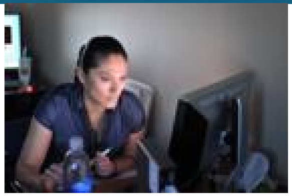
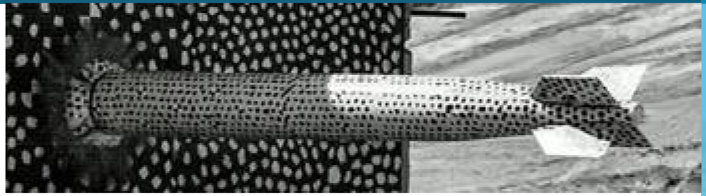
SAND2021-15274PE

Optimization of Control at Scale

David Schoenwald

Sandia National Laboratories

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Overview of Talk

Primary Objective of Work

Develop computationally tractable control and optimization techniques for stable, resilient operation of large-scale power grids

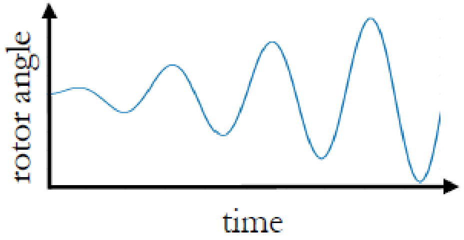
Key Enablers of Successful Control Strategies

- Distributed Controls Using Energy Storage
- Power Injection from Inverter-based Renewable Energy
- Wide-Area High Speed Measurement Systems
- Modulation of High Voltage DC Transmission

Power System Stability Definitions

- **Power System Stability** — Ability to remain in operating equilibrium
  - **Angle Stability** — Ability to maintain synchronism
    - **Small-Signal Stability**
      - **Non-oscillatory Stability**
      - **Oscillatory Instability**
        - Insufficient damping torque
        - Unstable control action
    - **Transient Stability**
  - **Voltage Stability** — Ability to maintain steady acceptable voltage

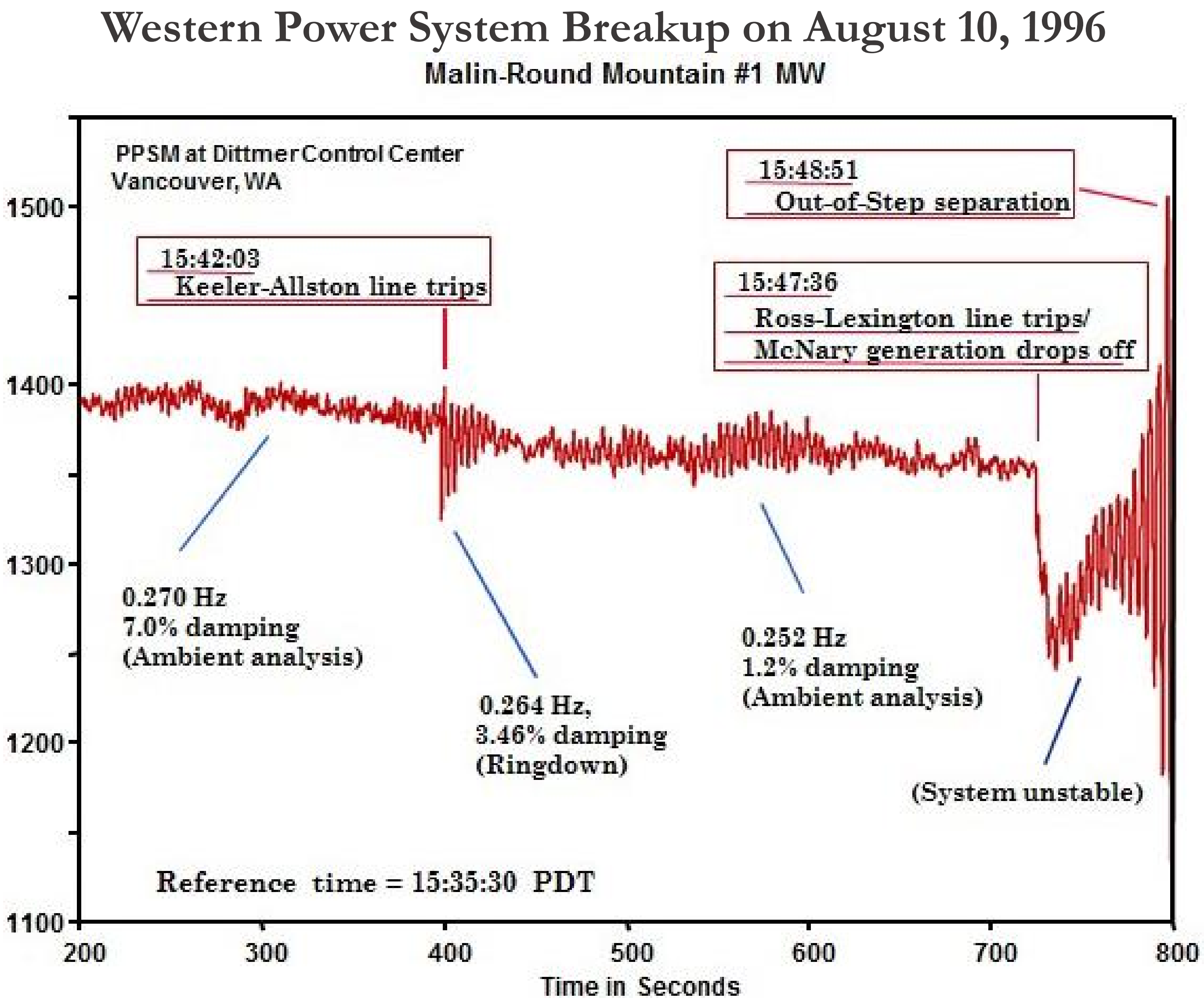
Small disturbances occur continually because of small variations in loads and generation.



Kundur, "Power system stability and control," McGraw-Hill, 1994.

Inter-Area Oscillations Jeopardize Grid Stability

- Low frequency (0.1-1 Hz) oscillations characteristic of interconnected power systems separated by long transmission corridors excited by normal variations in system load.
- Can lead to instability and system breakup if poorly damped.
- Power system stabilizers (PSS) were primarily designed to damp local oscillations.
- Recently, the availability of wide-area measurements enables wide-area damping control.



BPA Damping Controller Project

- Based on 1970s BPA experiments on Pacific DC Intertie (PDCI) later shown to have destabilized BC-US oscillatory mode.
- Idea revived in 2012 by leveraging Phasor Measurement Unit (PMU) deployments in Western Interconnection.
- Project launched in June 2013 as a collaboration of Sandia, Montana Tech, BPA, and DOE-OE (Energy Storage & Transmission Reliability Programs) to develop and demonstrate damping control on the North-South oscillatory mode using wide-area PMUs for real-time feedback.
- Real-time PMU feedback is the key to stable control.

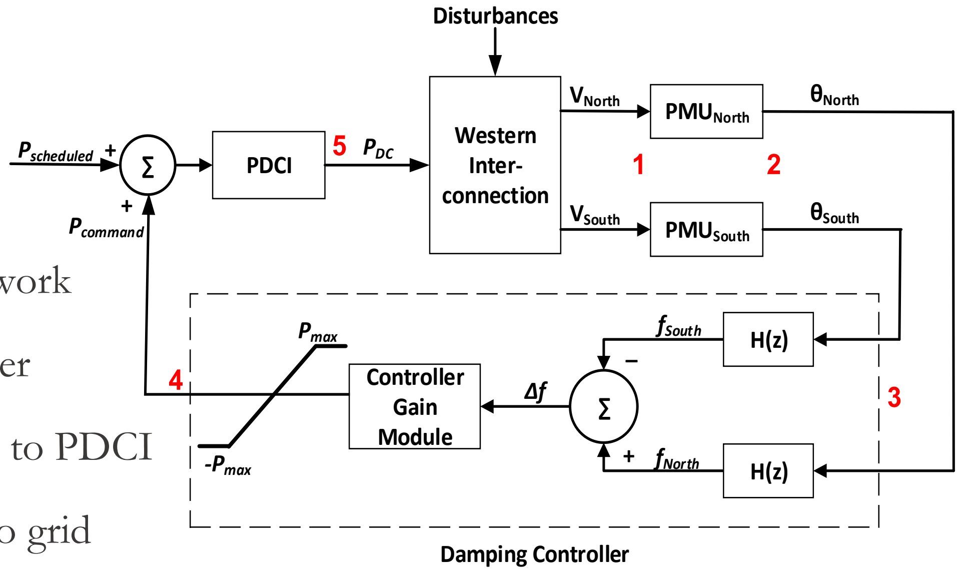
1 PMUs take measurements

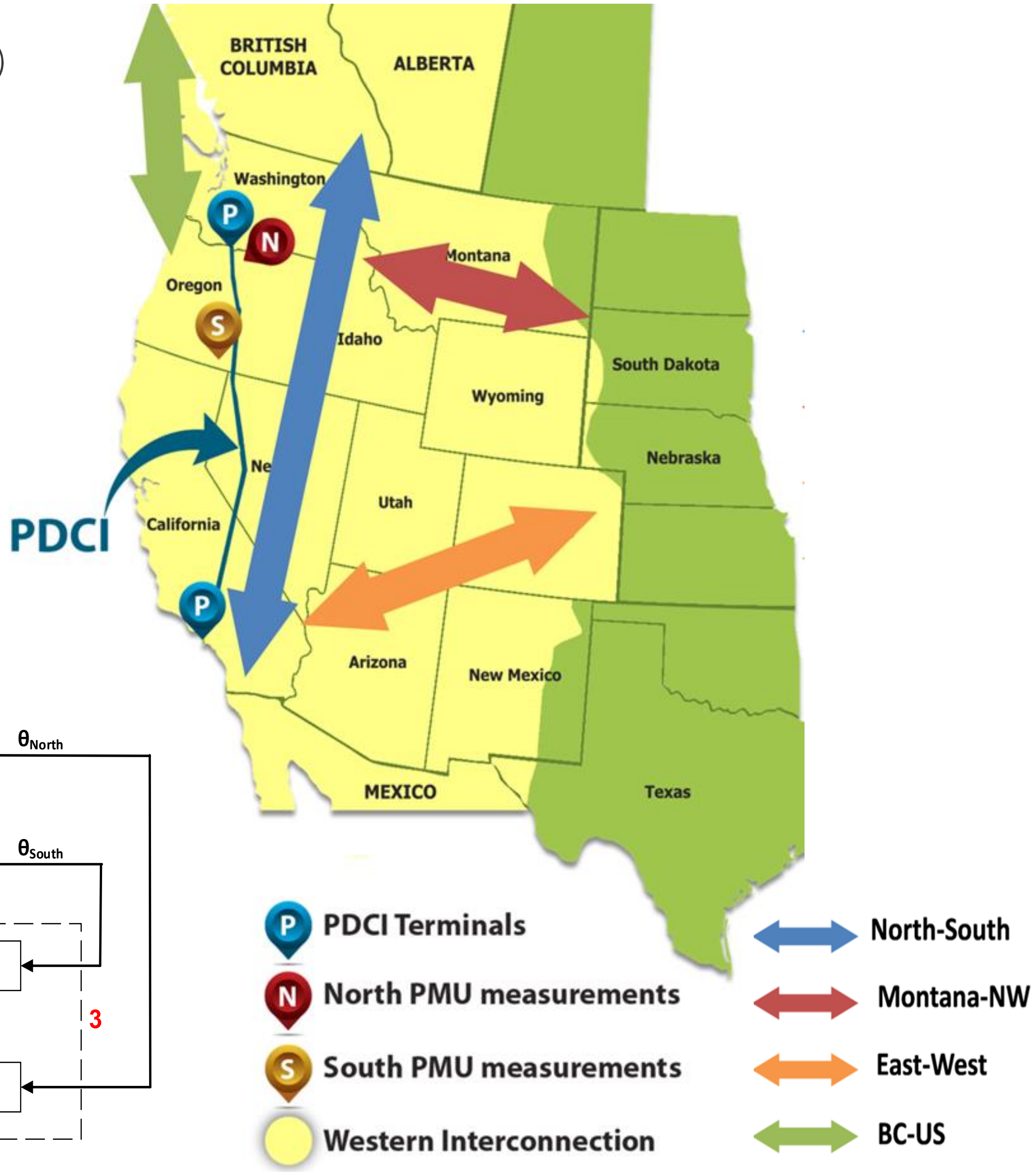
2 PMUs send data packets over network

3 Packets arrive at damping controller

4 Controller sends power command to PDCI

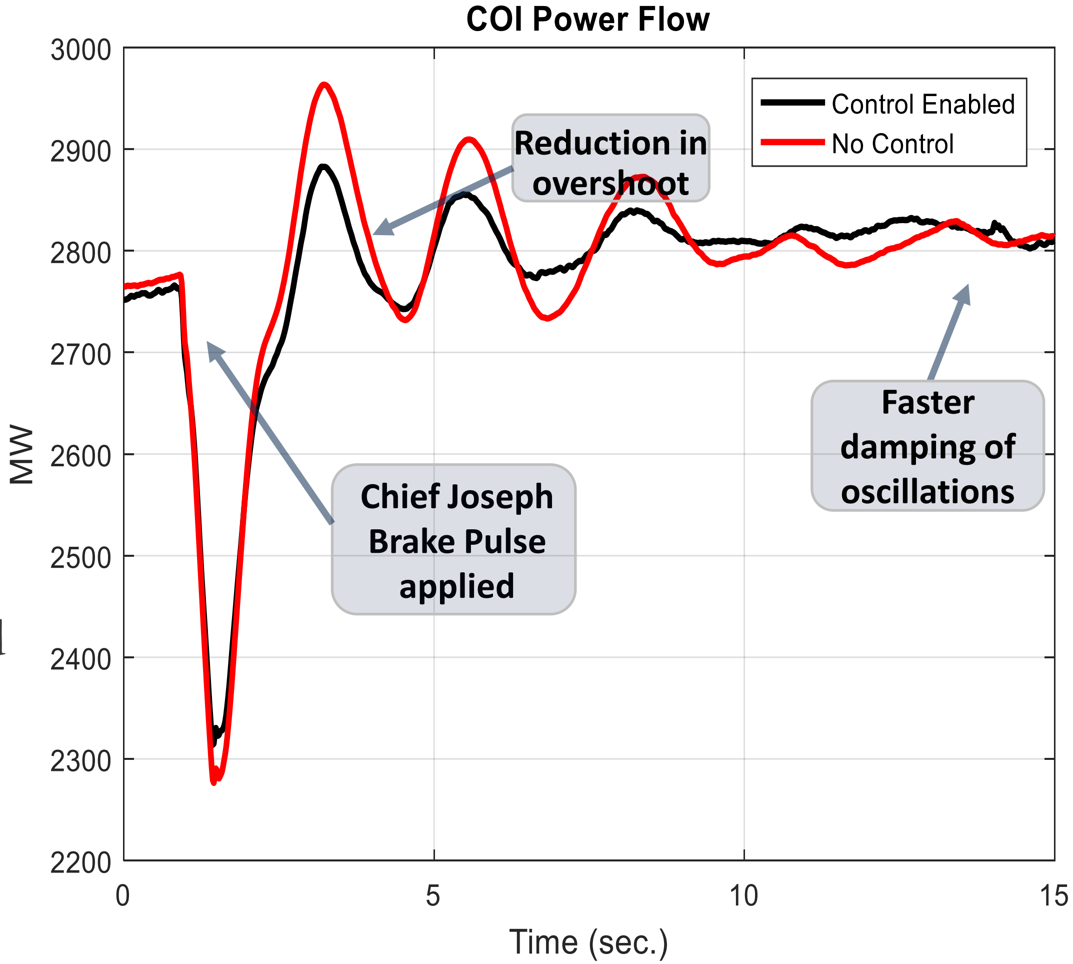
5 PDCI injects power command into grid

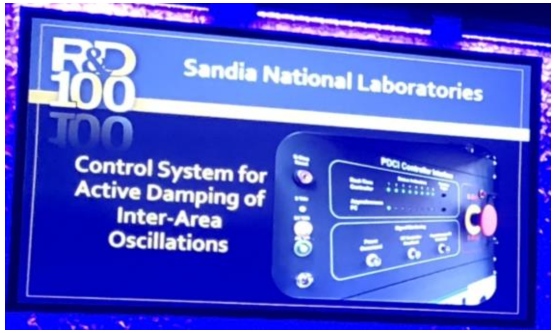




Tests Conducted at Celilo Converter Station, The Dalles, OR

- First successful demonstration of wide-area control using real-time PMU feedback in North America.
- Experience gained in networked controls will advance control design using distributed assets, such as energy storage and smart inverters.
- Supervisory system architecture can be applied to future real-time grid control systems to ensure “Do No Harm”.
- 2017 R&D 100 Award
- US Patent 11,050,262 B1 Issued June 29, 2021



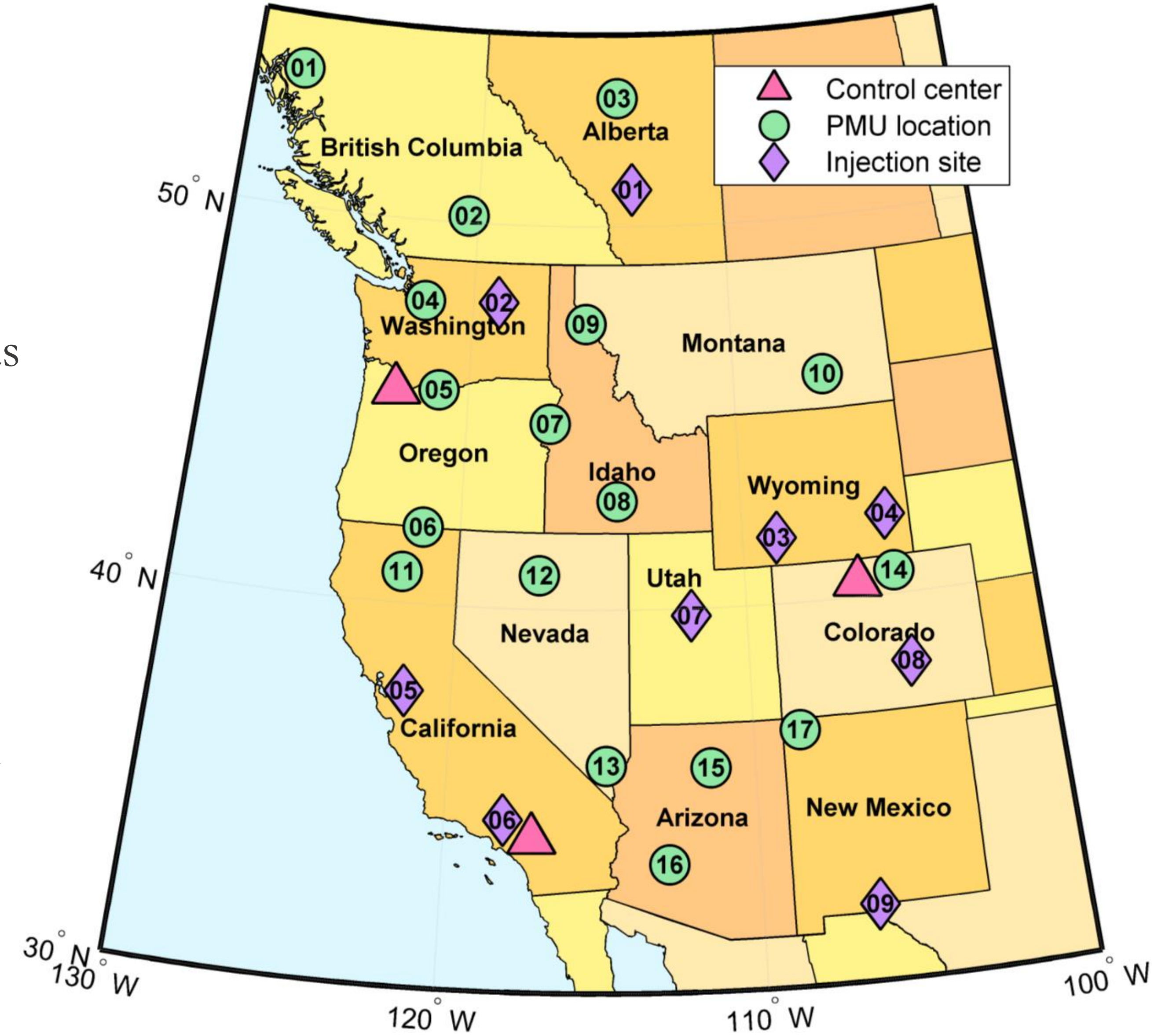


Chief Joseph brake test	Damping of North-South B Mode improved 4.5 percentage points (11.5% to 16.0%) in closed-loop vs. open-loop operation.
Square wave pulse test	Damping controller significantly reduces amplitude of North-South B mode oscillations in 15 seconds vs. 23 seconds in open-loop tests for the same reduction.
All tests	Controller consistently improves damping and does no harm to grid.

Damping Control Using Distributed Energy Storage

Advantages of using distributed energy storage:

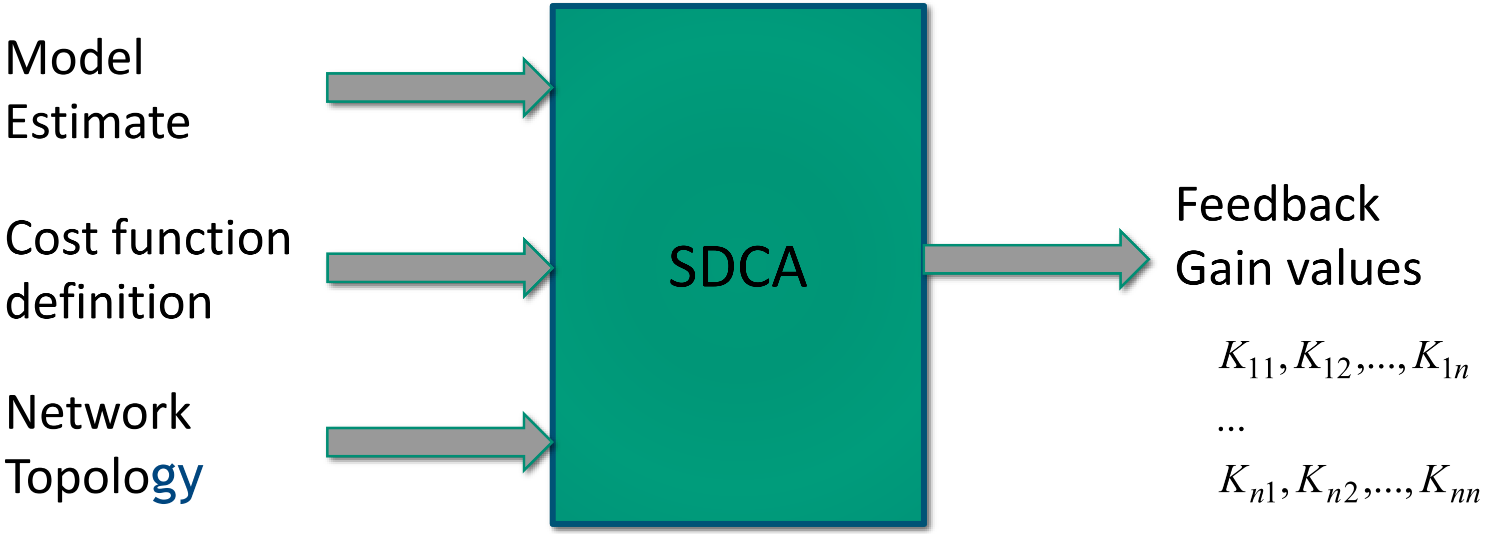
- Robust to single points of failure
- Controllability of multiple modes
- Size/location of a single site not critical as more energy storage is deployed on grid
- With potentially 10s – 100s of storage sites engaged, single site power capability ≈ 10s – 100s kW can provide improved damping
- Control signal is energy neutral and short in time duration ➔ storage sites can perform other applications



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

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



An Optimization Problem is Formulated

To attain the control law

$$u_d = -K_d y$$

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

$$\text{subject to:}$$

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

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

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

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

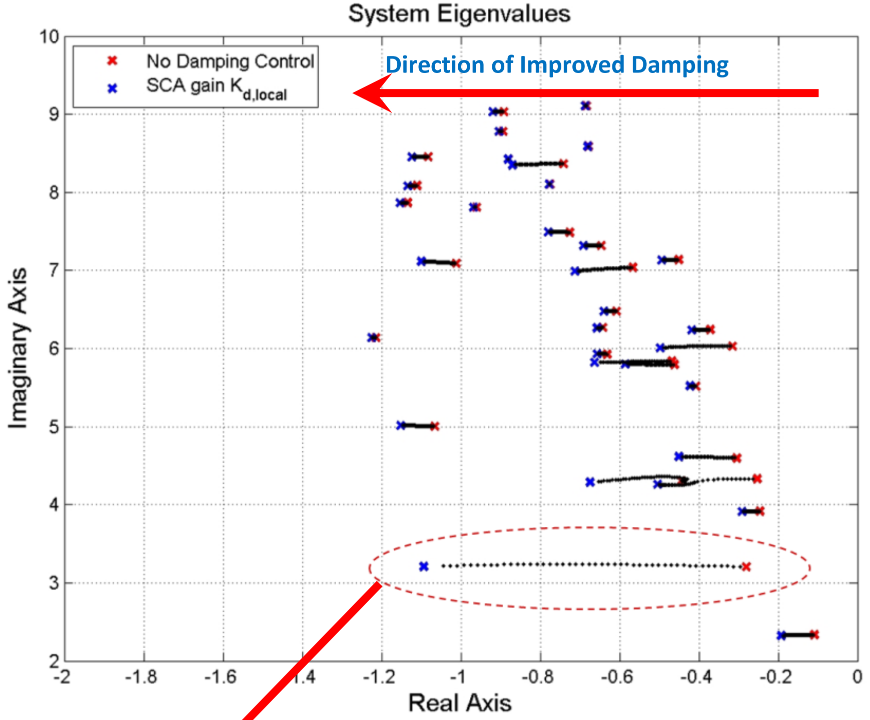
The above optimization problem must be solved iteratively

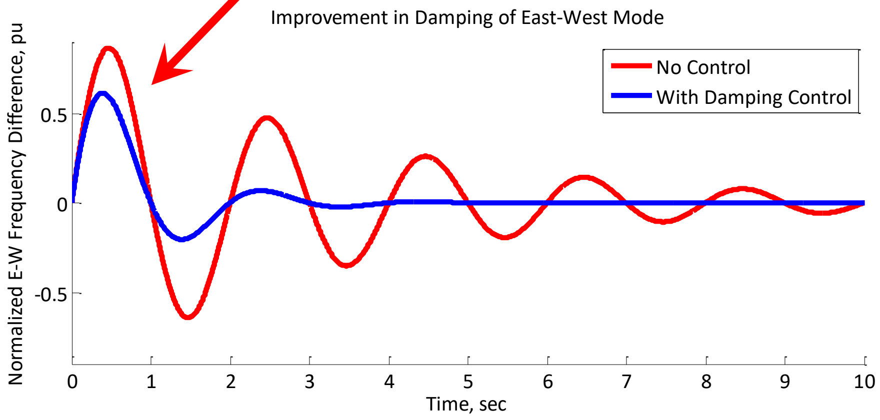
For solution details, see the journal paper:

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.

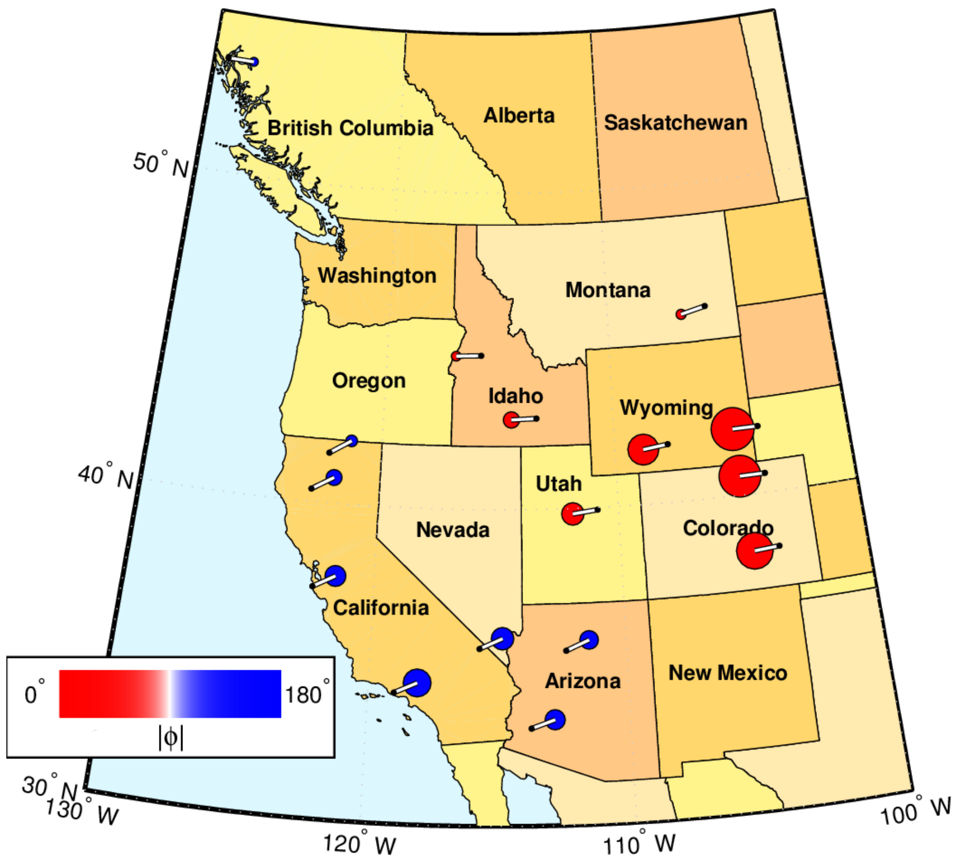
Example: Structured Optimal Control

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





East-West Mode



Transient Stability Control Objectives

- Prevent loss of synchronism following large disturbances (e.g., faults)
- Minimize underfrequency load shedding (i.e., keep the lights on)
- Increase line ratings on stability-limited transmission corridors
- Build in tolerance to communication delays and measurement noise

Voltage Stability Control Strategies

Local Control

- Local voltage measurements
- Active/ Reactive power support
- No communication
- Control stability cannot be guaranteed

Decentralized and Distributed Control

- Low-form of communication typically between neighboring nodes
- Improved control stability
- Does not guarantee optimality

Centralized Control

- Control based on full system measurement
- Sophisticated communication
- Stability and optimality can be guaranteed

Control Strategies Utilizing Hybrid/Hierarchical Architectures

Network Considerations

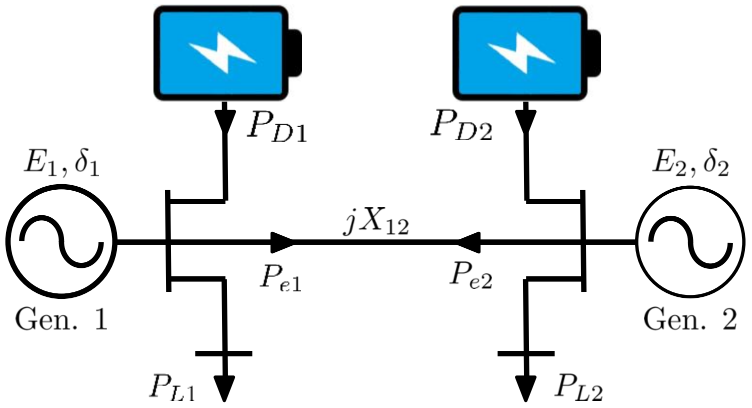
Future implementations will not always be on secure, resilient, efficient networks.

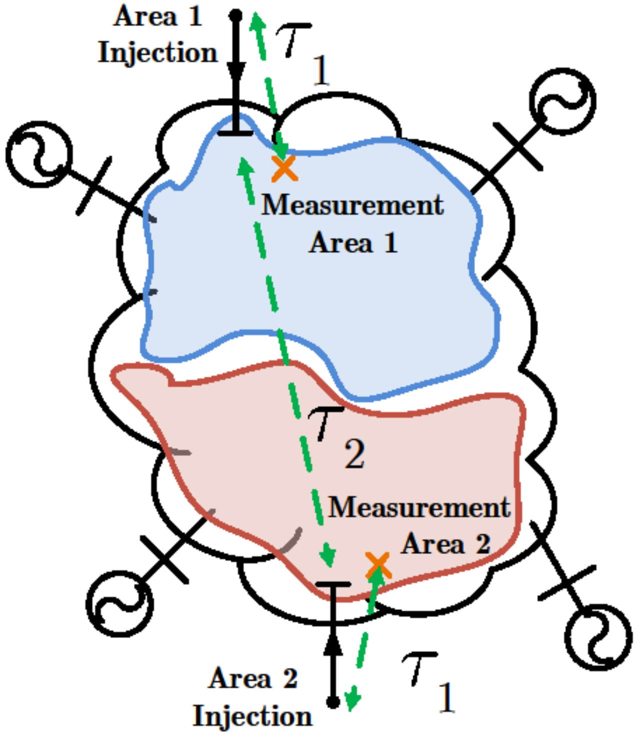
Must accommodate:

- Packet dropouts
- Privacy concerns
- Latency (time delays)

How much delay can the system handle?

How is the performance of the distributed controls impacted by the presence of delays?





Grid Energy Storage - Gaps?

- Technology - Need further improvements in cost and performance
  - Lower cost, longer duration energy storage is a major gap
  - Technologies that can scale from microgrids to large transmission applications
  - Further improvements in safety and reliability
- Energy storage is new for the electric utility industry
  - Markets and Operations – Business Models and Operational Tools
  - Analytics – Economics and Planning tools
  - Appropriate Regulatory Policy – Business Models, Asset Classification
- Industry needs cycles of learning - manufacturing scale through deployments
  - Project finance - bankable, warrantees, Performance guarantees, risk management
  - Standardization- equipment, permitting, construction processes

Future Work in Distributed Control Using Energy Storage

- Big data methods to handle thousands of sensor measurements
- Cyber security concerns using network-based approaches
- Hybrid control strategies that combine distributed ES with other sources of power injection, e.g., PSSs, SVCs, HVDC
- Demonstrations of control strategies – at scale on large grids
- Better simulation tools to capture dynamic behavior of large # of inverter-based resources

Acknowledgements

Co-contributors on this work:

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