulation Results for the Pacific DC Intertie Wide Area Damping Controller," IEEE Power & Energy Society General Meeting, Chicago, IL, July 2017.
6. Schoenwald et al., "Test Results for the Pacific DC Intertie Wide Area Damping Controller," submitted to the *IEEE Transactions on Power Systems*, June 2017.
7. Pierre et al., "Open-Loop Testing Results for the Pacific DC Intertie Wide Area Damping Controller," 12th IEEE Power & Energy Society PowerTech Conference, Manchester, UK, June 2017.
8. Schoenwald, "WECC-BPA Project Using PMU Data to Damp Inter-Area Oscillations," Invited Talk, CURENT Industry Conference, Knoxville, TN, November 2016.

***Selected for Best Paper Session on Power System Stability, Control, and Protection, IEEE PES General Meeting, Chicago, IL, July 2017.**

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Impact of Project Results on Future Grid Controls

- First wide-area controller using real-time PMU feedback in North America → Design expertise in using PMUs for control can be leveraged by other projects on a rapidly evolving network-enabled grid.
- Experience gained in networked controls will advance distributed control of networked assets (energy storage, smart inverters, DG, demand response).
- Supervisory system architecture and design process can be applied to real-time control systems for other grid functions.
- 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.