SAND2018-12843PE

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Real-Time Damping Control Using PMU Feedback

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Sandia National Labs

JSIS Meeting
Portland, OR
November 9, 2018

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Acknowledgements and Contributors

- **We gratefully acknowledge the support of DOE and BPA:**
  - DOE-OE Transmission Reliability Program – PM: Phil Overholt
  - DOE-OE Energy Storage Program – PM: Imre Gyuk
  - BPA Office of Technology Innovation – TIP# 289

- **Bonneville Power Administration (BPA):**
  - Dmitry Kosterev (Tech. POC)
  - Gordon Matthews (PM)
  - Jeff Barton
  - Tony Faris
  - Dan Goodrich
  - Michael Overeem
  - Sergey Pustovit
  - Greg Stults
  - Mark Yang
  - Steve Yang

- **Sandia:**
  - Dave Schoenwald (PI)
  - Brian Pierre
  - Felipe Wilches-Bernal
  - Ryan Elliott
  - Ray Byrne
  - Jason Neely

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

Outline

- DCON Tests at Celilo
    - Tuning of DCON Gain (May 23, 2018)
    - Implement +/- 0.2 mHz dead-zone (May 23, 2018)
    - Events during "Walkaway" Test (May 24, 2018 – June 21, 2018)
- PMU Latencies
    - Characterization of latencies
    - Impact on controller
- PMU Data Considerations
    - Time alignment
    - Corrupted data
- Other Control Architectures
    - Distributed control
    - Other sources of power injection

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:

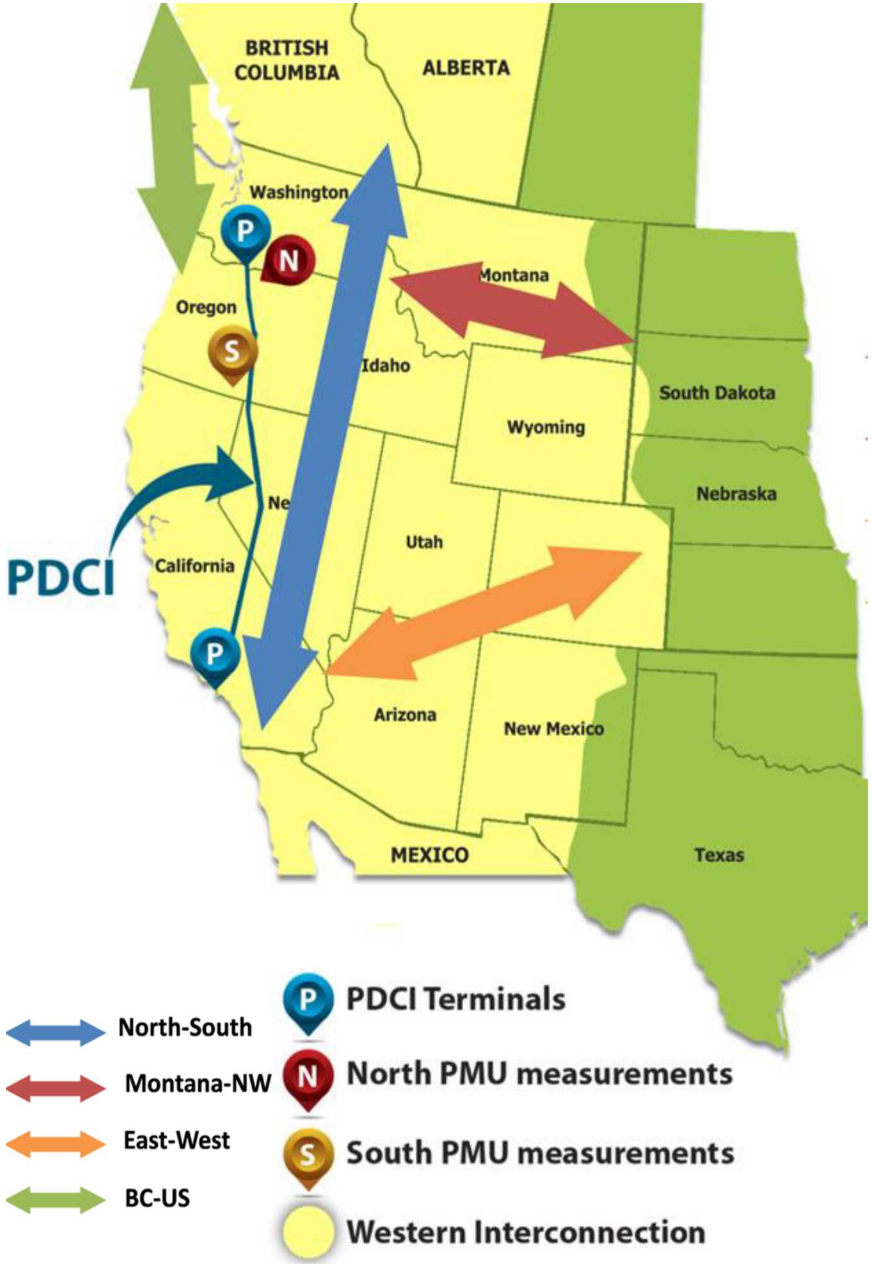
- **Feedback control using real-time PMU data: First demonstration of this in North America**
- **Real power injection by modulating PDCI power**
- **Supervisory system integrated with controller for ensuring "Do No Harm" to grid**

Benefits:

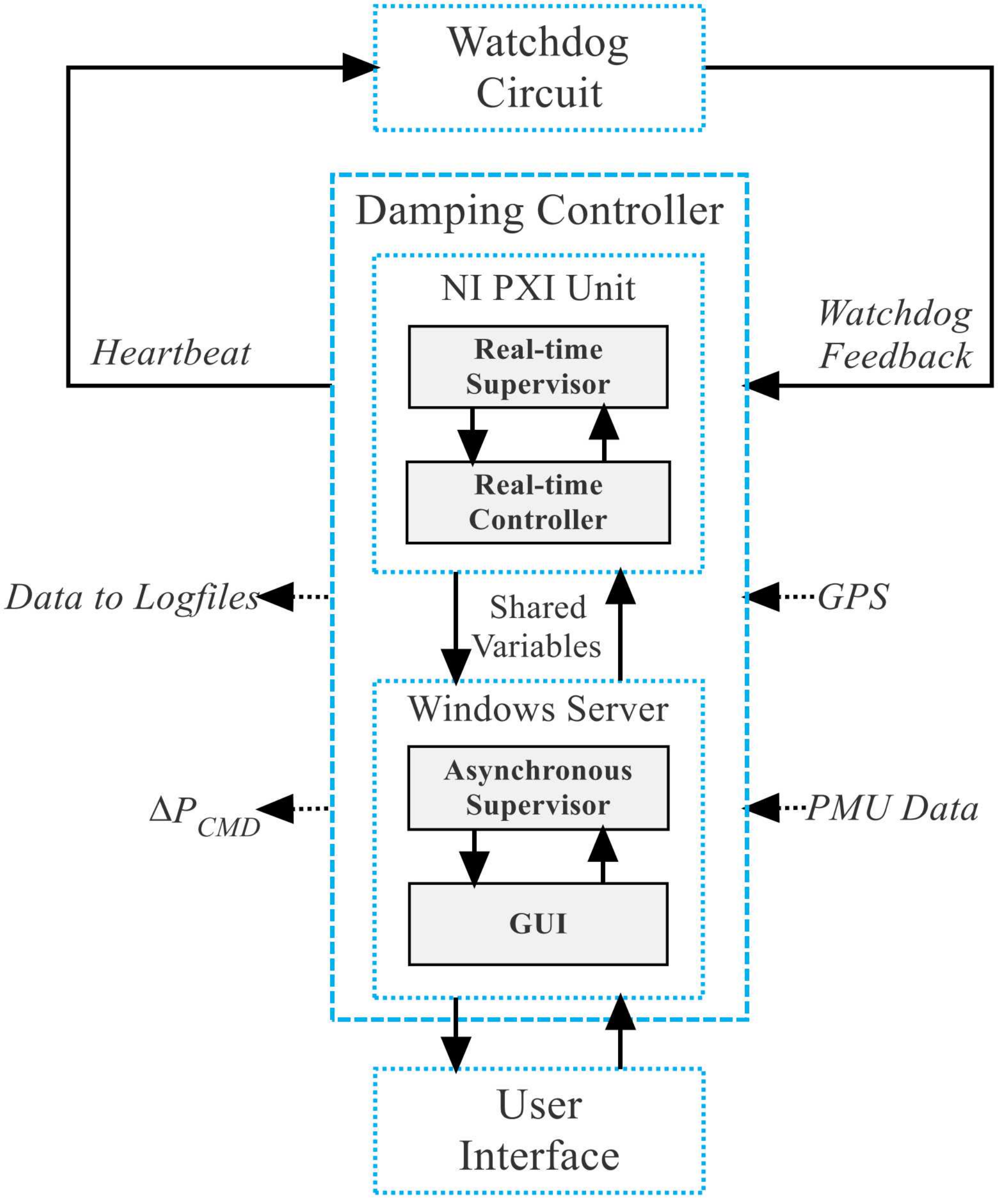
- **Improved grid reliability**
- **Additional contingency for stressed grid conditions**
- **Avoided costs from a system-wide blackout**
- **Reduced or postponed need for new transmission capacity**
- **Enables higher power flows on congested transmission corridors**

Background

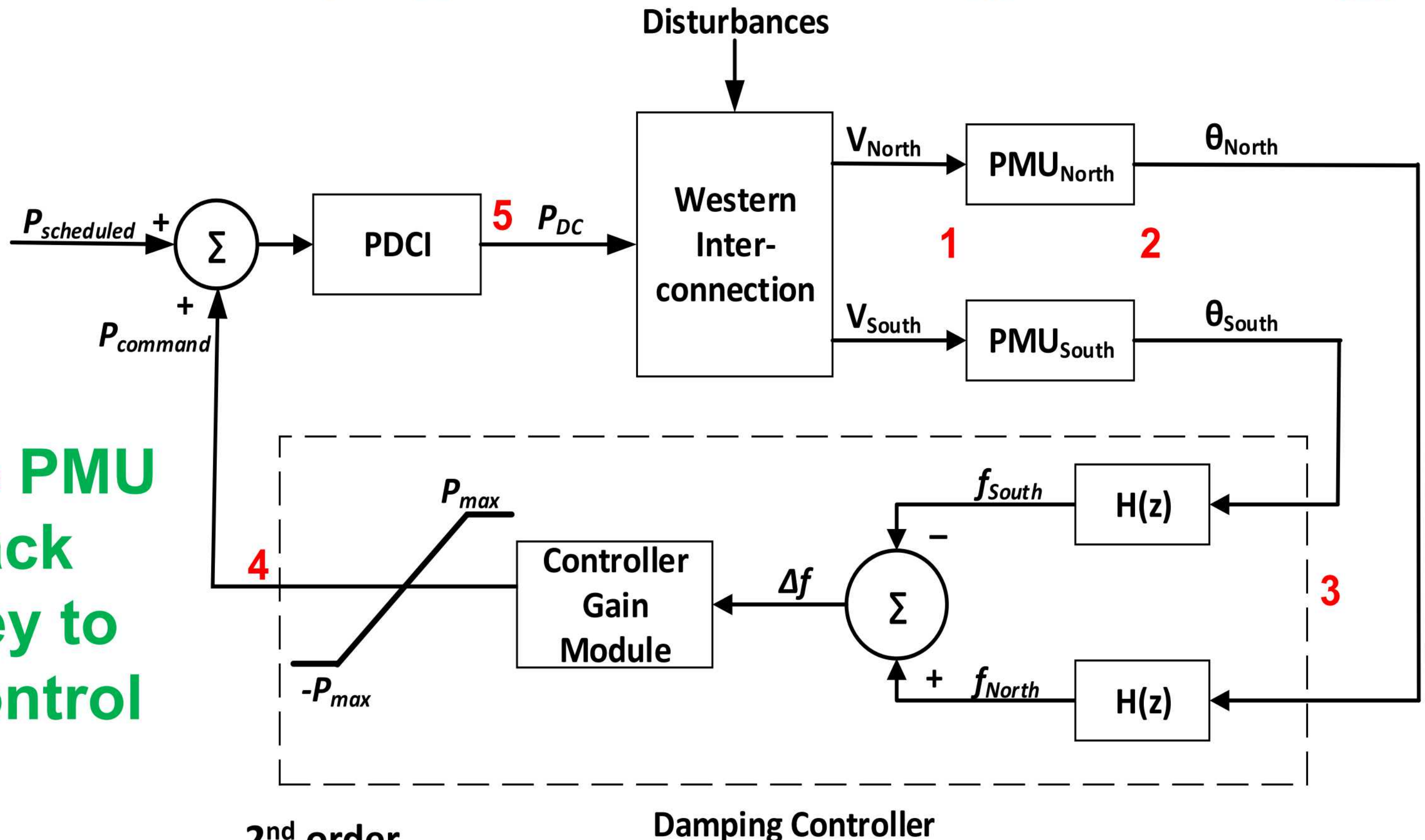
- Based on 1970s BPA experiments on PDCI later shown to have destabilized BC-US mode
- Revived in 2007 – 2012 by BPA with Montana Tech leveraging PMU deployments in WECC
- Current project launched in June 2013 as a collaboration of SNL, MT, BPA, and DOE to develop and demonstrate damping control
- Phase 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 – Present)
  - Conduct longer-term tests
  - Study transient stability potential
  - Assess impacts with DC side
  - Explore other sources of actuation



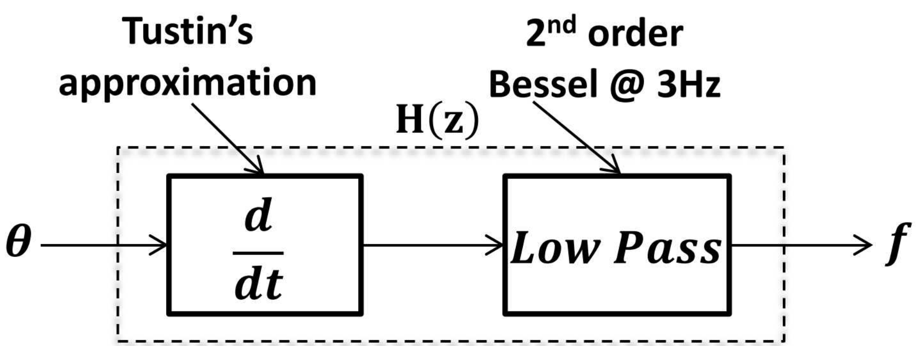
Damping Controller Overview



Damping Controller Strategy



Real-time PMU feedback is the key to stable control

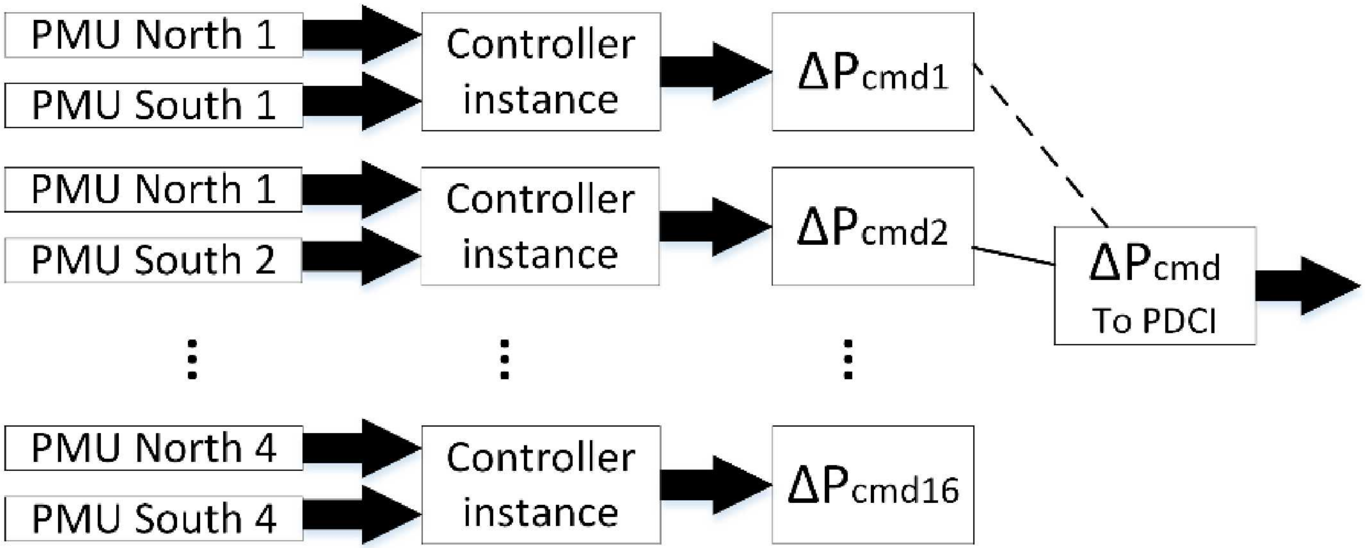


$$P_{command}(t) = K\big(f_{North}(t - \tau_{d1}) - f_{South}(t - \tau_{d2})\big)$$

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

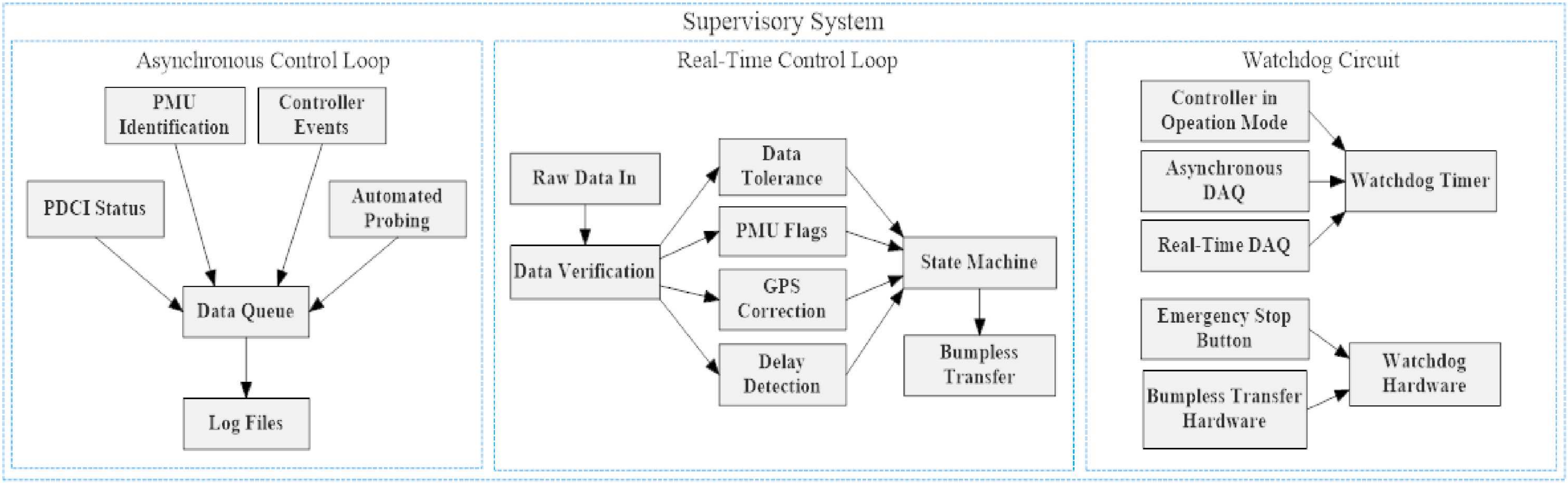
Controller Employs Diversity and Redundancy in Feedback



- **Diversity = Geographical Robustness**
- **Redundancy = Site Measurement Robustness**
- **Controller evaluates 16 feedback pairs every update cycle to provide options in case of network issues**
- **If needed, controller uses bumpless transfer to switch between feedback pairs to avoid injecting step functions into the system**

Supervisor Design Philosophy

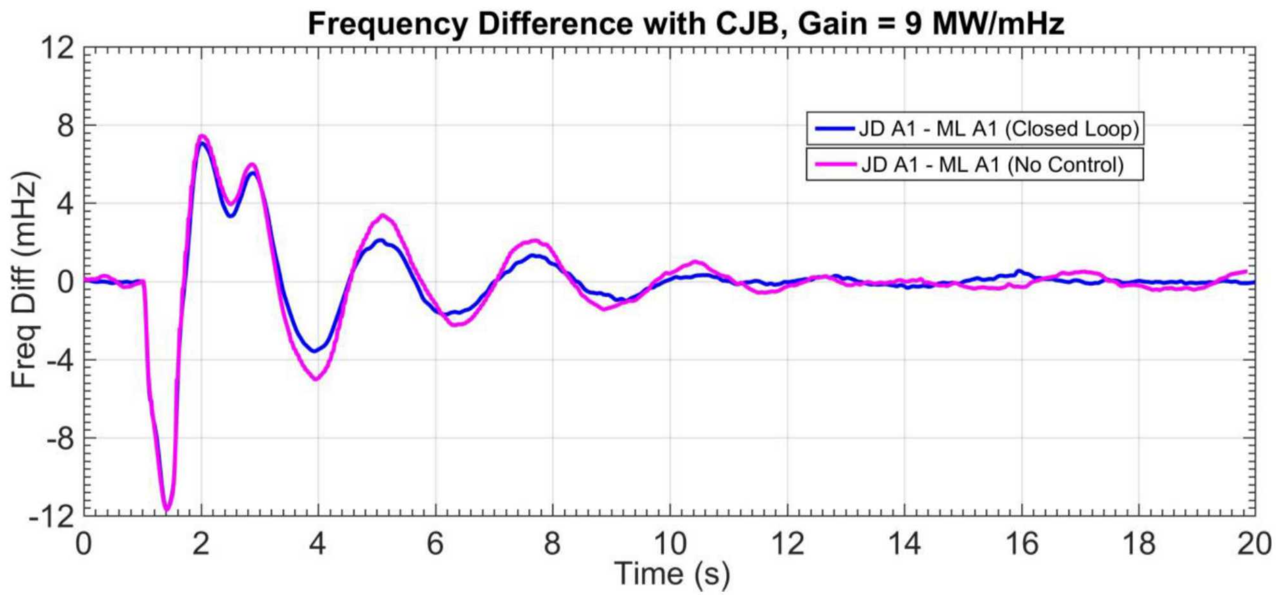
Design was driven by the need to detect and respond to certain system conditions in real-time as well as asynchronous monitoring functions at slower than real time



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

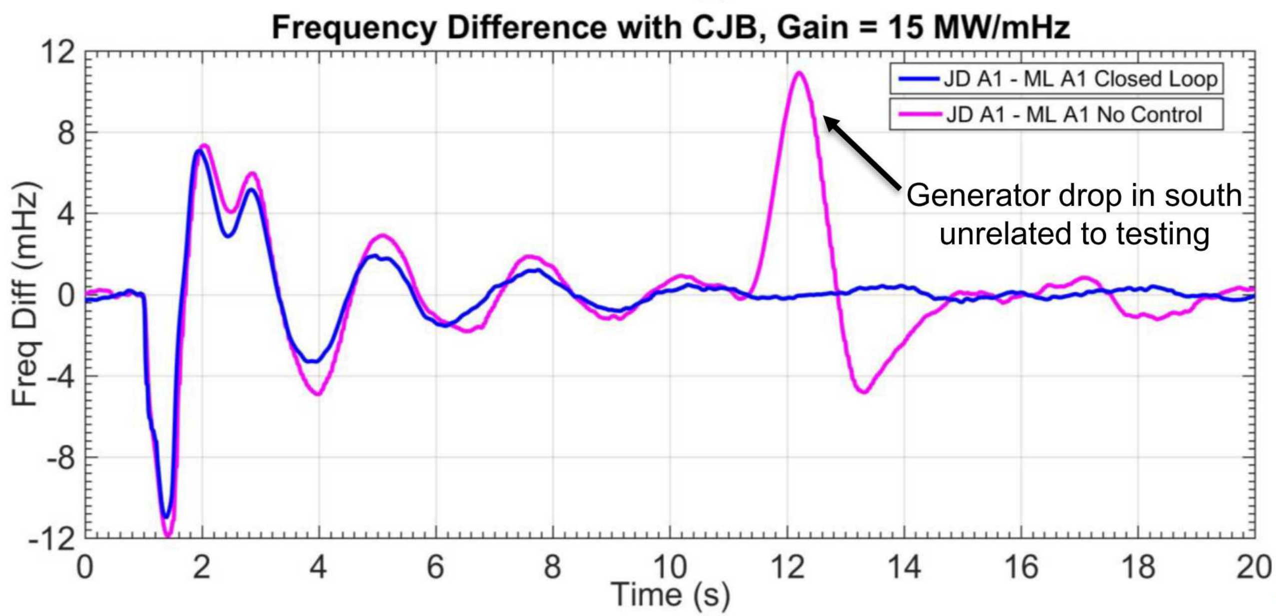
Chief Joseph brake test

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



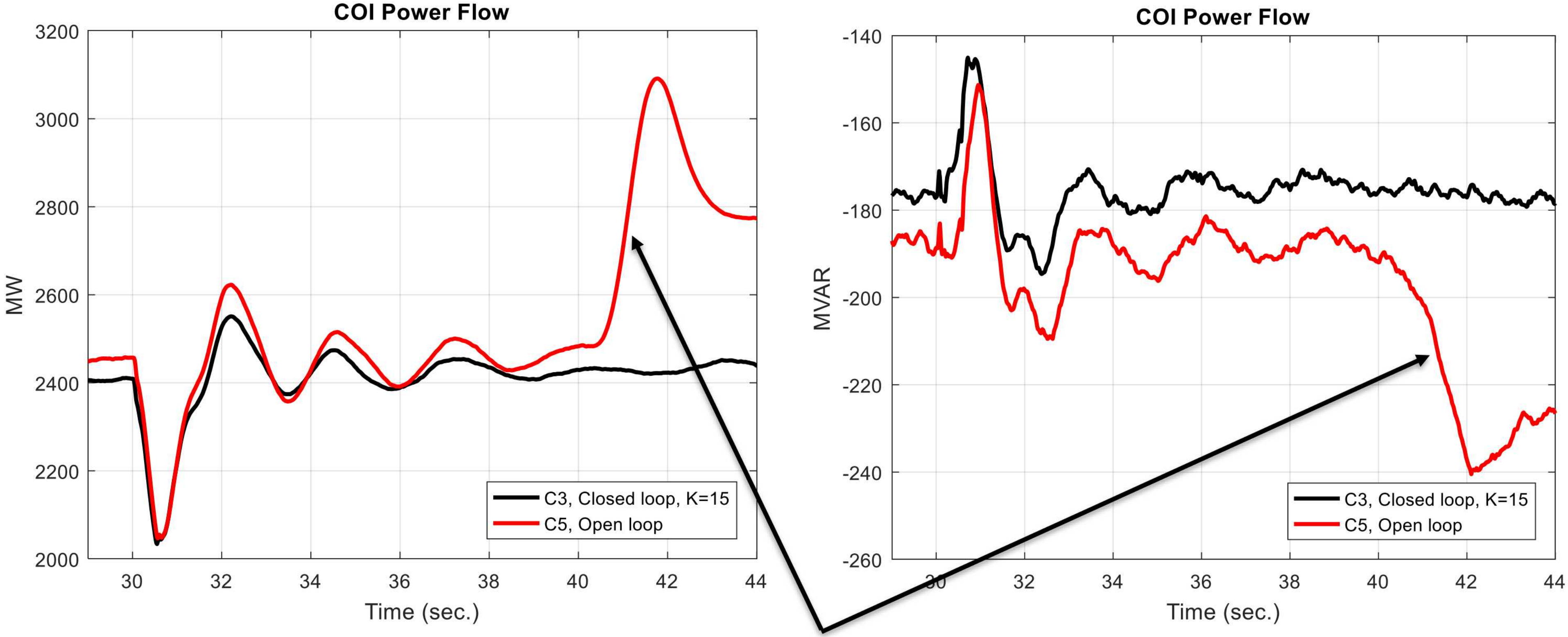
Chief Joseph brake test

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



COI Power Flows Show Similar Damping Improvement

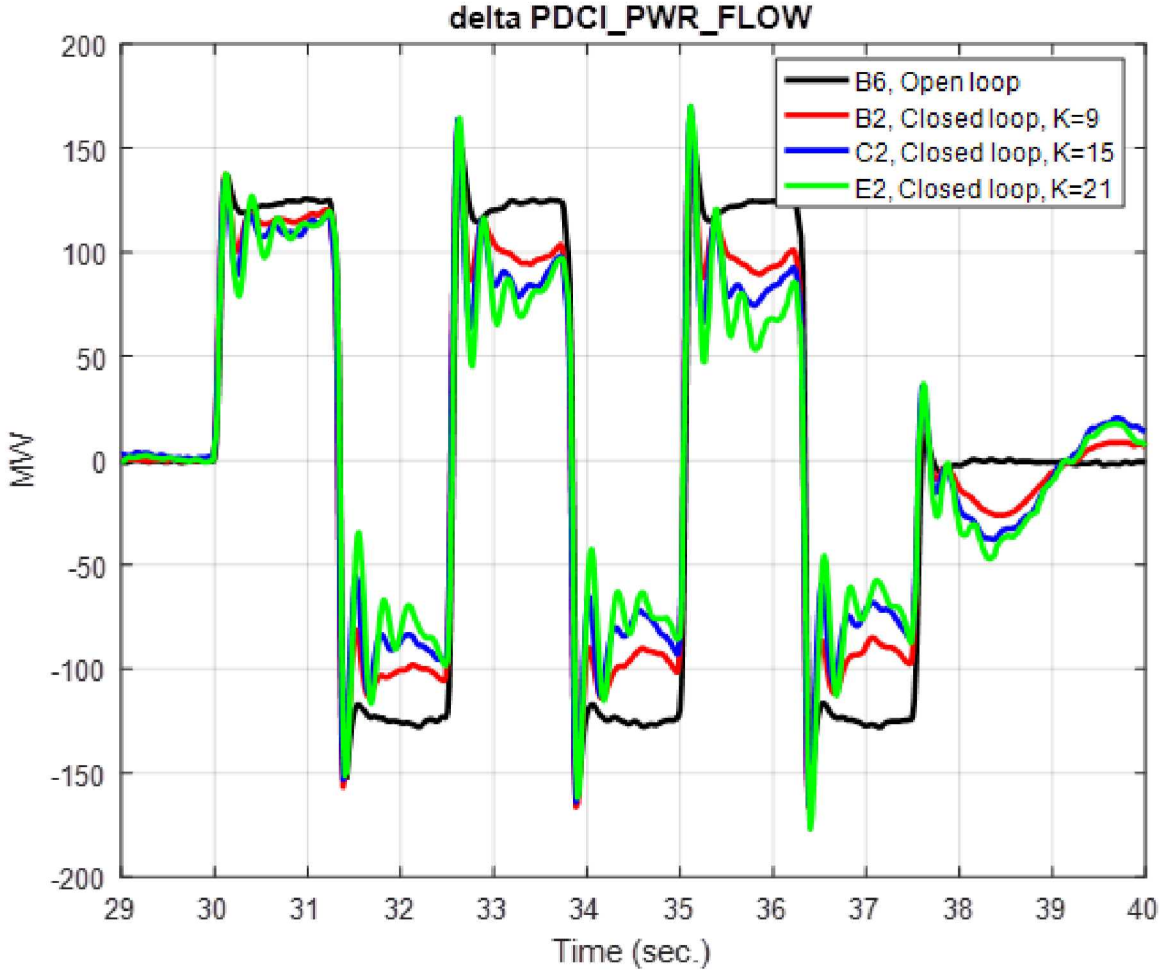
(Tests conducted at Celilo on May 23, 2018)



Generator drop in south
unrelated to testing

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

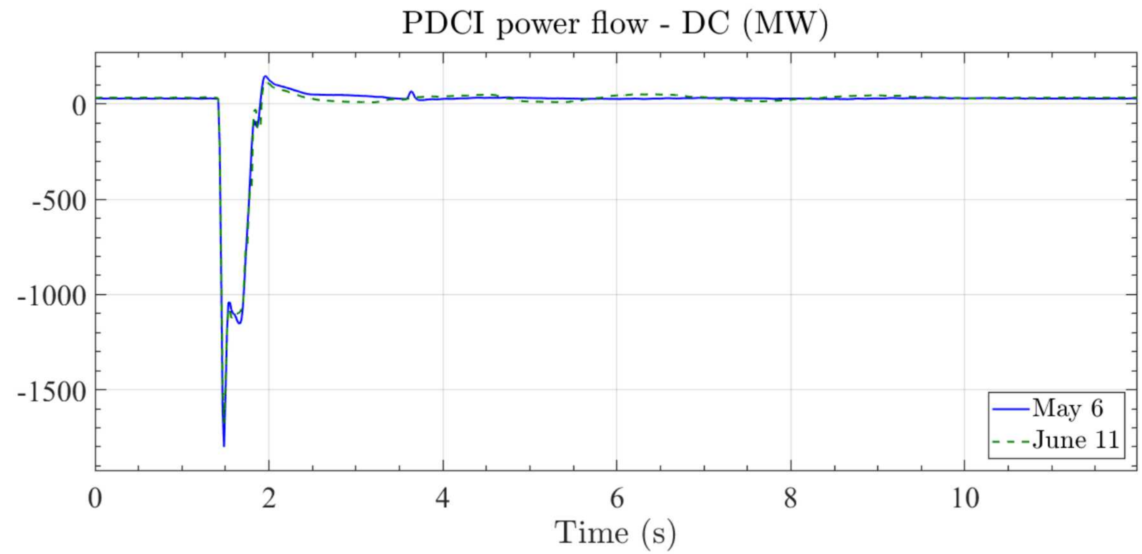
Gain Tuning was Informed by Square Wave Pulses
(Tests conducted at Celilo on May 23, 2018)



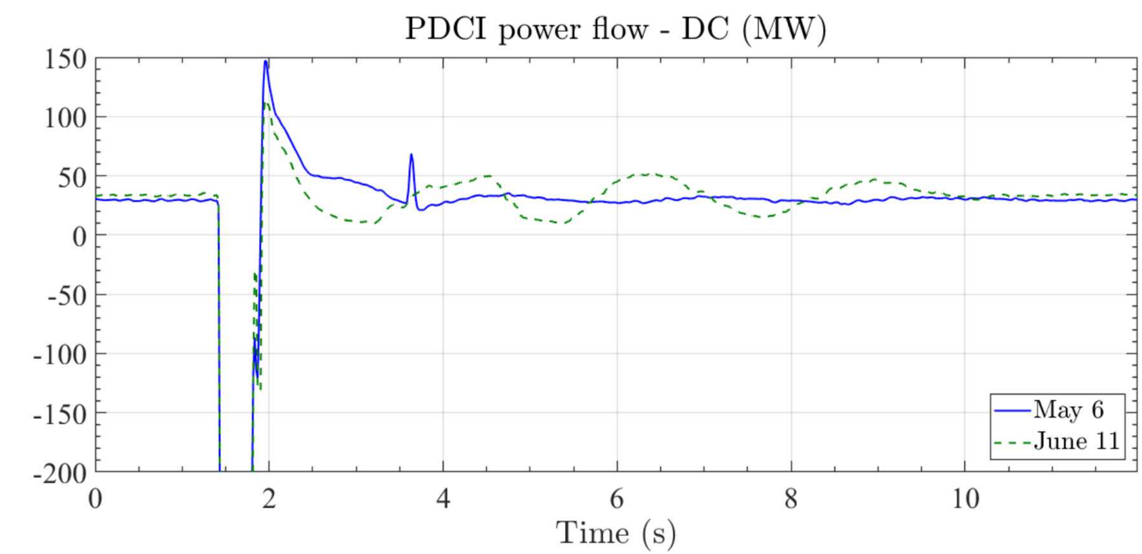
Lower gains ➔ less damping improvement
Higher gains ➔ more "ringing" on the DC side
Sweet spot ➔ K = 12 to 15 MW/mHz ➔ Gain Margin ≈ 6dB

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

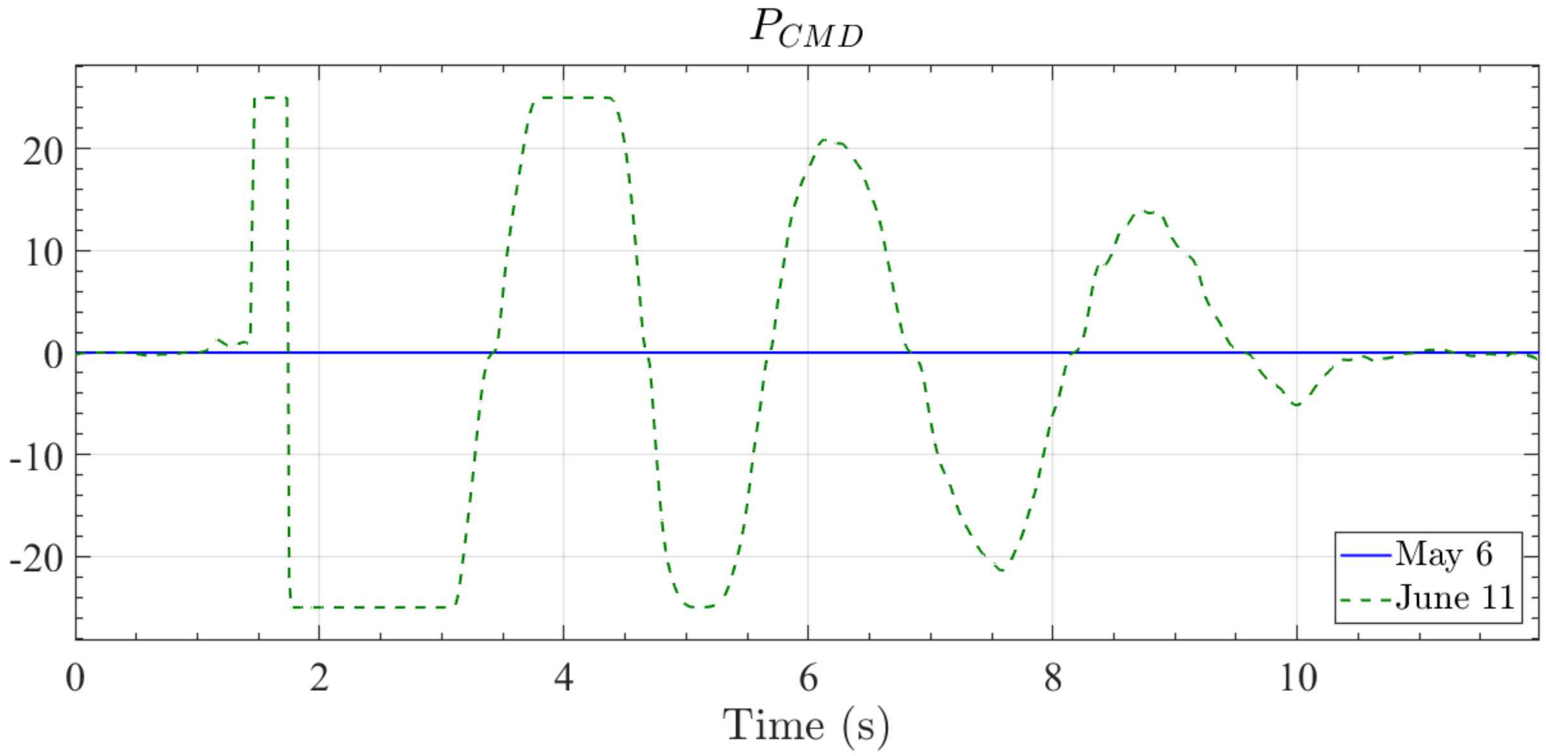
Two very similar events are captured. May 6 – controller was not connected. June 11 – controller was in closed-loop operation.



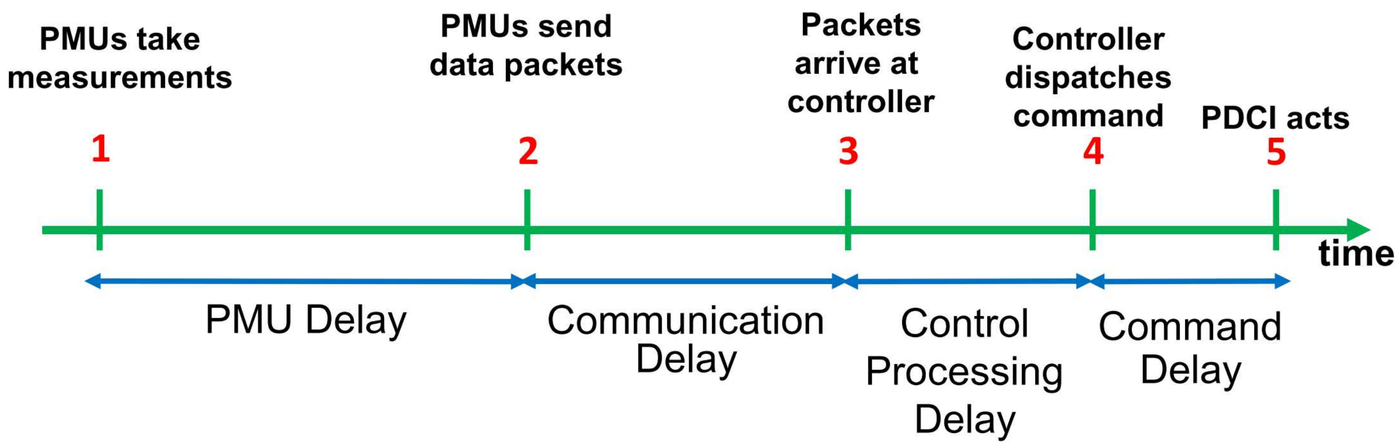
This plot zooms in on the y-axis to show controller modulation (June 11 curve).



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



Communication and Delays

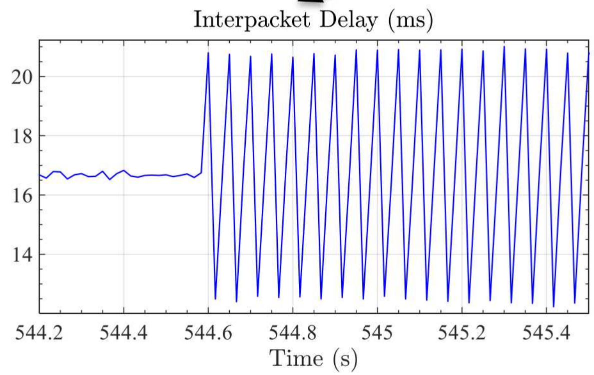


Name	Mean	Range	Note
PMU Delay	44	40 – 48	Dependent on PMU settings. Normal distribution.
Communication Delay	16	15 – 40	Heavy tail
Control Processing Delay	11	2 – 17	Normal around 9 ms, but a peak at 16 ms due to control windows when no data arrives (inconsistent data arrival)
Command Delay	11	11	Tests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

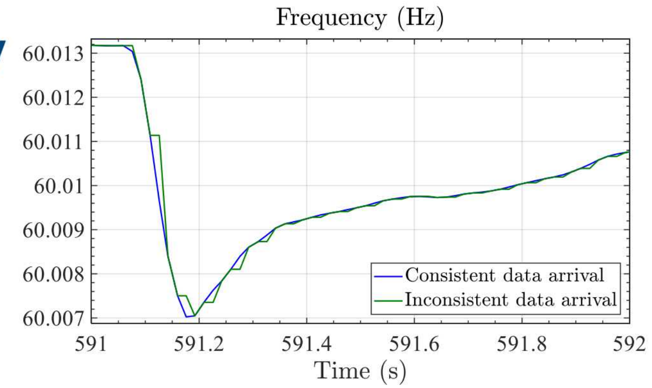
Total time delays are well within tolerances (< 150 ms)

PMU Data Considerations

- **PMUs have inconsistent interpacket delays**

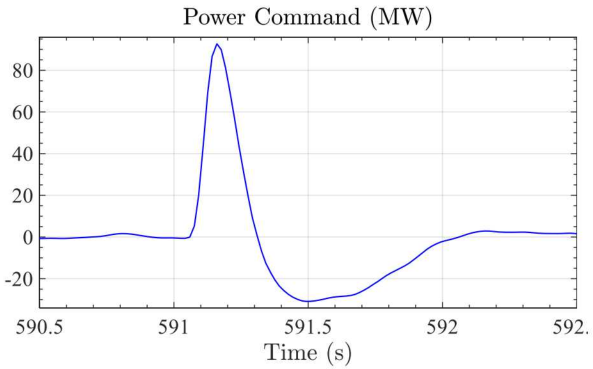


Delay inconsistency affects frequency estimation

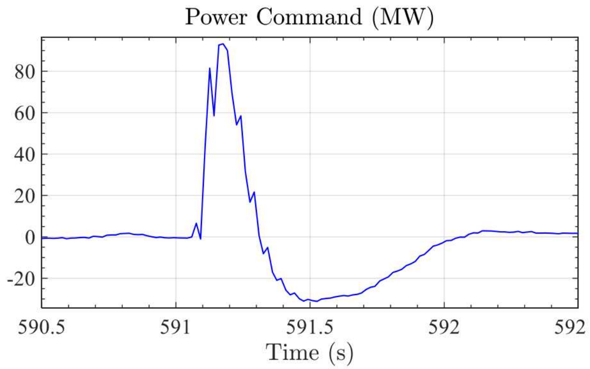


- **Delay inconsistency also affects the power command**

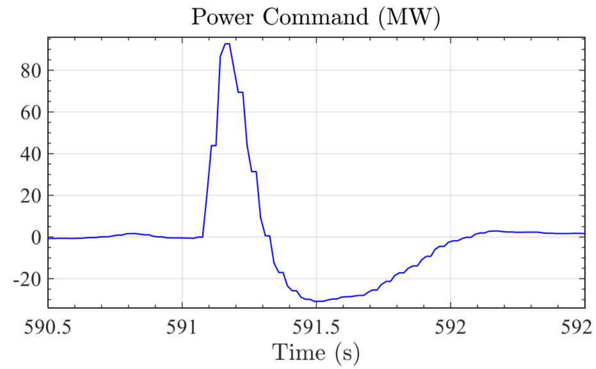
Ideal case



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

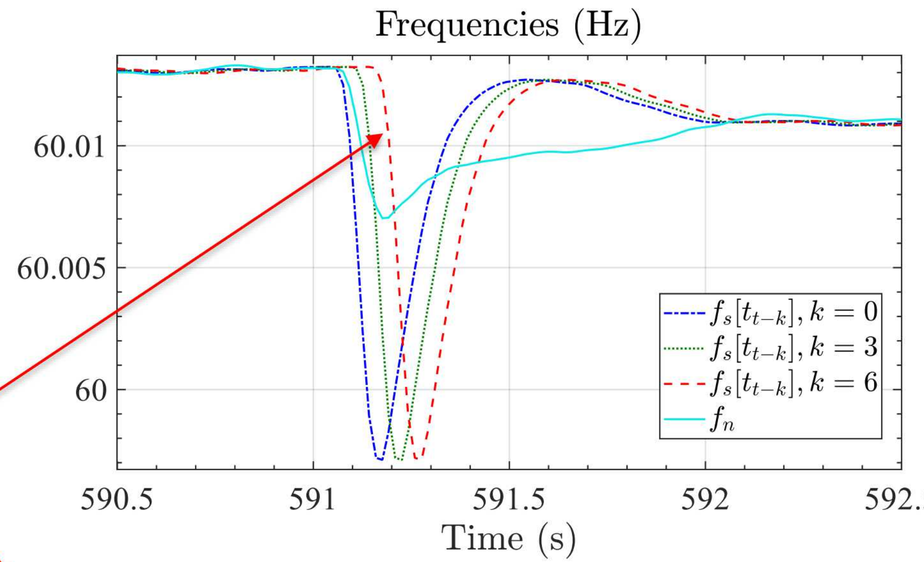


Delay inconsistency with time alignment

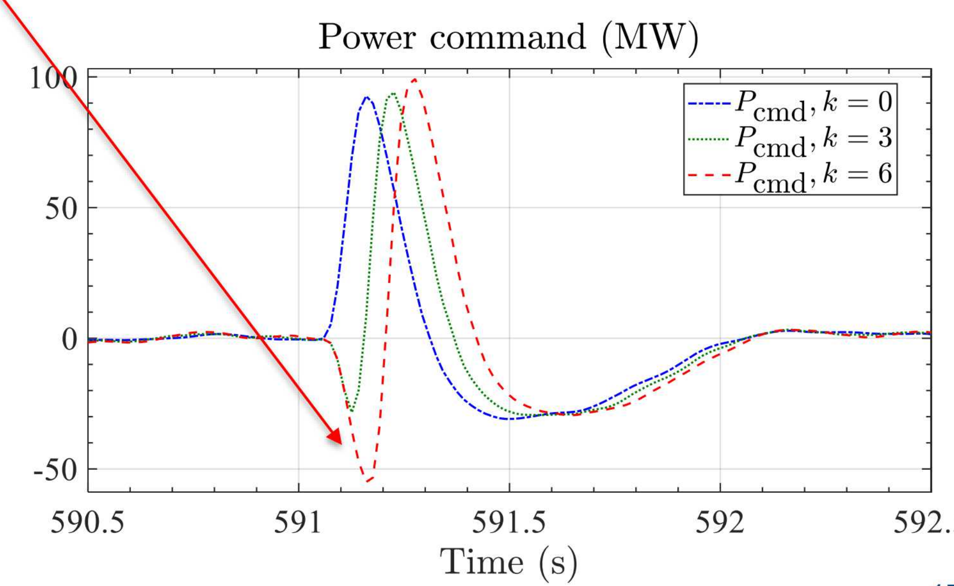


PMU Data Considerations

- **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

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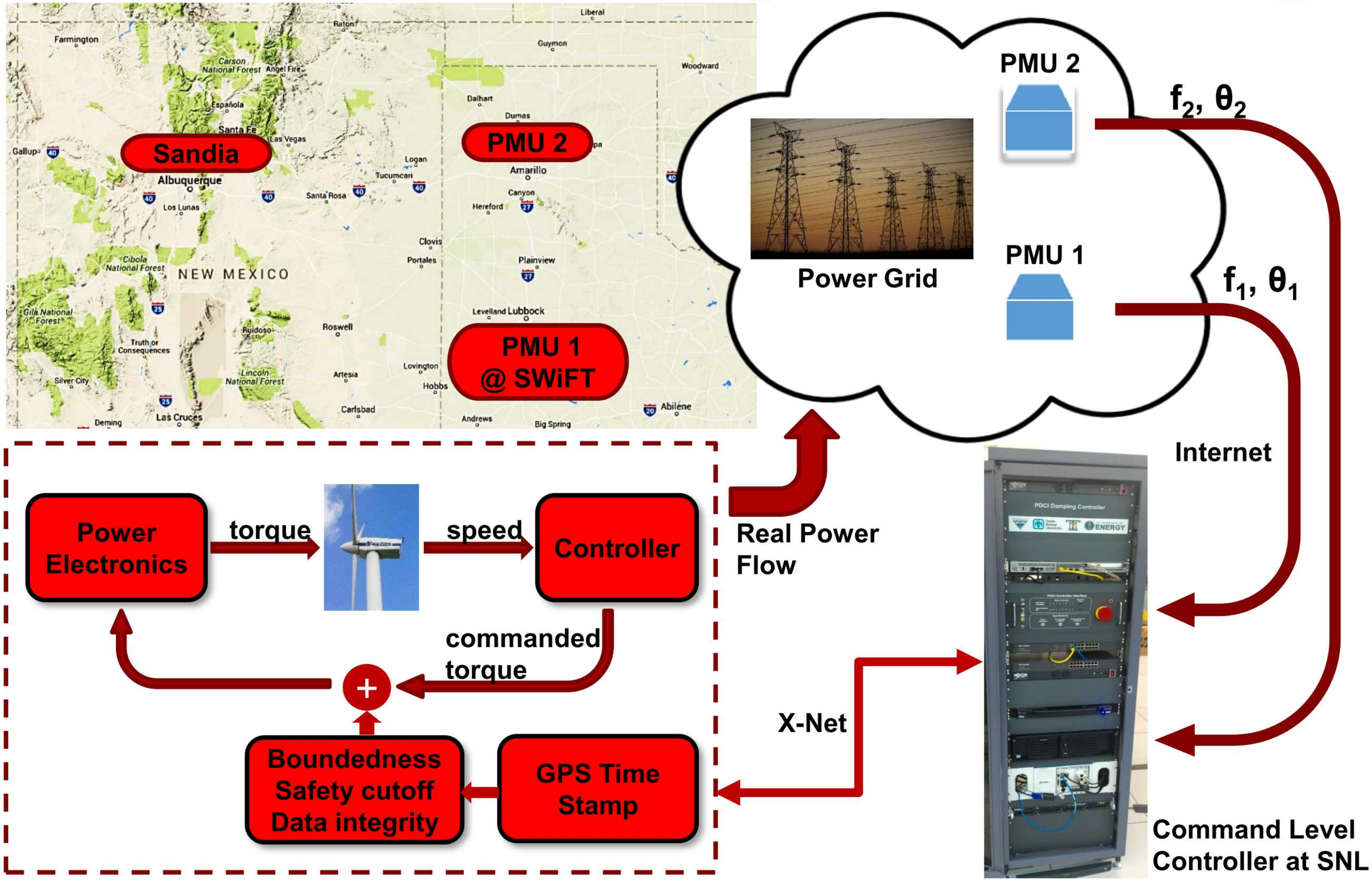
Advantages:

- 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

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

Conclusions & Recommendations

- First successful demonstration of real-time PMU feedback in N. America ➔ much knowledge gained in networked control systems
- Control design is actuator agnostic ➔ easily adaptable to other sources of power injection (e.g., wind turbines, energy storage)
- Supervisory system design ➔ easily extensible to future real-time grid control systems to ensure "Do No Harm"
- Control designs to improve transient stability and voltage stability on transmission grids
- Mitigation of forced oscillations – AC & HVDC
- 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 grid resilience
- 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