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Sandia National Laboratories

# Wide-Area Damping Control Using PMU Feedback

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## Oscillations Analysis Work Group (OAWG)
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# Acknowledgements and Contributors

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- **Montana Tech:**
  - Dan Trudnowski (co-PI)
  - Matt Donnelly

# 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:

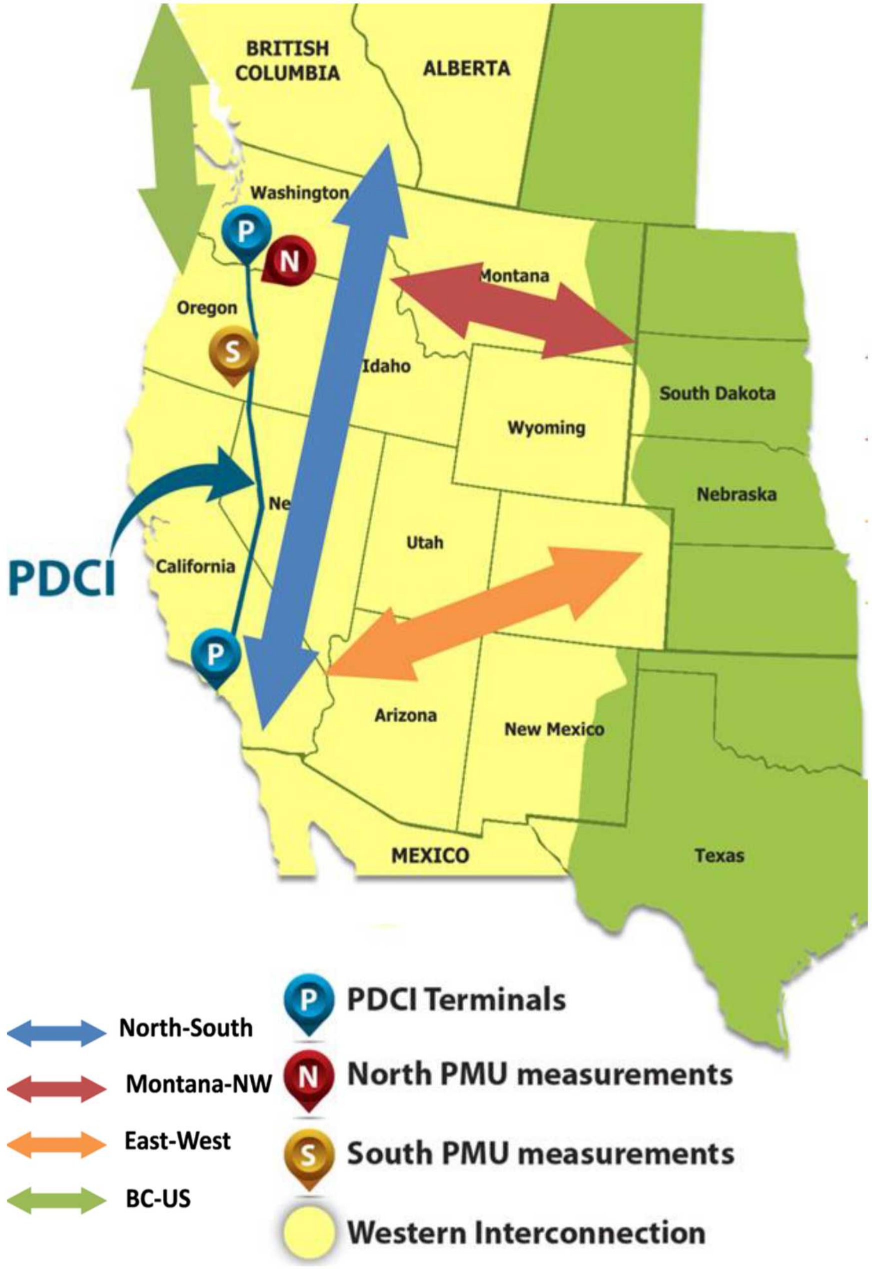
- Feedback control using real-time PMU data: First demonstration of this in North America
- Real power injection by modulating PDCI power
- Supervisory system integrated with controller for ensuring “Do No Harm” to grid

## Benefits:

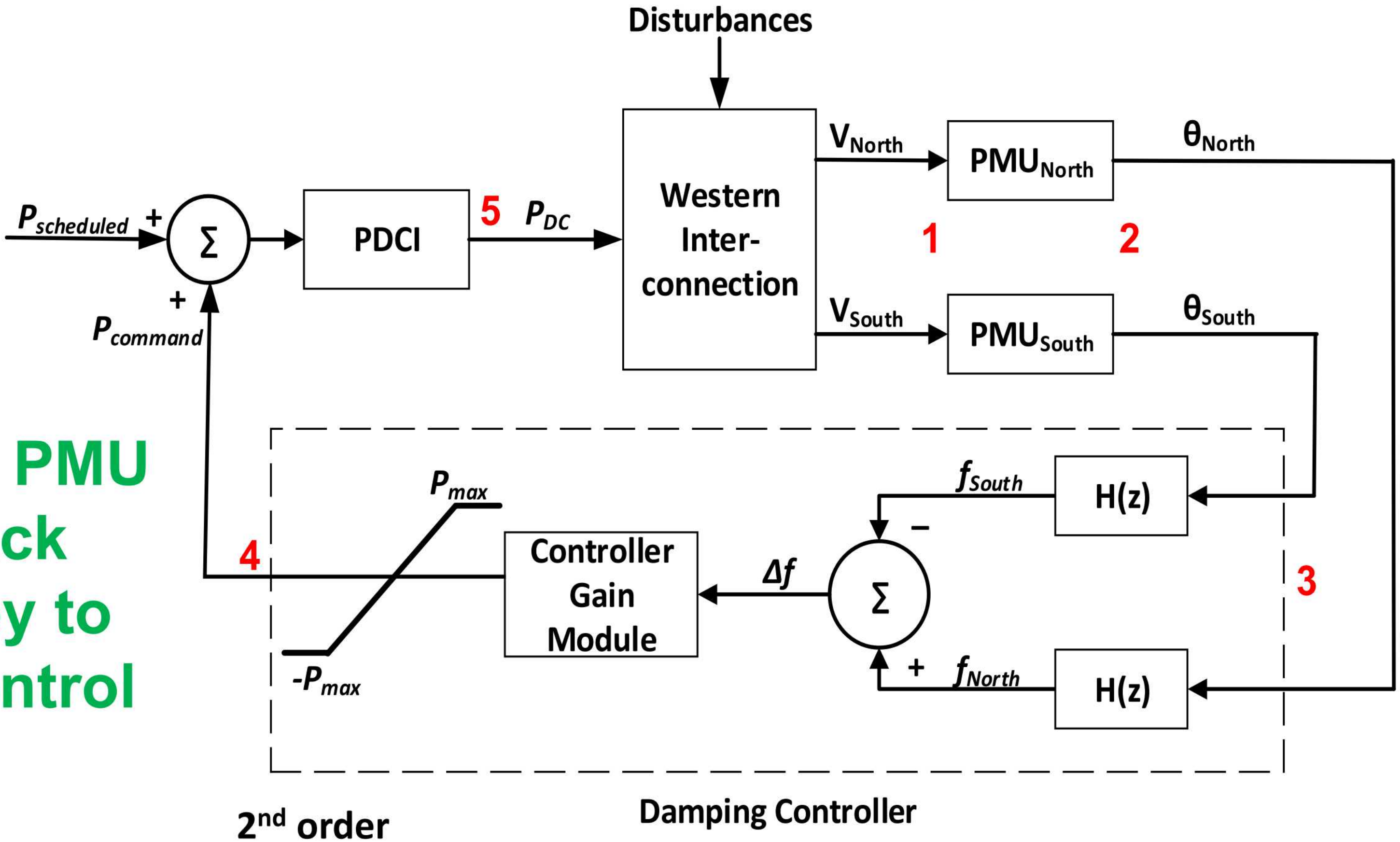
- Improved grid reliability
- Additional contingency for stressed grid conditions
- Avoided costs from a system-wide blackout
- Reduced or postponed need for new transmission capacity
- Enables higher power flows on congested transmission corridors

# Project Background

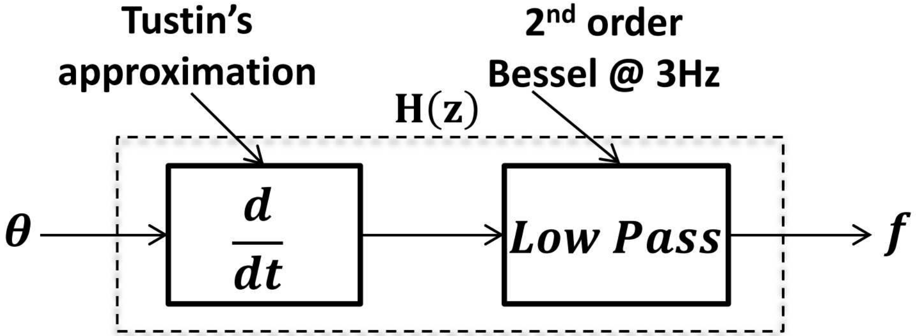
- Based on 1970s BPA experiments on PDCI later shown to have destabilized BC-US mode
- Revived in 2007 – 2012 by BPA with Montana Tech leveraging PMU deployments in WECC
- Current project launched in June 2013 as a collaboration of SNL, MT, BPA, and DOE to develop and demonstrate damping control
- Phase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



**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

# 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

## Supervisor

### Asynchronous Control Loop

- Automated probing
- Transfer function estimation
- Gain and phase margin estimation
- PDCI monitoring

### Real-time Control Loop

- State machine arch.
- Bumpless transfer (SW)
- Oscillation detection
- Separation detection
- Frequency tol. detection

### Watchdog Circuit

- Watchdog circuit for async. and RT loops
- Emergency stop button
- Bumpless transfer (HW)
- Reinitialization procedure

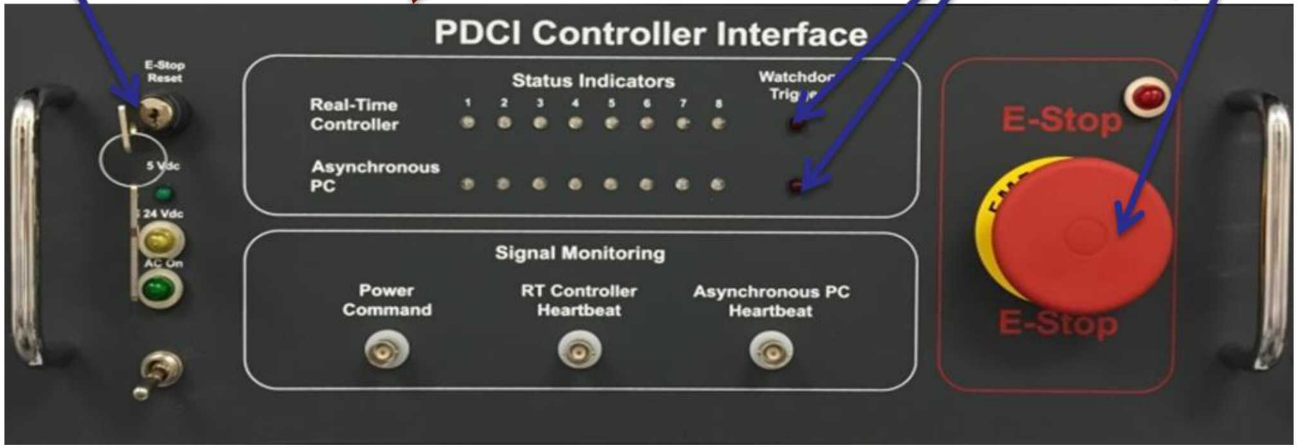
# Damping Controller Hardware

Watchdog circuit module

Key switch

Heartbeat indicators

E-Stop button

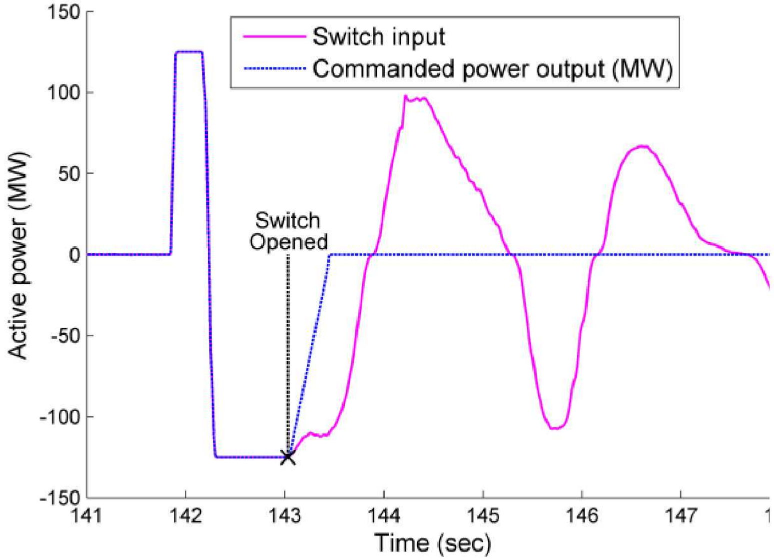


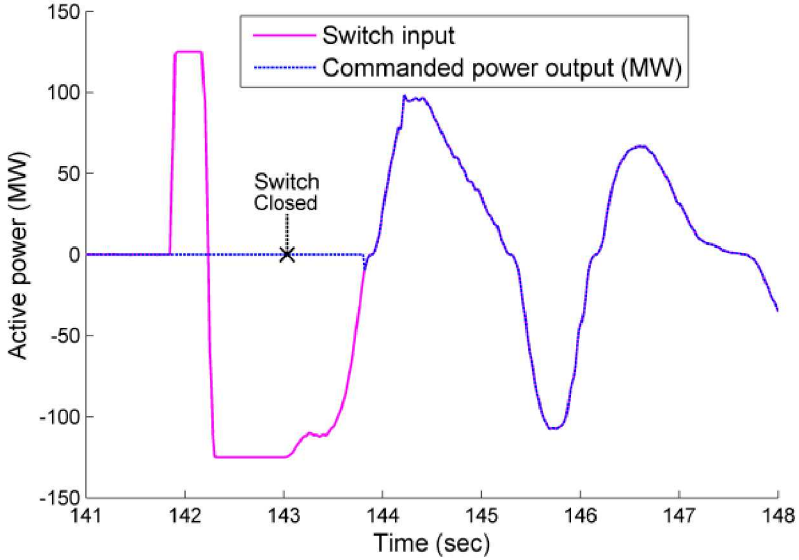
Server for select supervisory functions (“Do No Harm”)

Real-time Control platform

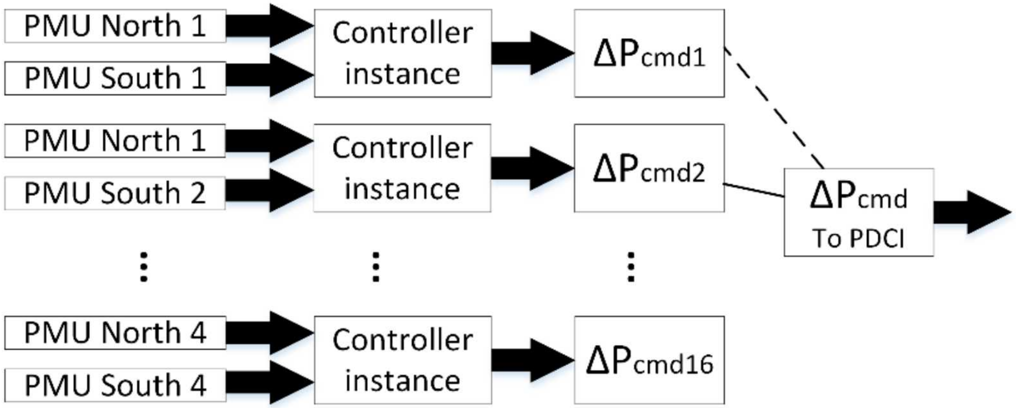
# Bumpless Transfer and Redundant Feedback

Controller seamlessly switches between system states to avoid injecting step functions into the system.





Controller evaluates 16 feedback pairs every update cycle to provide options for any network issues.



PMU North 1
PMU South 1
Controller instance
$\Delta P_{cmd1}$

PMU North 1
PMU South 2
Controller instance
$\Delta P_{cmd2}$

⋮

PMU North 4
PMU South 4
Controller instance
$\Delta P_{cmd16}$

$\Delta P_{cmd}$
To PDCI

# Current Project Tasks

- DCON Tests at Celilo
    - CJBs, Square Wave Pulses, FOs (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)

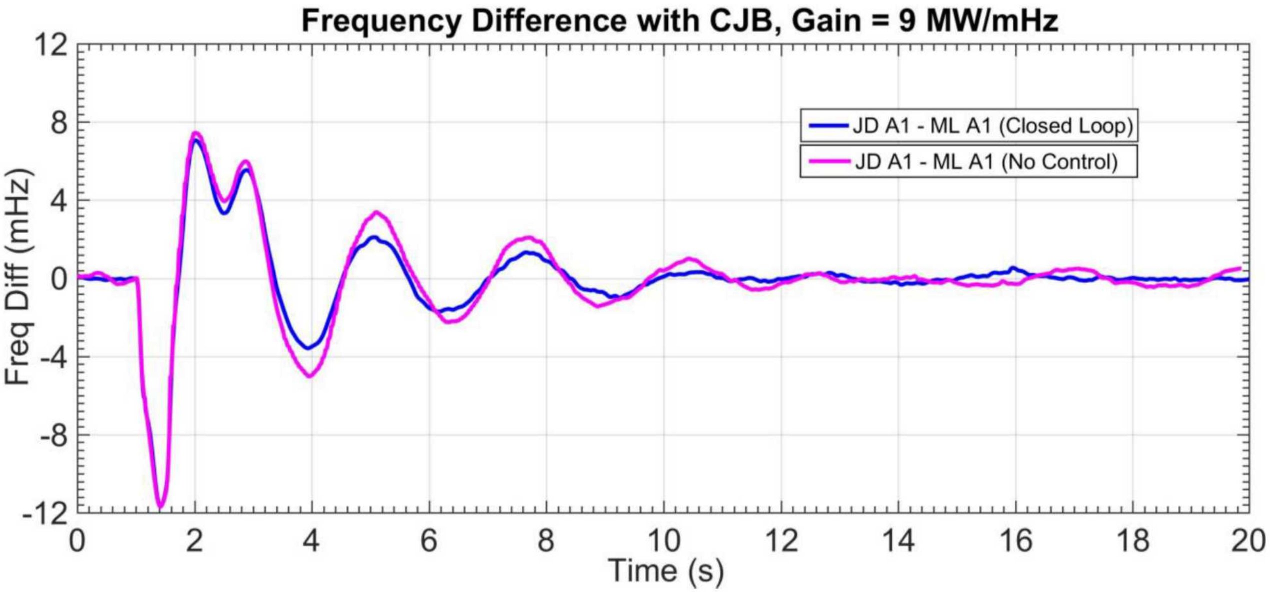
- Transient Stability Studies
    - Characterization of transient stability limited corridors
    - Assess capabilities of DCON for transient stability
    - Consider other sources of power injection, e.g. thyristor brakes

- Analysis of Forced Oscillations
    - AC side – DCON is effective on low frequency FOs
    - DC side – have been identified but need more study

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

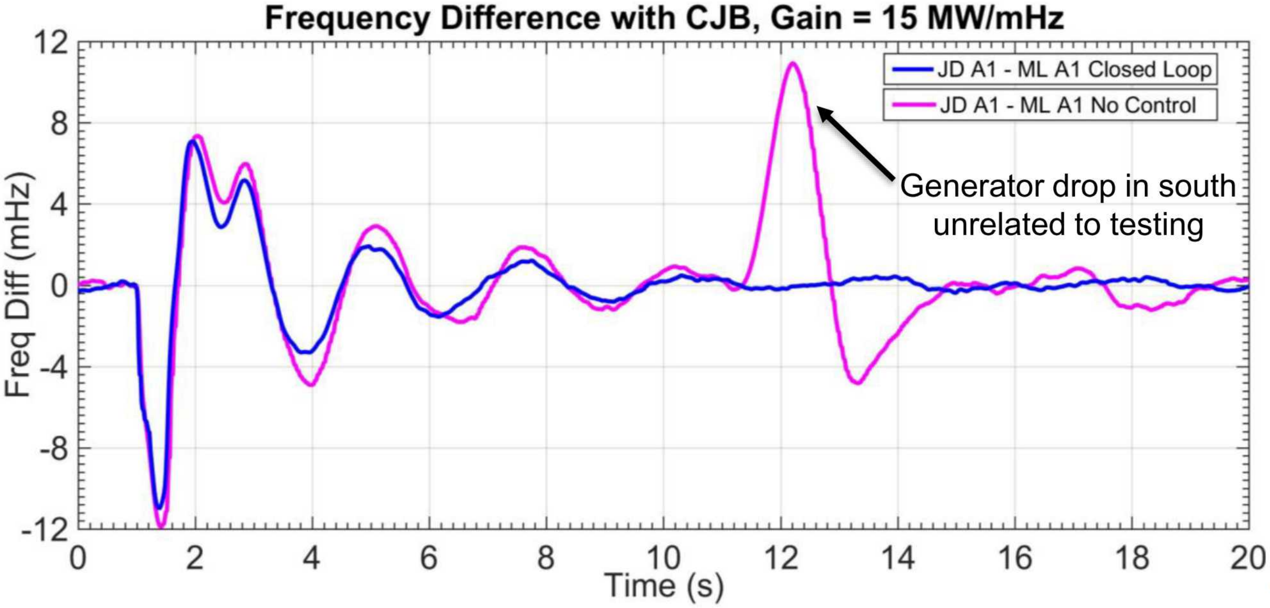
**Chief Joseph brake test**

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



**Chief Joseph brake test**

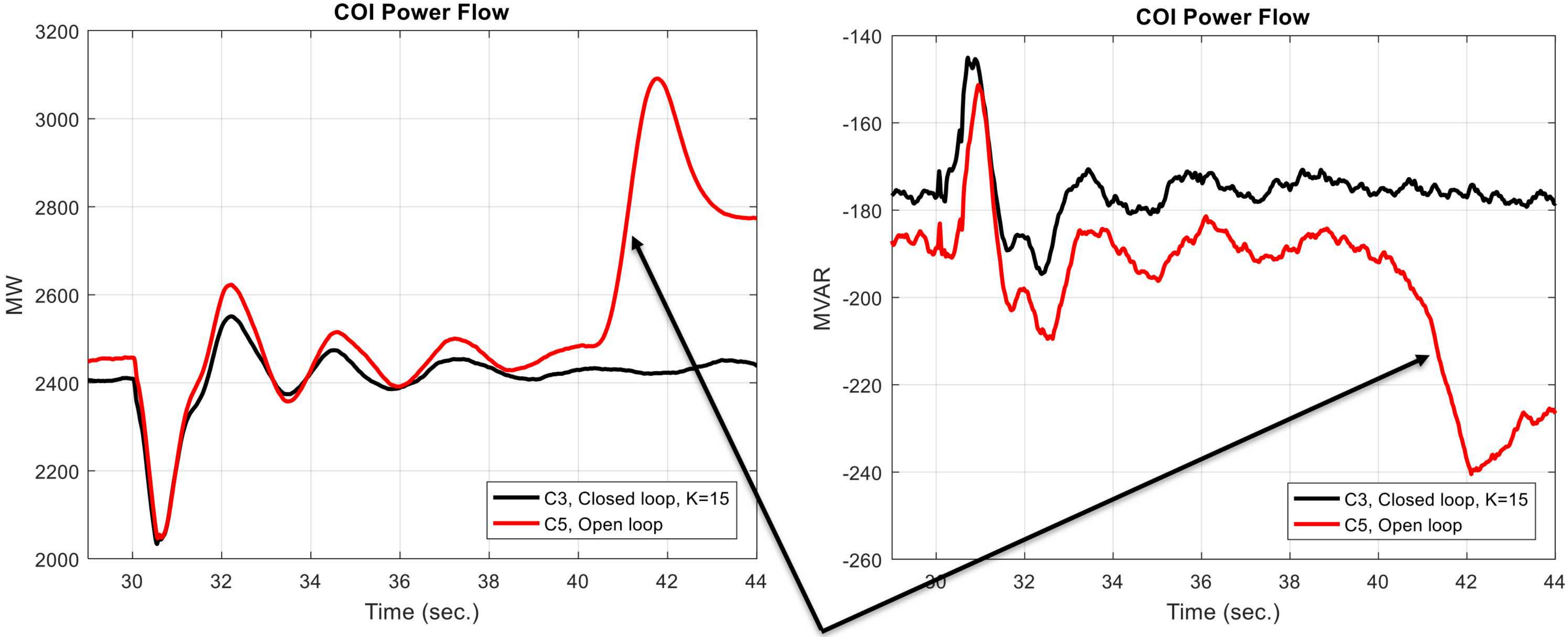
**Gain = 15 MW/mHz**
**Damping improved by 6 percentage points (10.0% to 16.0%)**



Generator drop in south unrelated to testing

# COI Power Flows Show Similar Damping Improvement

## (Tests conducted at Celilo on May 23, 2018)

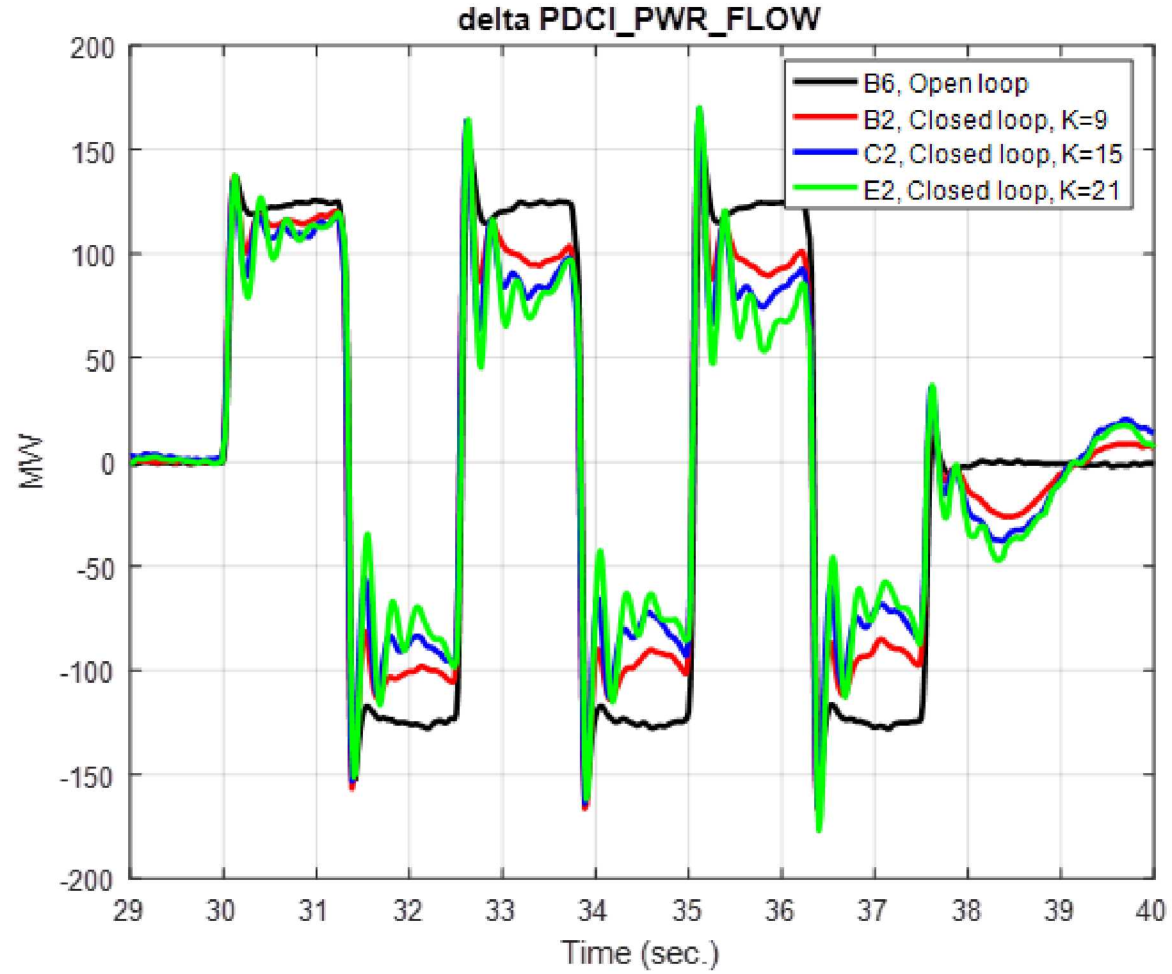


Generator drop in south
unrelated to testing

**Real and reactive power flows through the COI right after a Chief Joseph Brake insertion.**

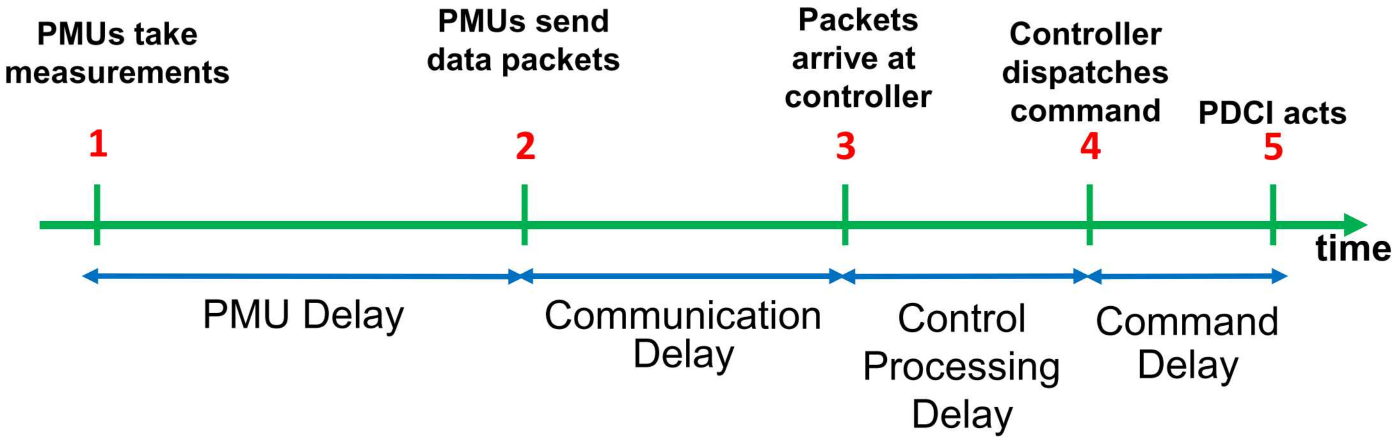
# Gain Tuning was Informed by Square Wave Pulses

## (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



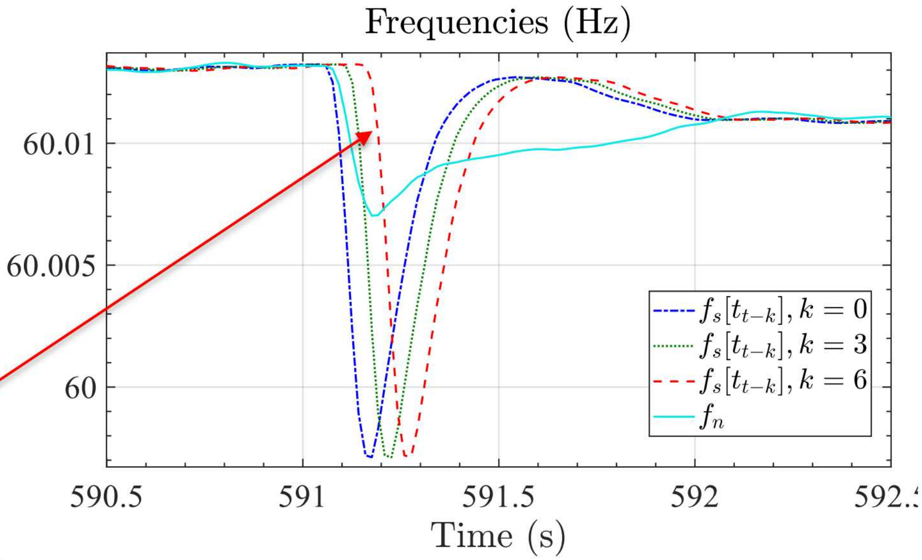
| Name | Mean | Range | Note |
|---|---|---|---|
| **PMU Delay** | 44 | 40 – 48 | Dependent on PMU settings. Normal distribution. |
| **Communication Delay** | 16 | 15 – 40 | Heavy tail |
| **Control Processing Delay** | 11 | 2 – 17 | Normal around 9 ms, but a peak at 16 ms due to control windows when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

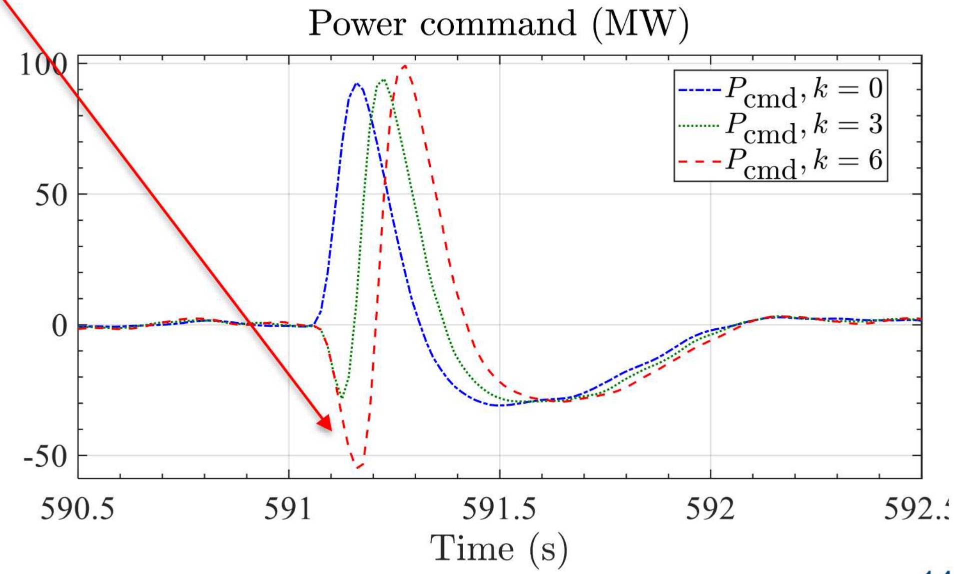
**Total time delays are well within our tolerances (<< 150 ms)**

# 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)**





# 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