SAND2019-6592PE

Wide-Area Damping Control

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Project Objectives (June 2018 – June 2019)

- Analyze potential of DCON to mitigate impact to WI from forced oscillations
- Complete analysis and final reporting of DCON project focusing primarily on 2018 test results, hardware, and software documentation
- Investigate control strategies for transient stability, focusing on WI as an example

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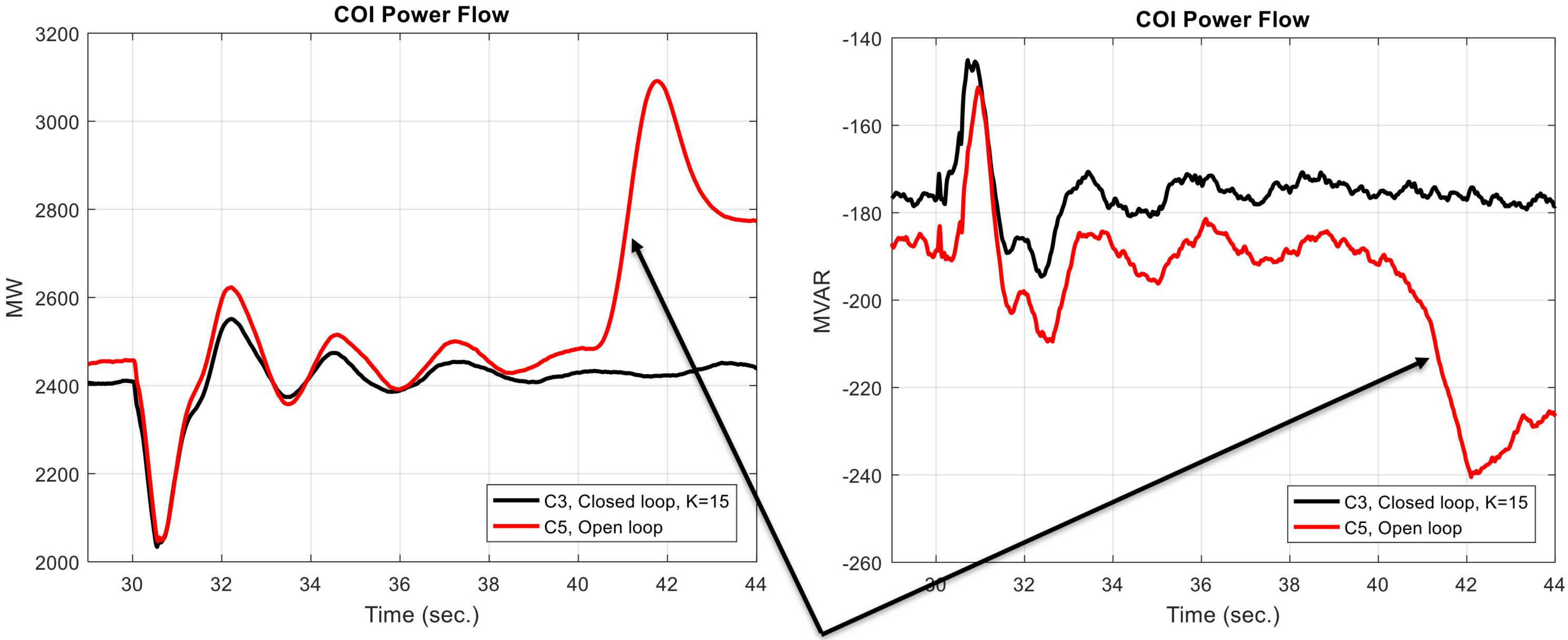
Highlights from 2018 PDCI Test Results

- Consistency of damping improvement vs. 2016 and 2017
- Unattended (4 weeks of 24/7) operation was successful and builds confidence in eventual operation
- Disturbance rejection results (probing signal generator)
- DC side issues – no evidence that DCON worsens these events
- Future DCON issues: HVDC dynamics investigation, distributed controls with storage

COI Power Flows Confirm 2016 & 2017 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.

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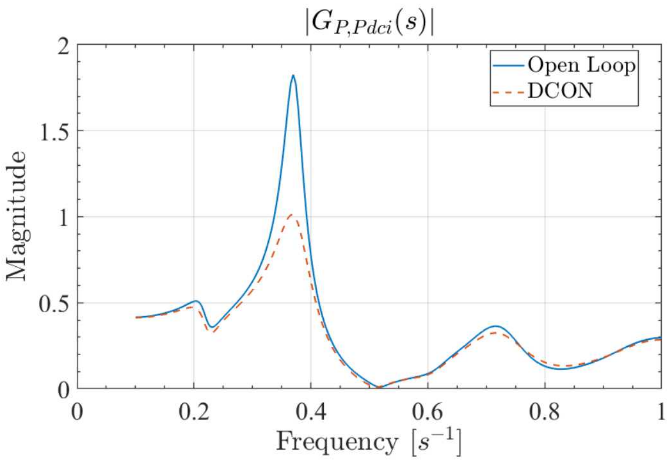
Forced Oscillations

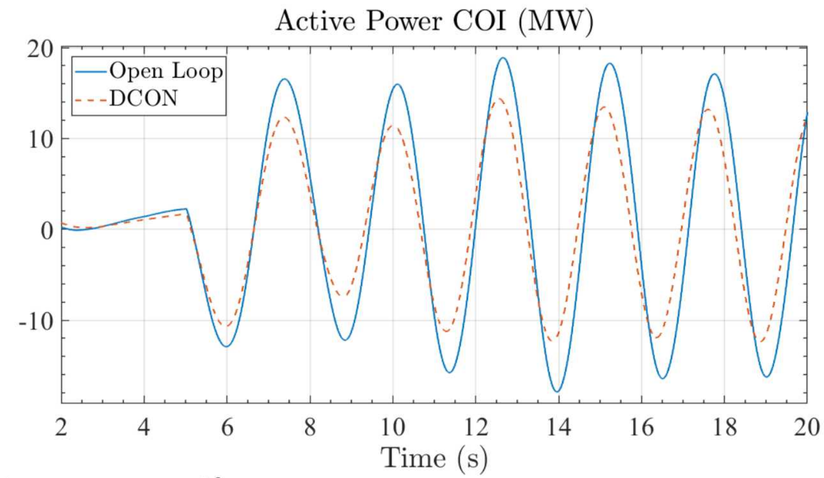
- **The effect that the PDCI damping controller has on forced oscillations in the Western Interconnection was studied in detail.**
  - Analysis in frequency domain
  - Analysis in time domain with simulations in the nonlinear system
  - Testing at Celilo on the PDCI was performed both in open and closed loop
- **The source of the forced oscillations could be from conventional generation or even from the PDCI itself.**
- **The damping controller is able to correctly mitigate forced oscillations in the frequency range of the inter-area oscillations it is designed to damp (< 1 Hz).**

Forced Oscillations

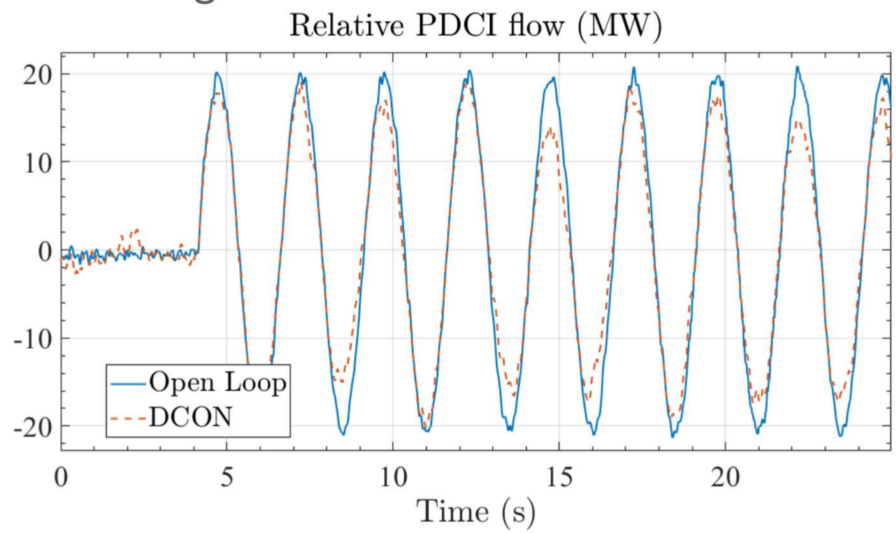
- Analysis in frequency domain



- Simulations in time domain



- Testing in the Western Interconnection



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Key Takeaways from PDCI Damping Controller 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

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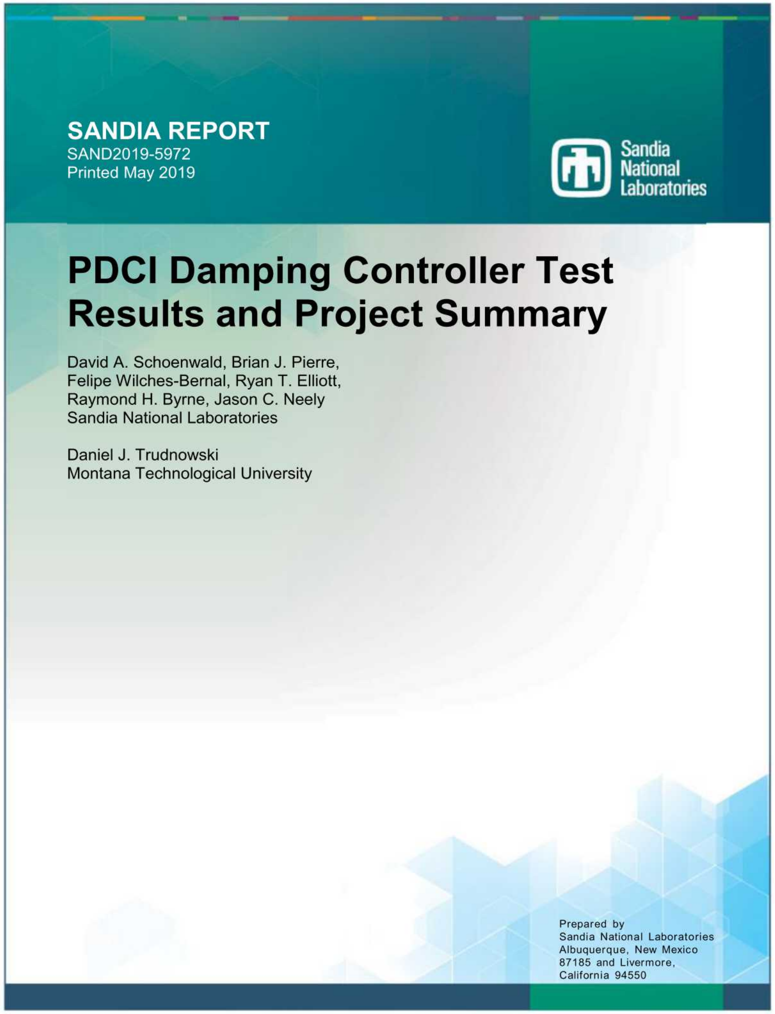
BPA Project Final Report and Summary of Achievements



SANDIA REPORT
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PDCI Damping Controller Test Results and Project Summary

David A. Schoenwald, Brian J. Pierre, Felipe Wilches-Bernal, Ryan T. Elliott, Raymond H. Byrne, Jason C. Neely
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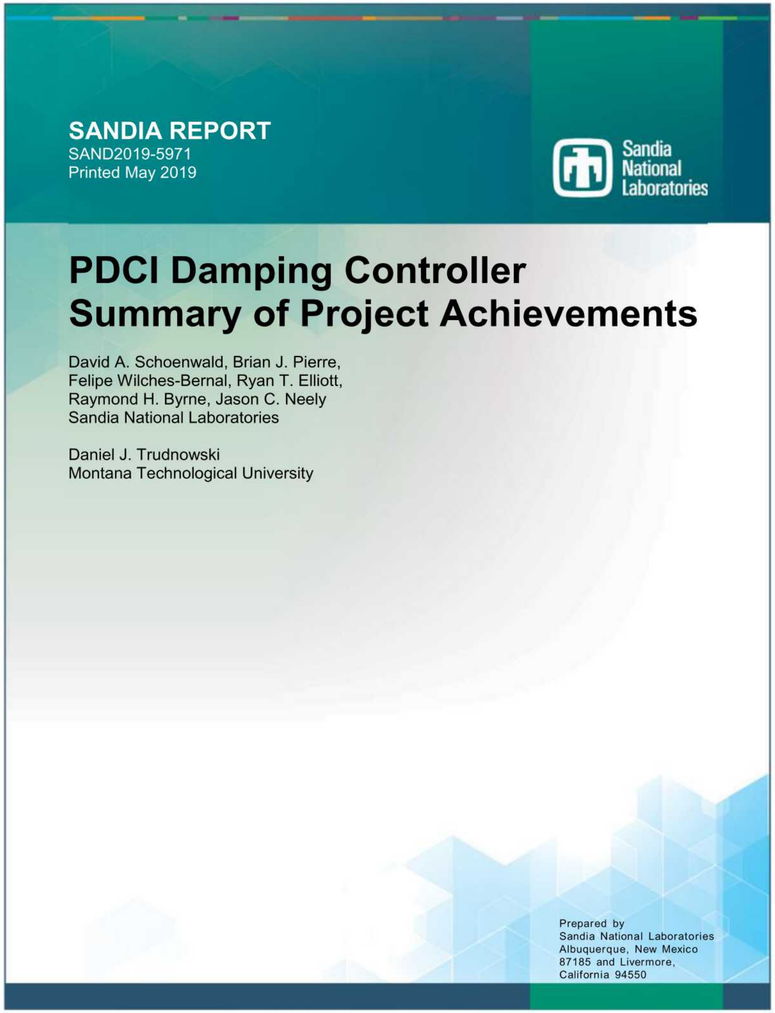

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PDCI Damping Controller Summary of Project Achievements

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Publications, Presentations: June 2018 – June 2019

Award

1. Felipe Wilches-Bernal, Outstanding Young Engineer Award, Albuquerque IEEE Section, "For outstanding development of control algorithms for distributed energy resources and wide area damping control," May 2019.

Journal Papers

1. B. J. Pierre, F. Wilches-Bernal, D. A. Schoenwald, R. T. Elliott, D. J. Trudnowski, R. H. Byrne, and J. C. Neely, "Design of the Pacific DC Intertie Wide Area Damping Controller," DOI 10.1109/TPWRS.2019.2903782, *IEEE Transactions on Power Systems*, accepted to appear in 2019, available now at https://ieeexplore.ieee.org/document/8663425.
2. C. Lackner, F. Wilches-Bernal, B.J. Pierre, D. A. Schoenwald, "A Tool to Characterize Delays and Packet Losses in Power Systems with Synchrophasor Data," *IEEE Power and Energy Technology Systems Journal*, Vol. 5, Issue 4, pp.117-128, December 2018.
3. M. Elizondo, R. Fan, H. Kirkham, M. Ghosal, F. Wilches-Bernal, D. Schoenwald, and J. Lian, "Interarea Oscillation Damping Control Using High Voltage DC Transmission: A Survey," *IEEE Transactions on Power Systems*, Vol. 33, Issue 6, pp. 6915 – 6923, November 2018.

Conference Papers

1. D. A. Schoenwald, F. Wilches-Bernal, B. J. Pierre, R. T. Elliott, and D. J. Trudnowski, "Data Considerations in Real-Time PMU Feedback Control Systems," North American SynchroPhasor Initiative (NASPI) Work Group Meeting, San Diego, CA, April 15-17, 2019.
2. F. Wilches-Bernal, D. A. Copp, G. Bacelli, R. H. Byrne, "Structuring the Optimal Output Feedback Control Gain: Soft Constraint Approach," IEEE CDC, Miami, FL, Dec. 2018.
3. R. A. Biroon, P. Pisu, and D. A. Schoenwald, "Inter-Area Oscillation Damping in Large-Scale Power Systems using Decentralized Control," 2018 ASME Dynamic Systems and Control Conference, Atlanta, GA, September 30-October 3, 2018.
4. F. Wilches-Bernal, D. A. Copp, D. A. Schoenwald, and I. Gravagne, "Stability Criteria for Power Systems with Damping Control and Asymmetric Feedback Delays," 50th North American Power Symposium, Fargo, ND, September 9-11, 2018.
5. F. Wilches-Bernal, B. J. Pierre, D. A. Schoenwald, R. T. Elliott, and D. J. Trudnowski, "Time Synchronization in Wide Area Damping Control of Power Systems," 2018 Probabilistic Methods Applied to Power Systems (PMAPS) Conference, Boise, ID, June 24-28, 2018.

Reports

1. D. Schoenwald, D. Trudnowski, B. Pierre, F. Wilches-Bernal, R. Elliott, R. Byrne, J. Neely, "PDCI Damp. Cont. Test Results & Proj. Sum.," SAND2019-5972, May 2019.
2. D. Schoenwald, D. Trudnowski, B. Pierre, F. Wilches-Bernal, R. Elliott, R. Byrne, J. Neely, "PDCI Damp. Cont. Sum. Proj. Achievements," SAND2019-5971, May 2019.
3. D. Schoenwald, C. Rawlins, B. Pierre, F. Wilches-Bernal, R. Elliott, "Exec. Sum. to PDCI Oscillation Damping Cont. Software Document," SAND2018-10049, September 2018.
4. C. Rawlins, D. Schoenwald, B. Pierre, F. Wilches-Bernal, R. Elliott, "PDCI Oscillation Damping Controller Software Documentation," SAND2018-10048, September 2018.

Presentations

1. D. Schoenwald, "Challenges in the Use of PMU Data for Real-Time Feedback Control," PMU Metrology Meeting, Richland, WA, April 16, 2019.
2. D. Schoenwald, "Real-Time Damping of Power Grid Oscillations Using PMU Feedback," CURENT Seminar, Knoxville, TN, March 1, 2019.
3. D. Schoenwald, "Lecture on Technology Transfer at Sandia National Labs," Webinar to Portland State Univ. Eng. Class, February 19, 2019.
4. D. Schoenwald and F. Wilches-Bernal, "Real-Time Damping Control Using PMU Feedback," JSIS Meeting, Portland, OR, November 9, 2018.
5. D. Schoenwald, "Grid Stability Using Distributed Energy Storage," DOE Energy Storage Program Review, Santa Fe, NM, September 26, 2018.
6. D. Schoenwald, "Wide-Area Damping Control Using PMU Feedback," Oscillation Analysis Work Group Webinar, July 17, 2018.

Next Steps

- Generalized Damping Control Theory/Methodology
- HVDC-side Impact Studies
- Distributed Control
- Transient Stability

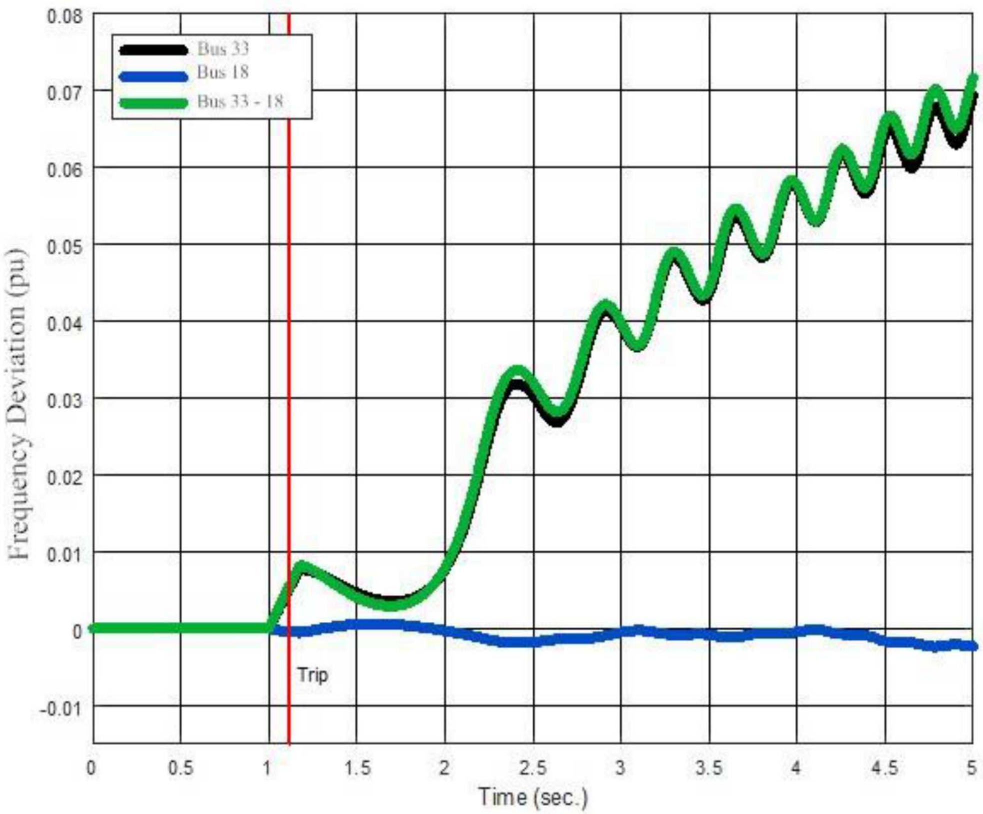
DOE/OE Transmission Reliability Program

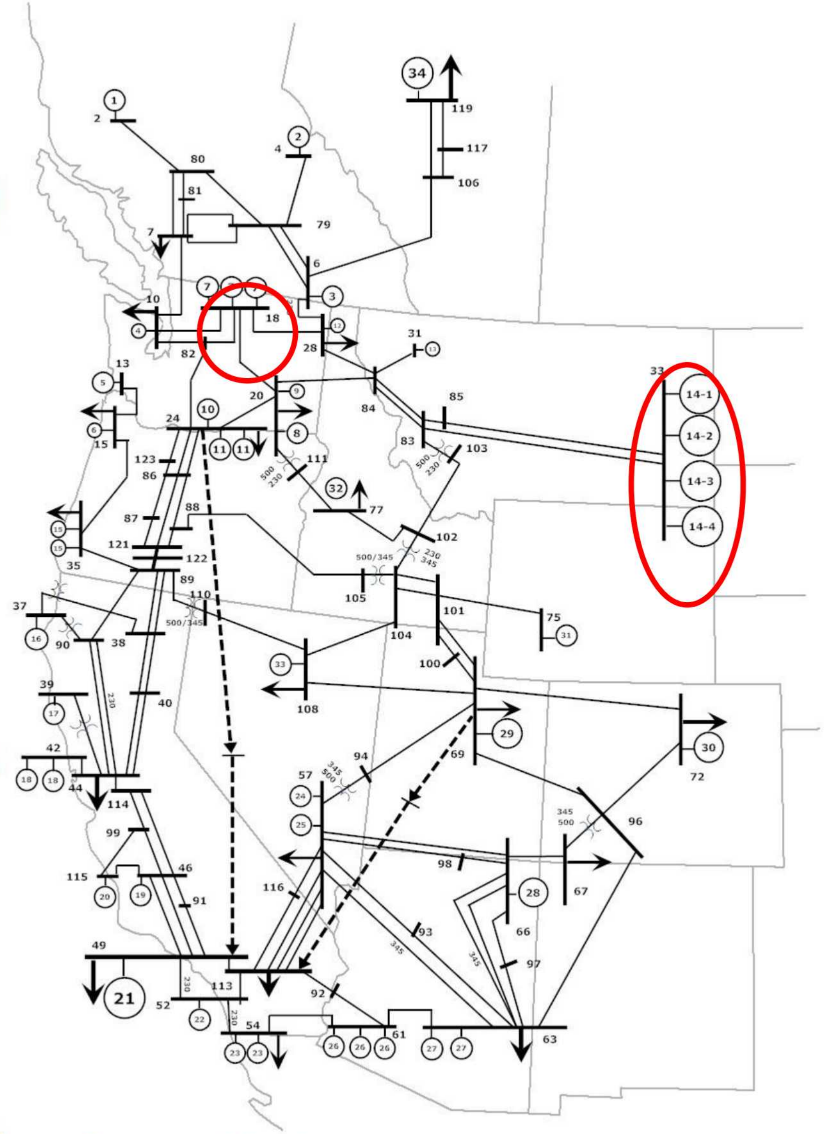
Transient Stability Control via Wide-Area Feedback

Overview

- Grid stability mechanisms
  - Transient stability (TS)
  - Small-signal stability (SSS)
  - Voltage stability.
- Past research focused on SSS, new research focused on TS.
- TS Control
  - Generator tripping
    - Extreme case
    - Widely used
  - Dynamic braking
    - Few cases of actual implementations
  - Other researched approaches – series and shunt FACTS devices (eg, TCSC)
- Today's TS state-of-the-art control based on locally measured signals. This poses the potential for invalid control (such as false tripping).
- Recent research has demonstrated reduced false generator tripping via wide-area measurements.
- New research focusing on TS controls:
  - Energy storage and Dynamic braking control
  - Use of wide-area measurements
  - Coordination of multiple devices

Local Fault Example





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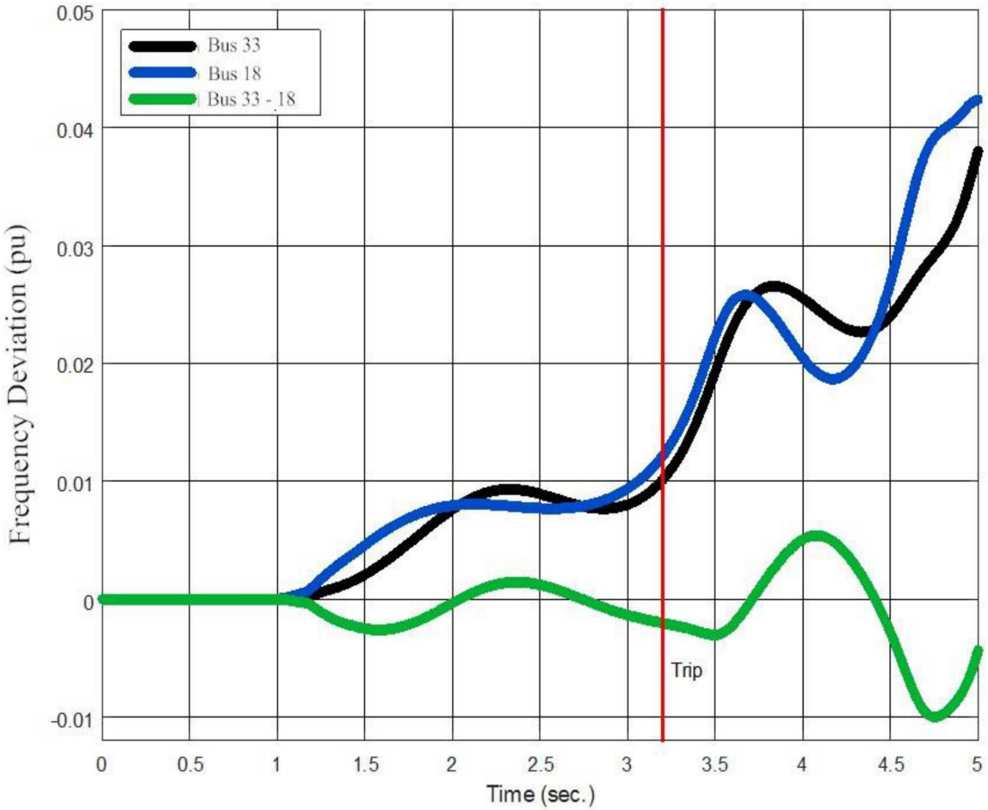
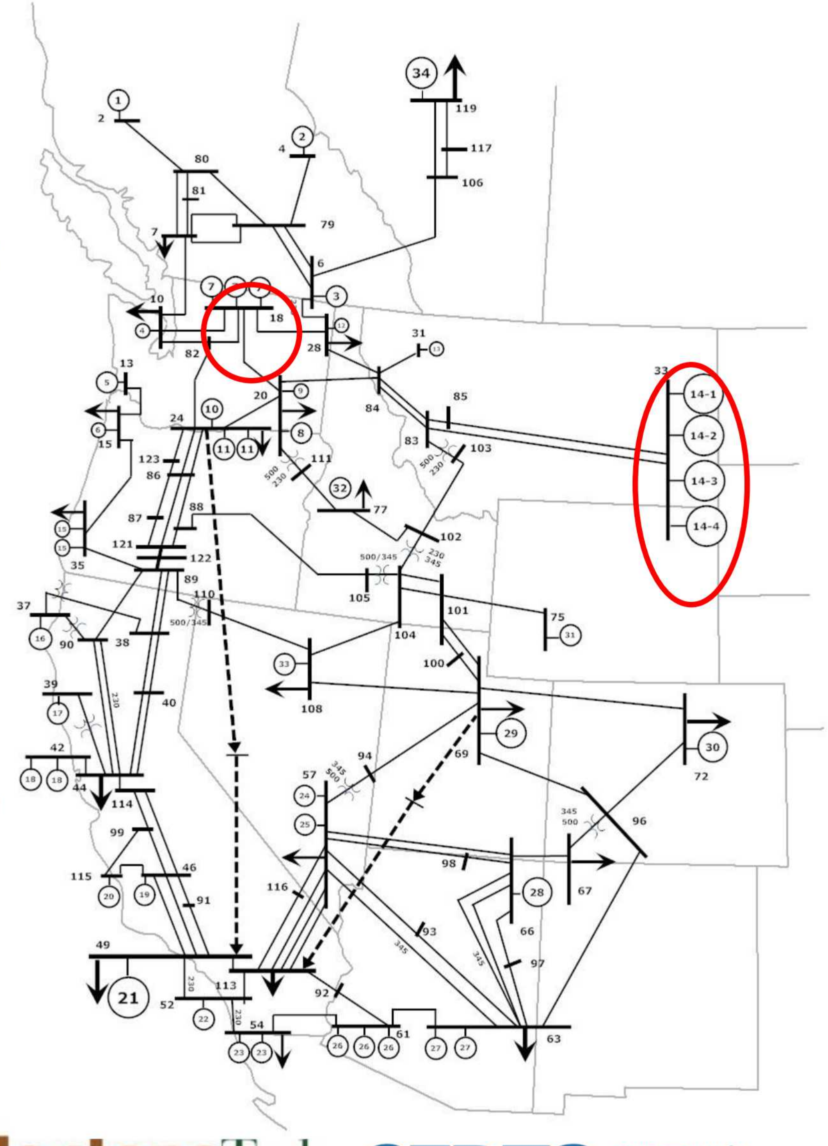
Remote Fault Example





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Control Concept

Relative Frequency Feedback

- Control based on relative speed of generator, $\Delta f \approx \dot{\delta}$
- Utilizes Center-of-Inertia (f_{CI}) frequency*.
- Controller goals:
  - Optimizes TS benefit
  - Does not interact with frequency regulation.
  - Control strategy based on Energy Methods (e.g., EAC)
- Initial concepts

Concept 1: Linear control

$$P_{ec} = K_v \Delta f + K_a \Delta \dot{f}$$

Concept 2: Nonlinear control

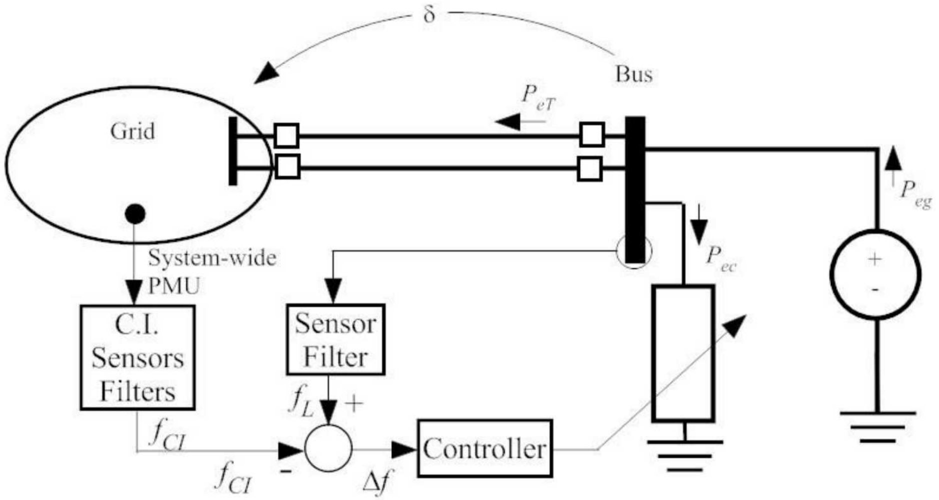
$$P_{ec} = f(\Delta f, \Delta \dot{f})$$

E.g.,

$P_{ec} = K|\Delta \dot{f}| sgn(\Delta f)$ = Phase plane design

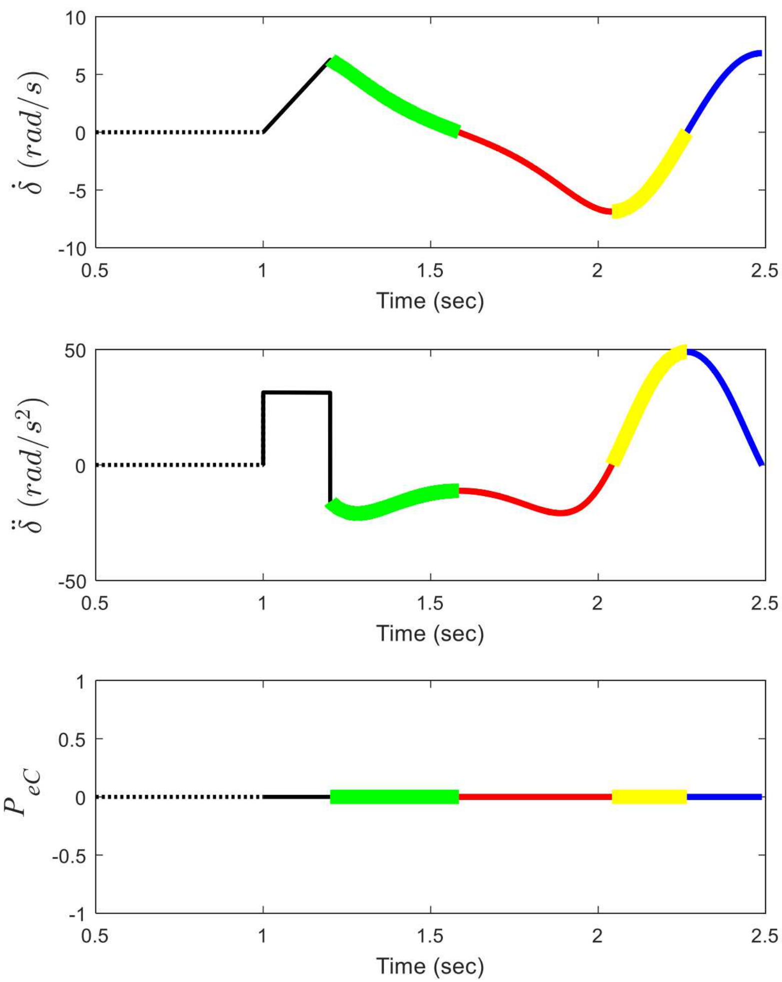
or

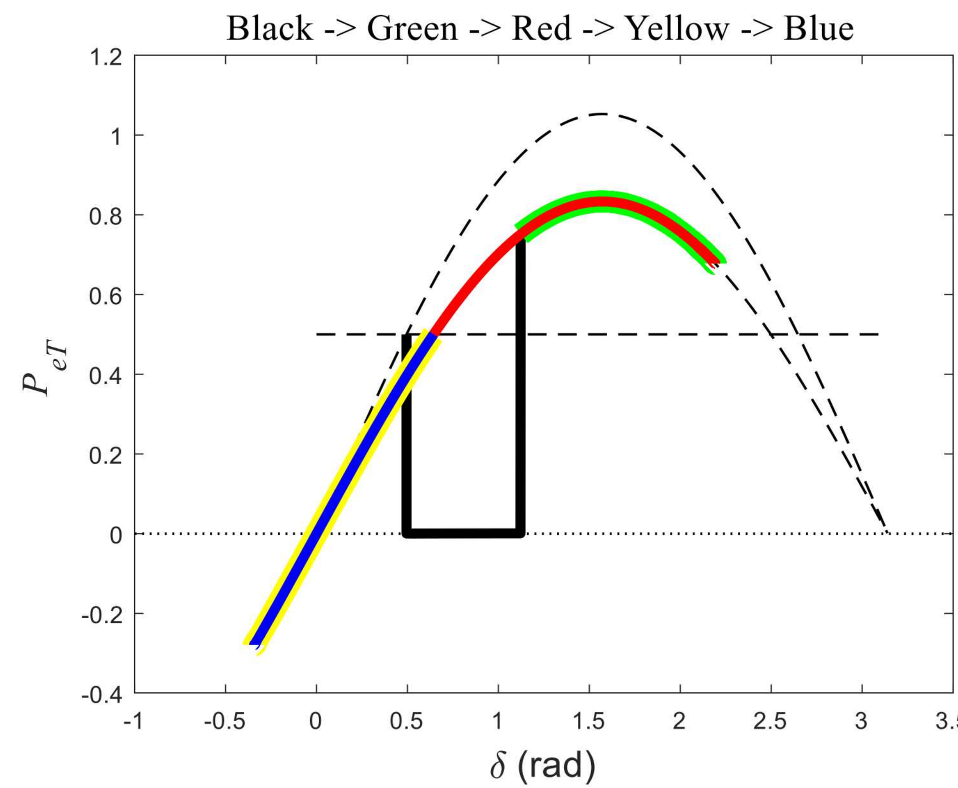
$P_{ec} = KE(\Delta f, \Delta \dot{f})$ = Kinetic Energy function



*S. Stanton, et. al., "Application of Phasor Measurements and Partial Energy Analysis in Stabilization of Large Disturbances," IEEE Trans. on P.S., vol. 10, no. 1, Feb. 1995.

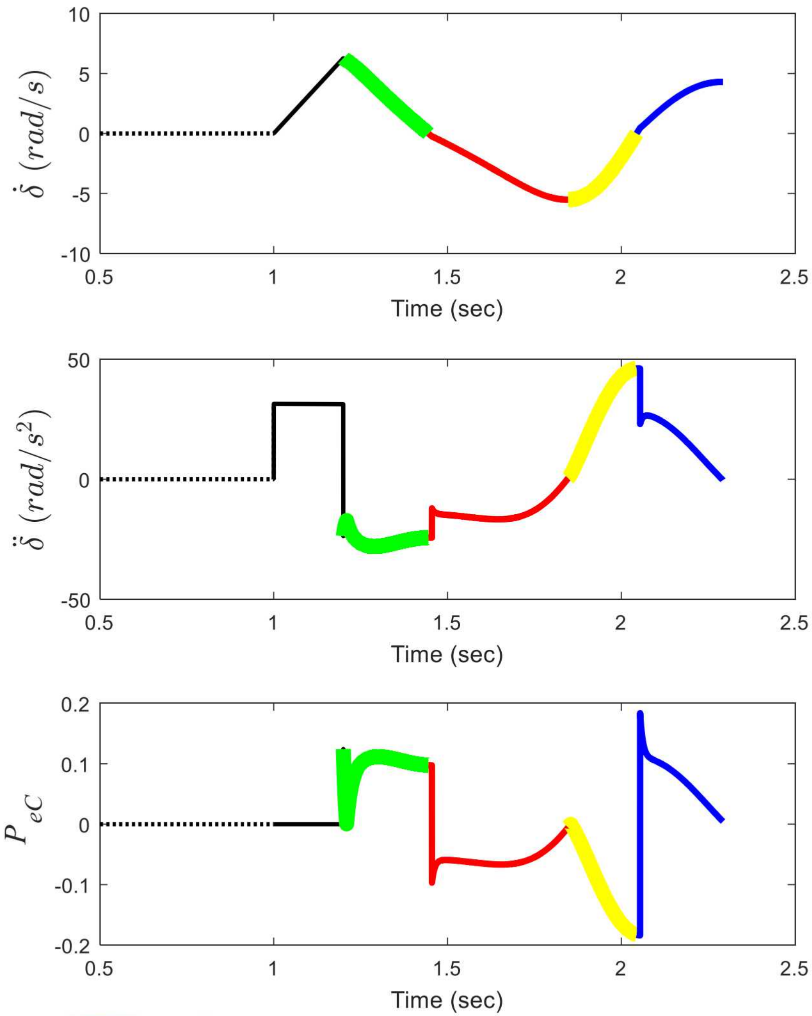
No Control Example

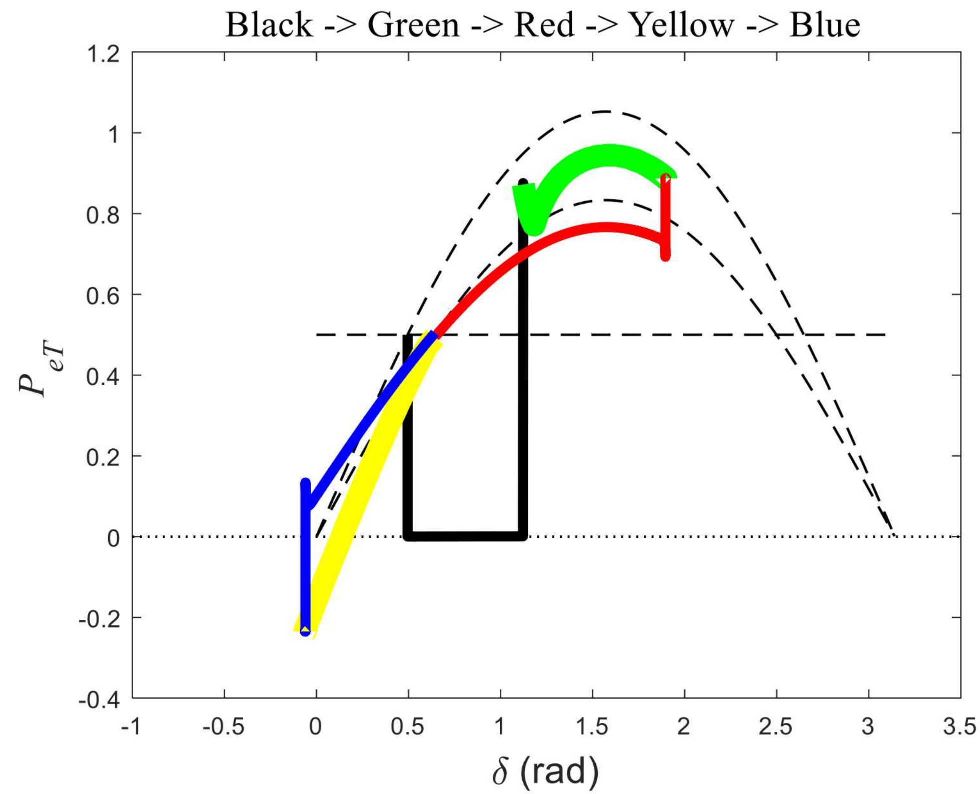




Control Example

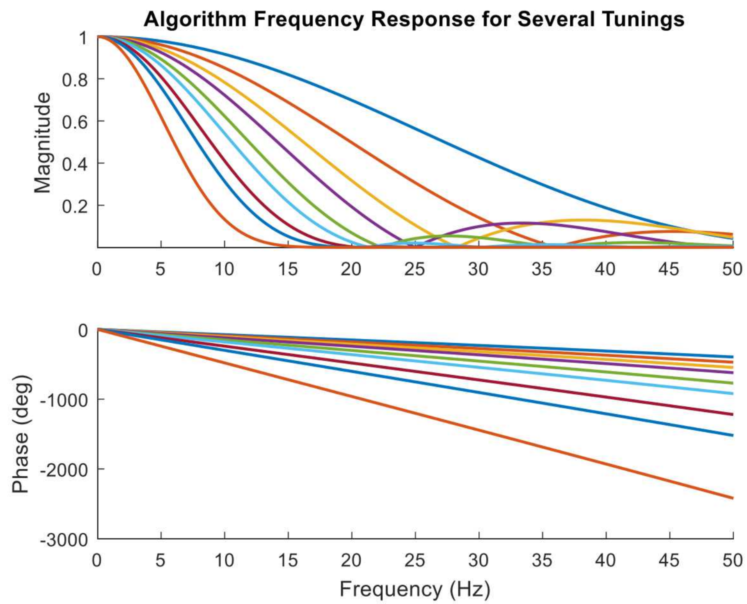
$$Pec = 0.004|\ddot{\delta}|sgn(\dot{\delta})$$

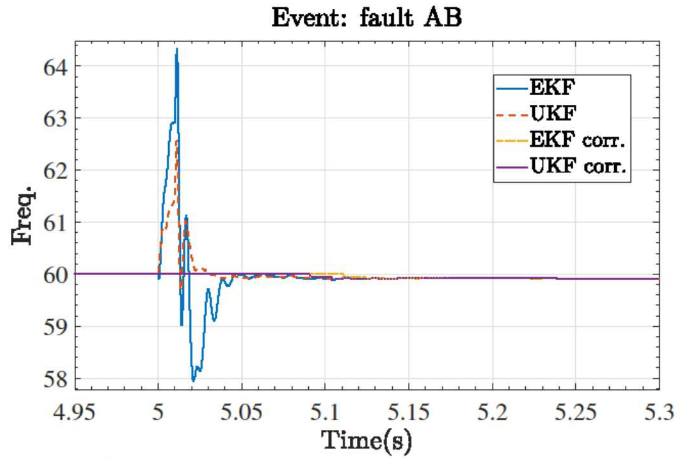




Frequency Measurement

- Frequency estimates required for feedback controller.
- Several algorithms have been evaluated:
  - DFT-based (used in many PMUs)
  - Phase-locked loops (used for inverters)
  - Kalman filter-based
  - Least squares curve-fitting
- DFT and PLL have greatest potential for application
- Algorithms can be tuned to trade off bandwidth/latency vs. noise immunity and to reject disturbances such as harmonics
- Nearby events can cause severe waveform deformities (such as phase jumps) which corrupt frequency estimates
  - Difficult for algorithms to maintain adequate bandwidth while at the same time rejecting these disturbances – seeking methods for graceful ride-through
- Future research – find appropriate models of the algorithms to include in transient stability simulation software





Research primarily performed under Frequency Estimation Project in DOE/OE Advanced Grid Modeling Program

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Research Plan

- Develop control strategies using wide-area feedback
  - Focused on dynamic braking and energy storage
  - Decentralized coordination of multiple devices
  - Grounded in energy methods
  - Linear vs. nonlinear methods
  - Optimize available brake/energy-storage usage
- Investigate and tune frequency and acceleration estimation approaches.
  - Both remote and local signals
  - Center-of-Inertia calculation and control areas
- WECC test cases
  - Develop transient stability base cases
  - Include inverter-based generation
  - Test and demonstrate TS control in base cases.

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