SAND2018-3654PE

Distributed Control for Improving Power System Stability

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April 12, 2018

Outline

- Motivation
  - Today's electric power grid
  - Changing resources and challenges
  - Power system stability
- Wide-area damping control
  - HVDC and other distributed resources
  - Communication network considerations
- Conclusions & future challenges

The Electric Power Grid

Millions of complex physical, communications, computational, and networked components and systems.

Our complex modern society depends on reliable electric supply, requiring a resilient electric power grid.

New instrumentation, sensing, communication, and automation:

- Pro: Situational awareness, efficient operation, and corrective action
- Con: Additional complexity

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National Academies Press 2017

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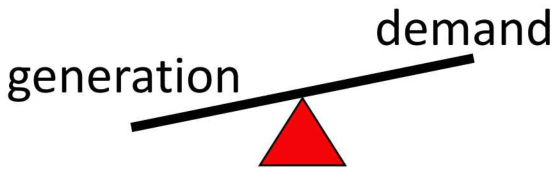
Power System Operation and Control

- Balance power generation and demand continuously



- Maintain scheduled voltages
- Monitor flows and thermal limits
- Maintain system stability
- Operate system reliably even if a contingency occurs, such as the loss of a generator or transmission facility

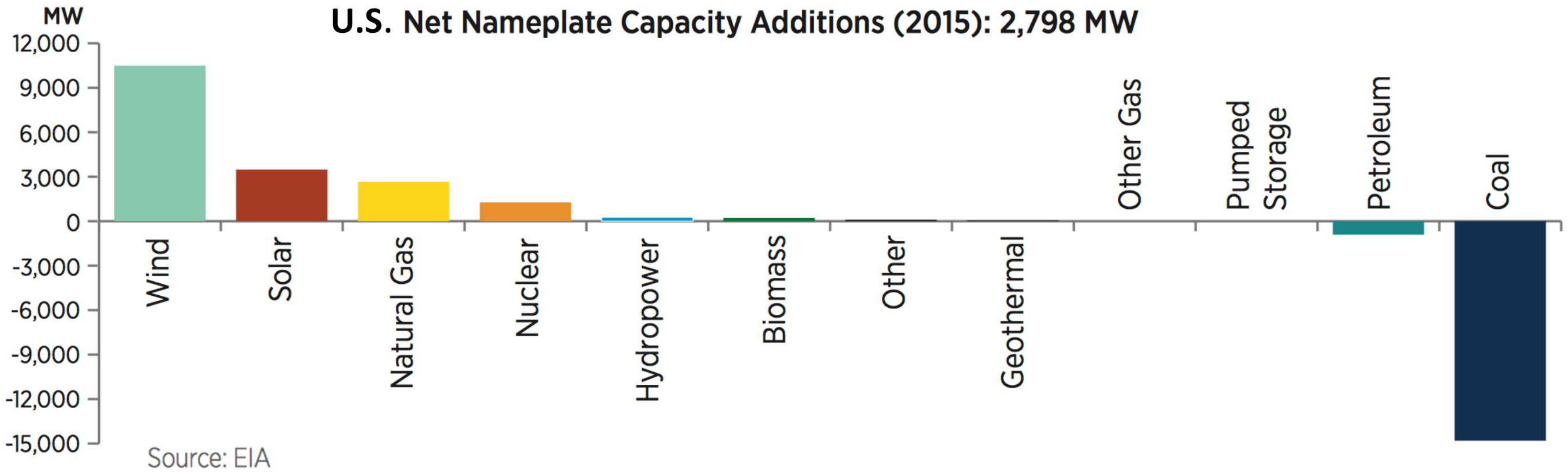

phys.org

Historically done with local resources, such as:

- Generator governor
- Power System Stabilizer (PSS)
- etc.

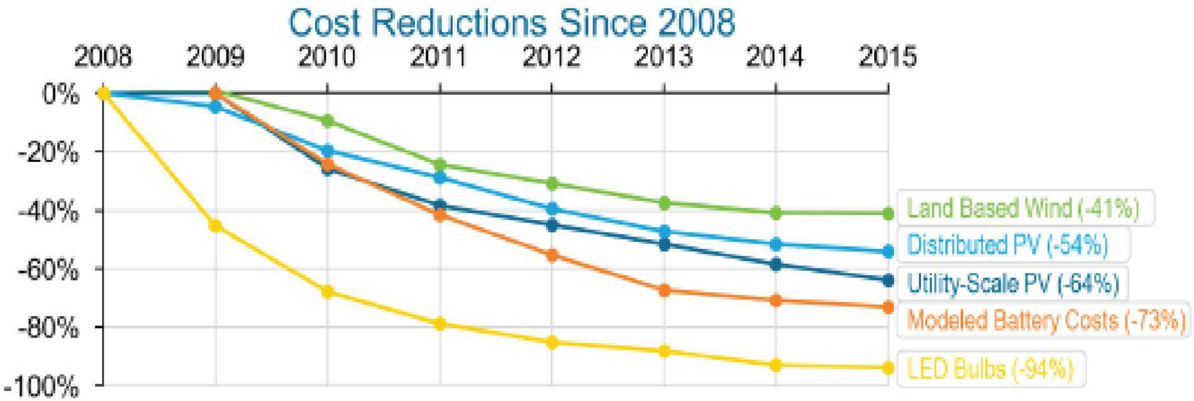
<u>Now, distributed resources may be used.</u>

Changing Generation Mix



Reductions in solar and wind capital costs and clean energy tax credits sustaining rapid renewable growth.

Cost reductions primarily due to high volume manufacturing and large scale deployments.



http://energy.gov/eere/downloads/revolutionnow-2016-update

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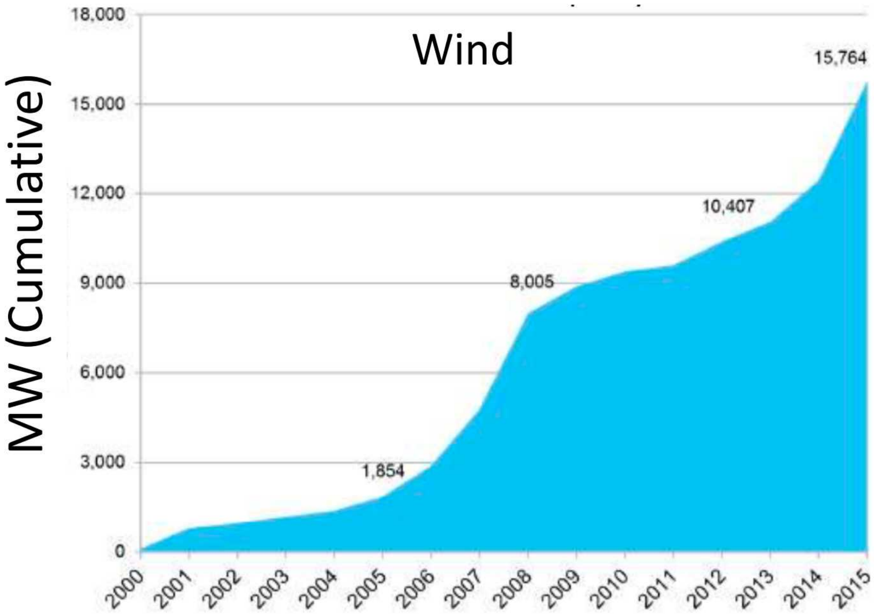
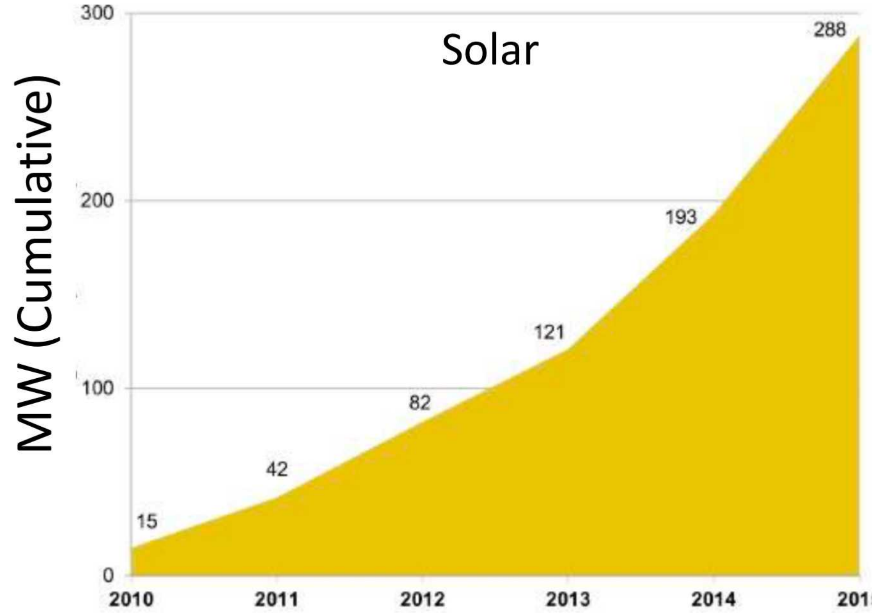
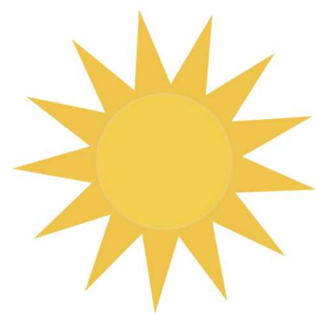




>19,900 MW of installed wind capacity, the most of any state in the nation.

Wind Generation record:
16,141 MW (March 31, 2017)

Wind Penetration record:
54 percent (October 27, 2017)



1,000 MW of utility-scale installed solar capacity as of October 2017

Solar capacity in queue:
2017: 109 MW
2018: 791 MW

State of the Grid Report 2015 & ERCOT Quick Facts

CAISO "Duck Curve"

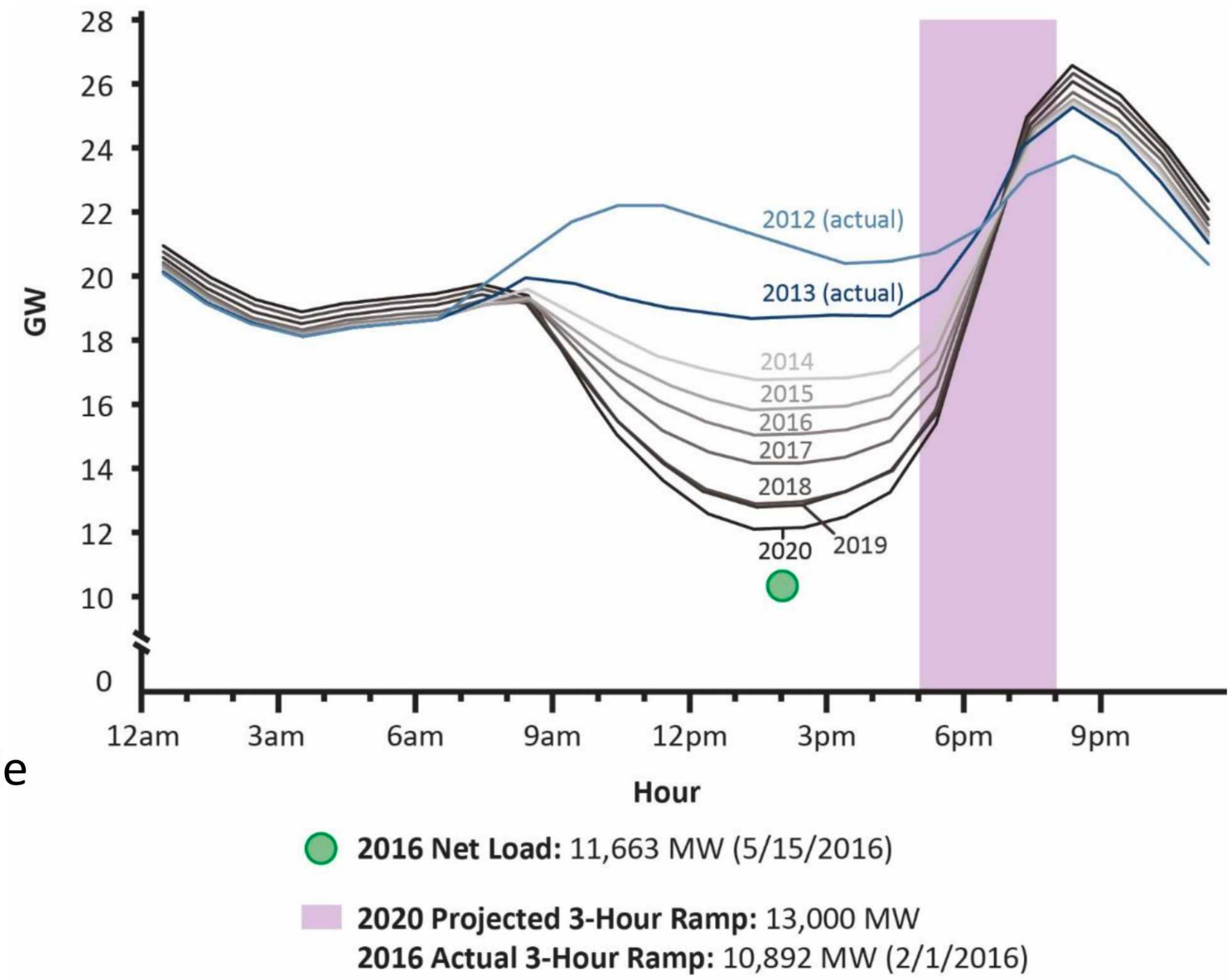
Energy and environmental goals are driving change.

Emerging grid conditions:

- Short, steep ramps
- Oversupply risk
- Decreased frequency response
    - Lower inertia

Need flexible, controllable resources to match variable demand and variable supply.

www.caiso.com



13 GW / 3 hr > 72 MW / min

NERC State of Reliability June 2017

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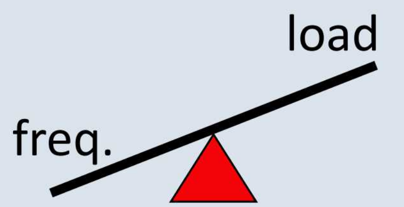
Stability Challenges Related to Renewables

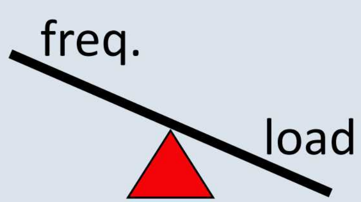
- Need to be firmed and made dispatchable
- Mostly cannot respond to frequency changes
- Lower inertia → faster rate of change of freq. (RoCoF) and lower nadir
- Often steep ramps

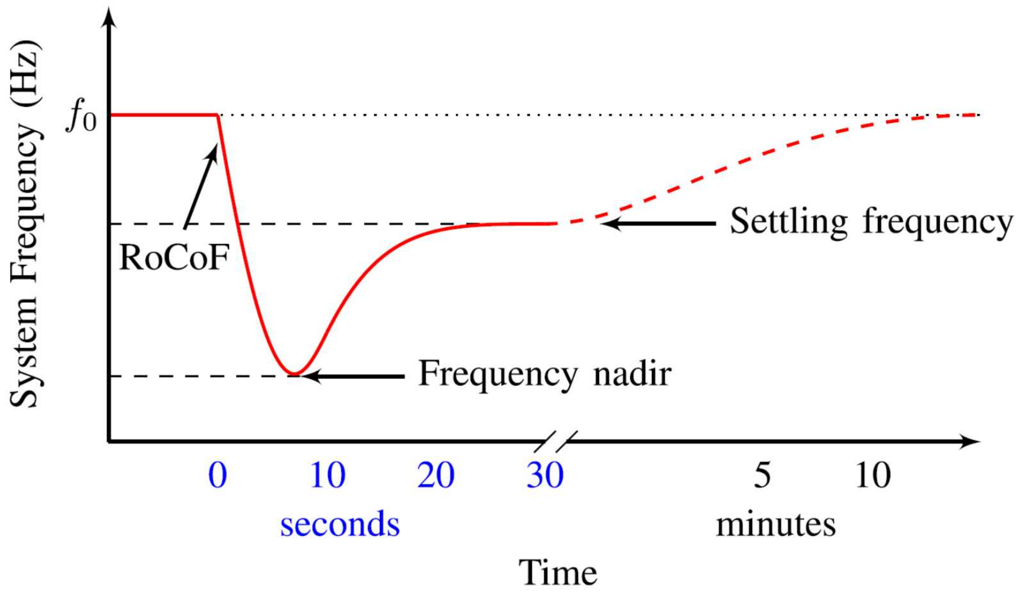
<u>Frequency control:</u>

Freq. ↓ with active power deficit.



Freq. ↑ with active power surplus.



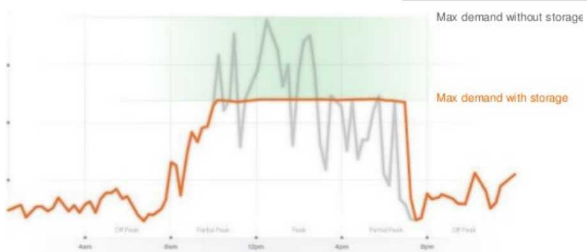


Energy Storage as Flexible Resource

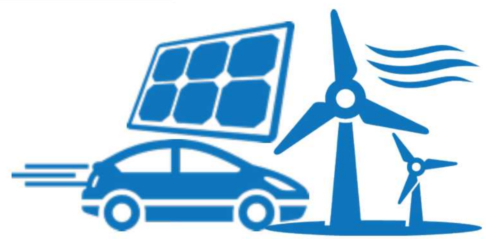
Grid-scale energy storage can enable significant cost savings to industry while improving infrastructure reliability and efficiency

Mitigate $79B/yr in commercial losses from outages

Reduce $2T in required T&D upgrades



Reduce commercial and industrial electrical bills through demand charge management. 7.5 million U.S. customers are enrolled in dynamic pricing (EIA 2015)



Balance the variability of 825 GW of new renewable generation while improving grid reliability and efficiency.

Energy Storage as Flexible Resource

Grid-scale energy storage can enable significant cost savings to industry while improving infrastructure reliability and efficiency

ULTIMATELY…

Can act as a controllable, flexible resource (source and sink) that can firm renewables, provide synthetic inertia, frequency regulation, limit ramp rates, etc.

Reduce commercial and industrial electrical bills through demand charge management. 7.5 million U.S. customers are enrolled in dynamic pricing (EIA 2015)

Balance the variability of 825 GW of new renewable generation while improving grid reliability and efficiency.

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U.S. DEPARTMENT OF ENERGY

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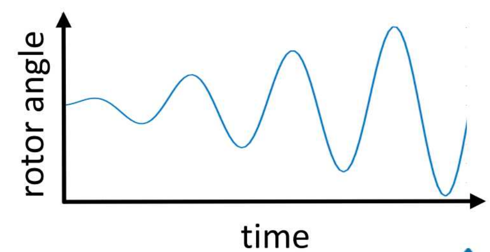
Power System Stability

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.

Small Signal Stability - Power System Oscillations

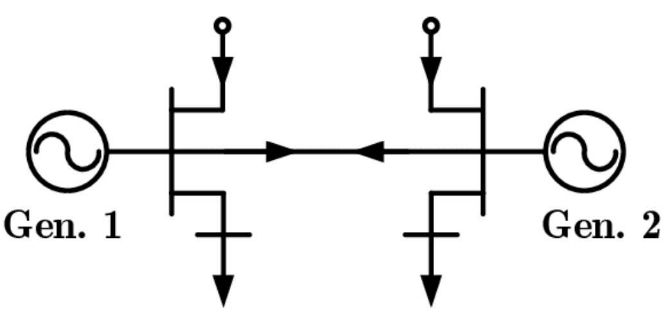
Oscillations can lead to instability and system breakup, so they must be damped effectively to maintain secure and stable system operation.

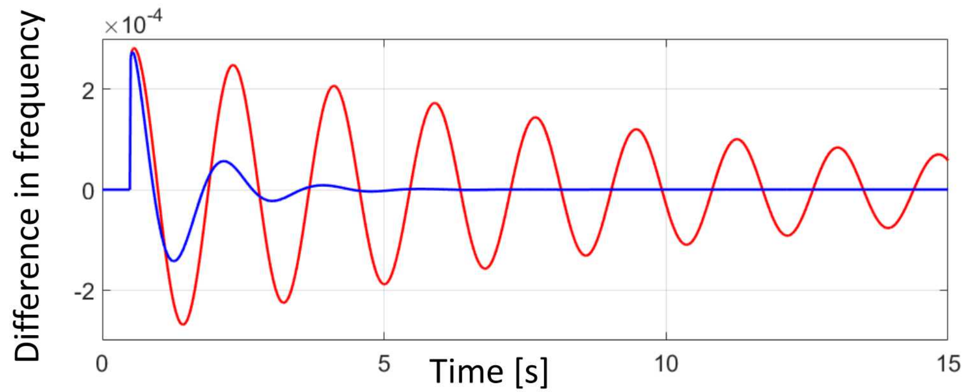
Intra-area oscillations:

- Low frequency (1-3 Hz) oscillations characteristic of interconnected power systems with synchronous generators in a local region excited by normal variations in system load.
- Power system stabilizers were designed to damp these oscillations.

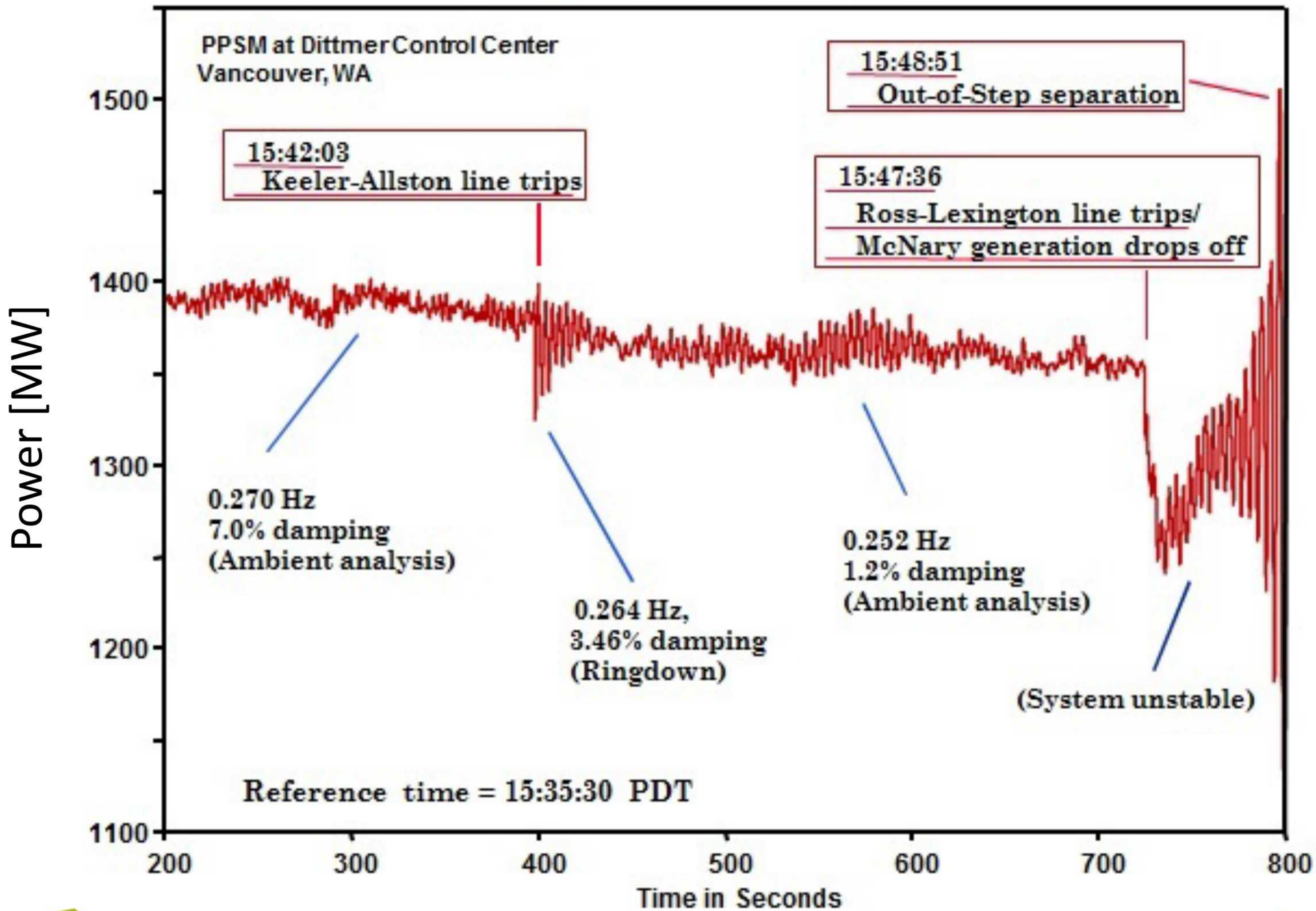
Inter-area oscillations:

- Very low frequency oscillations (0.1-1 Hz) characteristic of wide-area power grids in which synchronous generators in different regions oscillate against one another.
- Prominent in grids with major load and generation centers separated by long (hundreds of miles) AC transmission corridors.





USA/Canada Western Power System Breakup



August 10, 1996

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Control System for Active Damping

POWER

More

Business & Technology for the Global Generation Industry Since 1882

Official Publication of: CONNECTEDPLANT CONFERENCE ELECTRIC POWER

Decade-Old Power Grid Problem Solved by Smart Grid Technology

01/11/2018 | Sonal Patel

- Only safe and effective way to prevent oscillations has been to reduce the amount of power sent through a transmission line.
- Inter-area oscillations have been studied for more than 40 years.
- Damping (or controlling) them has been elusive, owing to a lack of real-time measurement data throughout the grid.

Other resources:

- Sandia Labs News Release
- ECN Magazine
- Phys.org
- Science Magazine
- Daily Energy Insider
- Metering & Smart Energy International
- Pbsi
- EnvironmentGuru
- Electric Energy Online
- R&D Magazine
- In Compliance Mag
- Power Mag
- T&D World
- Machine Design

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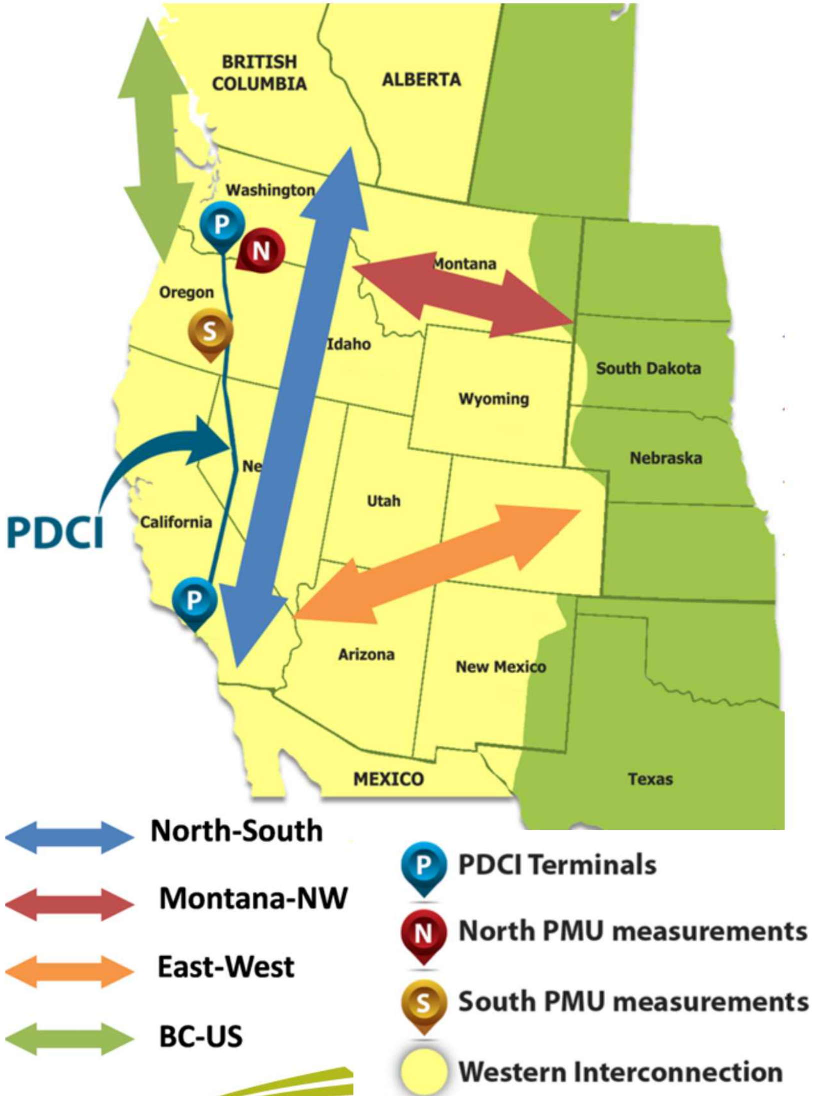
Modulation of Pacific DC Intertie (PDCI)



Project launched in Summer 2013:

- Build, install, and demonstrate a damping controller via real-time feedback modulation of PDCI (Pacific DC Intertie) power.
- Control signal based on wide-area PMU (Phasor Measurement Unit) feedback.

Oct 2015 – Sept 2017:

- System install at BPA Celilo Converter Station, The Dalles, Oregon.
- Closed-loop testing on western North American grid using PDCI.

Jan 2018 – Sept 2019:

- Operationalize controller (cyber security compliance).

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High-voltage DC (HVDC) transmission

- Promoted in 1930s in Europe.
- Proven technology in 1950s in Russia.
- Gigawatts, thousands of kilometers, up to 1000kV

<u>Advantage</u>:

- Improved system stability with lower losses

<u>Pacific DC Intertie (PDCI)</u>:

- High Voltage DC line: +/- 500 kV
- 3220 MW capacity
- 850 miles long – Celilo to Sylmar
- Operational since 1970
- Annually used for probing tests since 2008 to identify and better understand inter-area oscillations on the western grid

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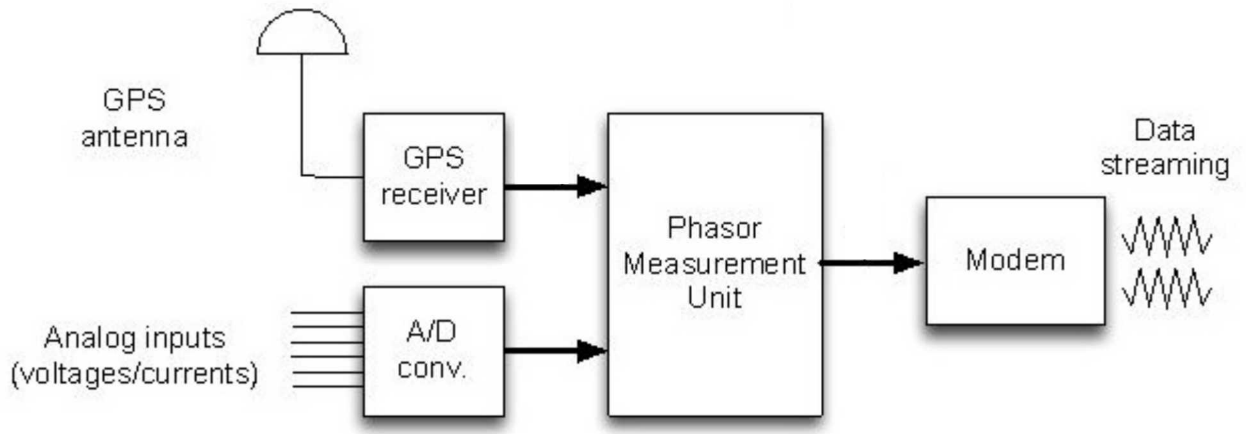
Phasor Measurement Units (PMUs)

Availability of wide-area measurements has recently enabled wide-area damping control (automated frequency response).



- Prototypes developed at Virginia Tech 1995.
- Time-synchronized using GPS
- Provide measurements throughout system providing significant improvements in monitoring and situational awareness
- Measures 50/60 Hz waveform (voltages and currents)
- In general, 30-240 samples per second (often 60 for existing devices)

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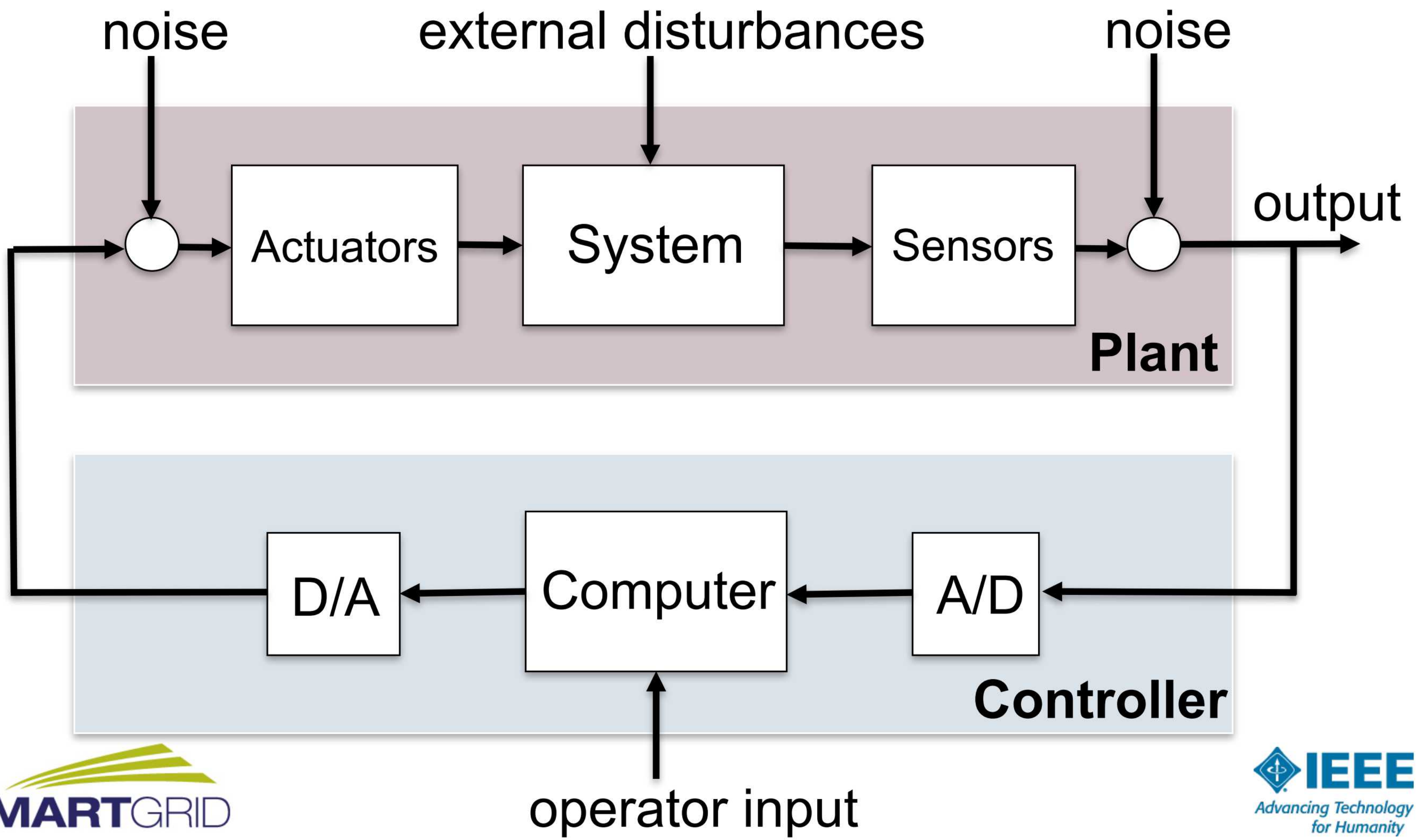
(Feedback) Control System

Control: The design of an action that affects a system in a desired way.



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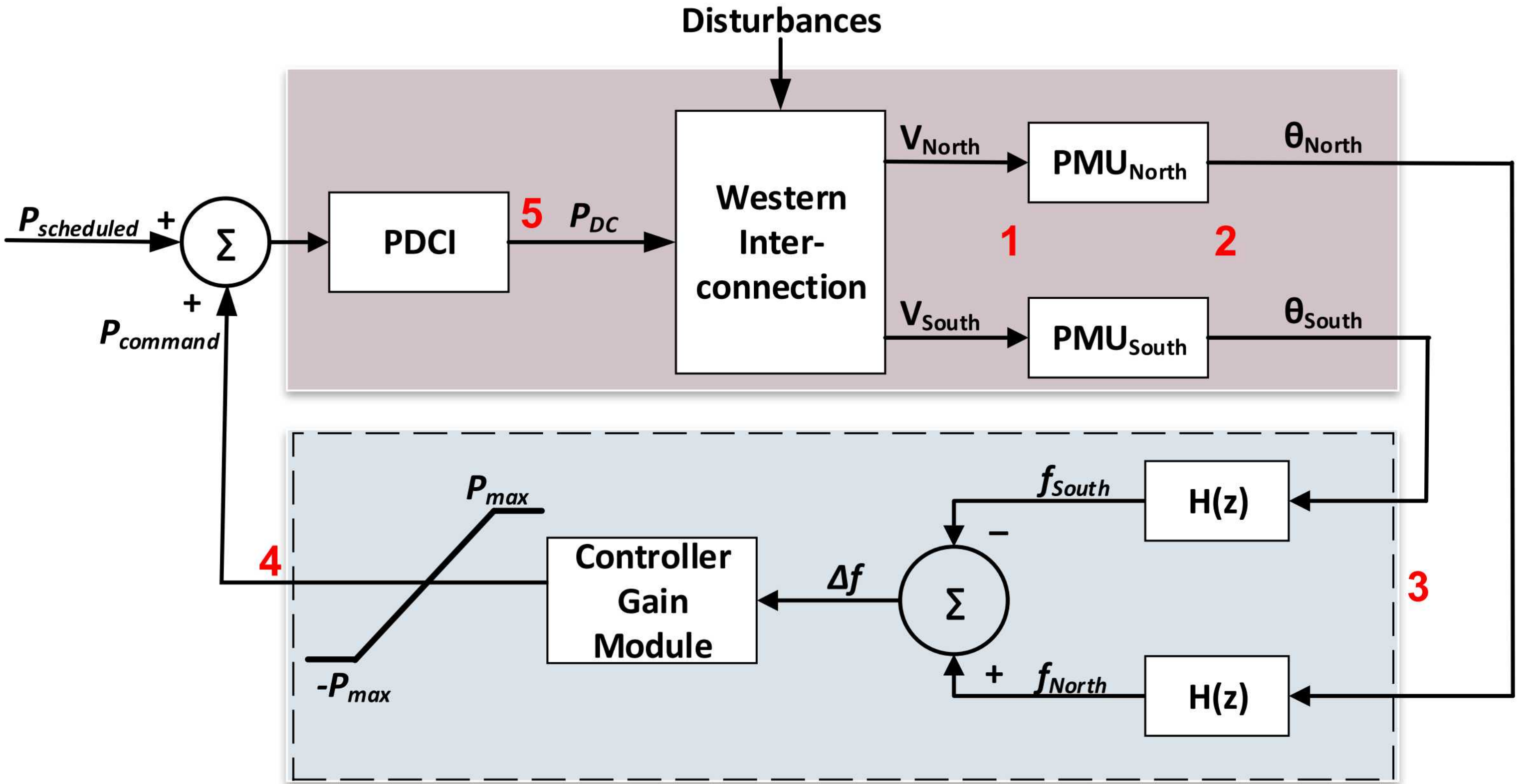
Damping Controller



Damping Controller

1 PMUs take measurements

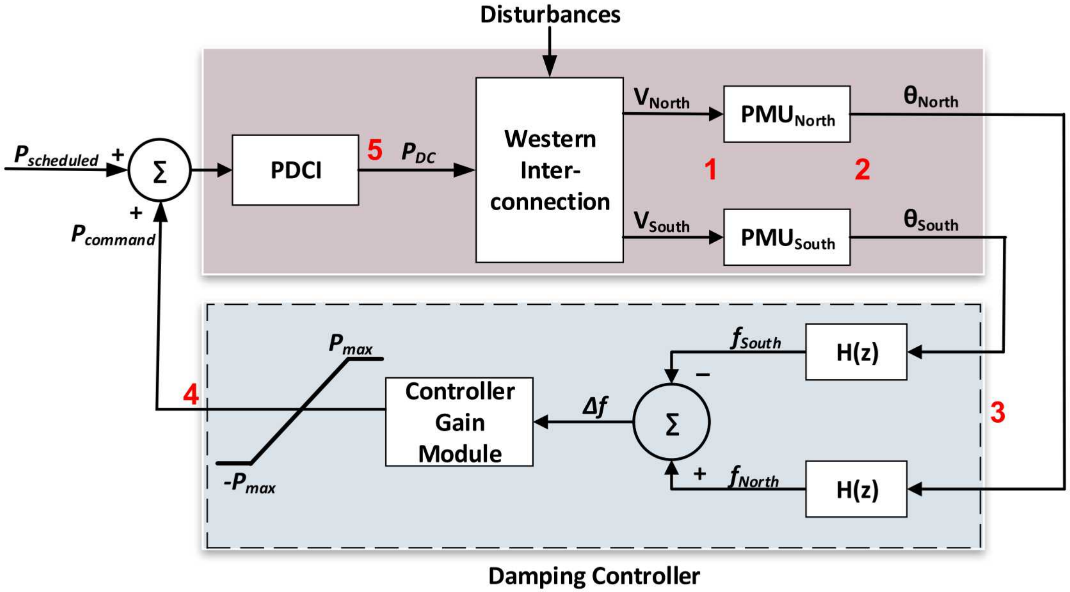
2 PMUs send data packets over network

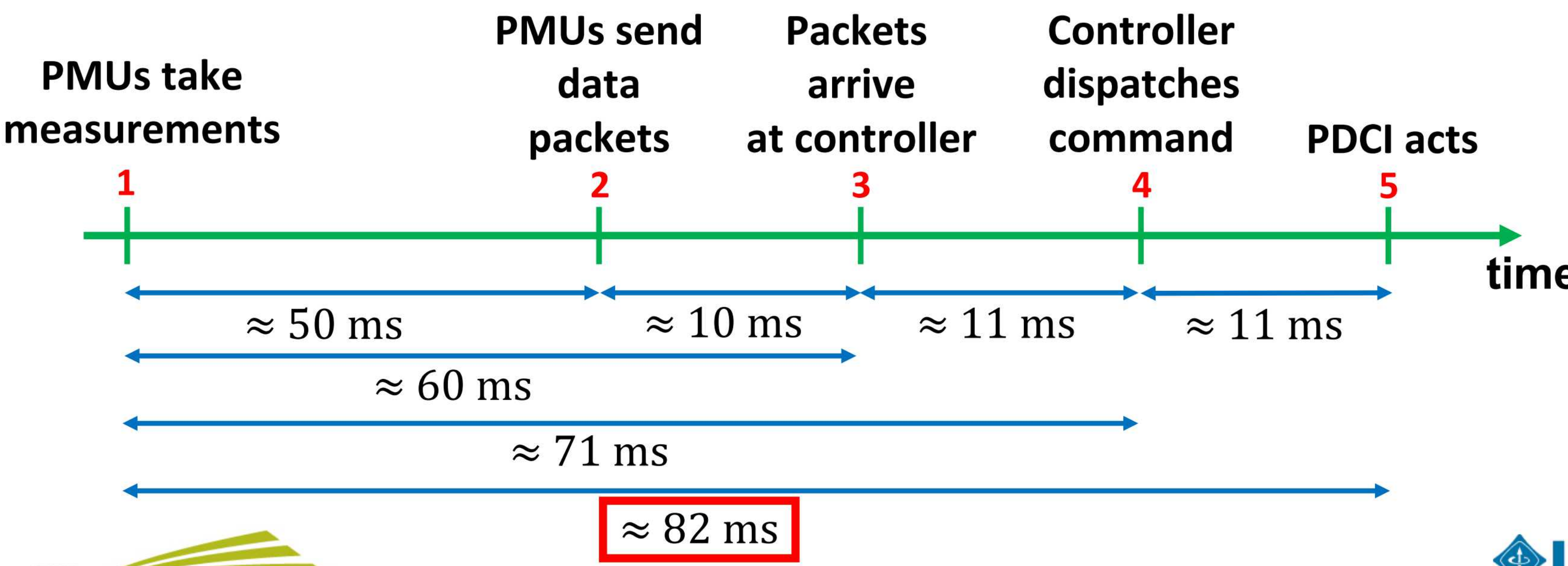
3 Packets arrive at damping controller

4 Controller sends power command to PDCI

5 PDCI injects power command into grid

Time Delays in PDCI Damping Control





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Additional Requirements

<u>Real-time Supervisor</u>

Disarm controller if abnormal condition detected.

Oscillation detection

- Detect out-of-band oscillations in feedback signal or on PDCI

Islanding detection

- Detect islanding between local and remote signal locations

PMU validity & latency management

- Monitor measurements and latencies

Emergency stop

<u>Asynchronous Supervisor</u>

Gain/Phase margin monitoring

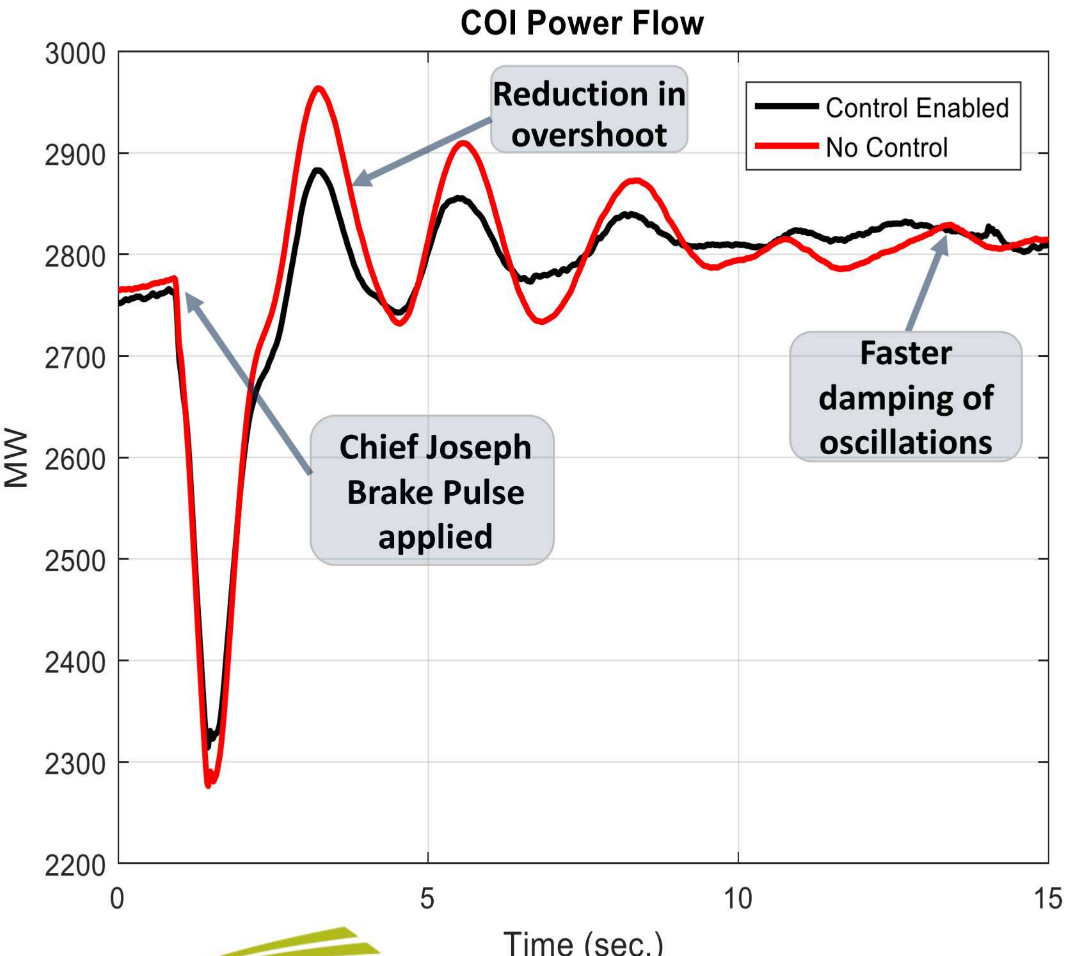
- Makes sure controller is **NOT** destabilizing any modes
- Requires periodic low-level probing

PDCI monitoring

- Makes sure commanded modulation is entering PDCI system

Grid Demonstrations

Experiments conducted at Celilo Converter Station Sept 2016, May & June 2017



Chief Joseph brake test	Damping of North-South Mode improved in closed-loop vs. open-loop operation. 
All tests	Controller consistently improves damping and does no harm to grid.

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Summary of Project Accomplishments

- 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 other network-enabled assets, such as energy storage, smart inverters, and demand response.
- Supervisory system architecture and design can be applied to future real-time grid control systems to ensure "Do No Harm".

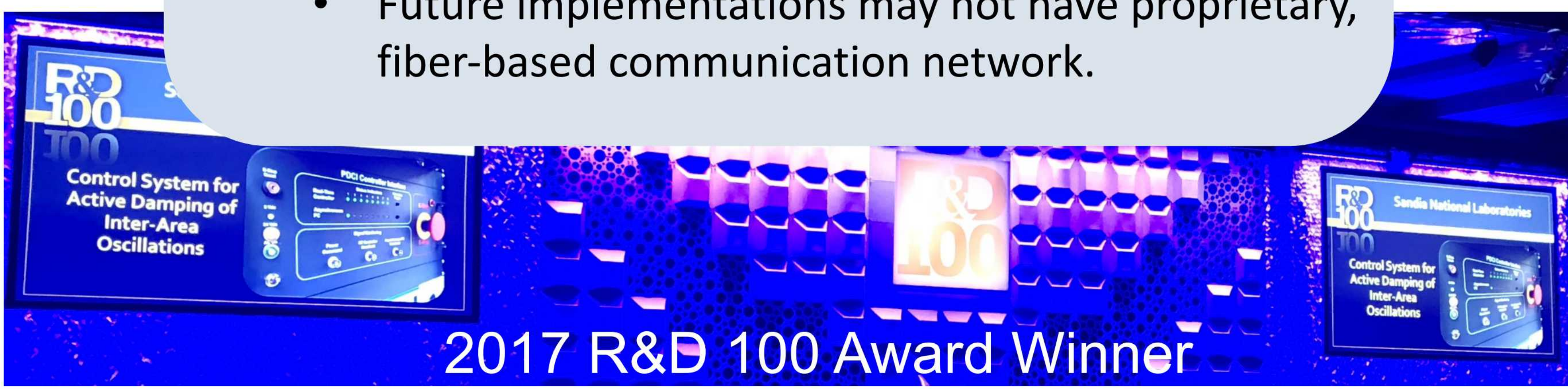
Summary of Project Accomplishments

- First ... PMU feed...
- Exp... n usin... inve...
- Sup... e real-time...

But…

Damping via HVDC transmission modulation has some limitations:

- **Need HVDC line installed**
- Only area-pairs can be damped
- Limited controllability of some modes
- Approximately symmetric power flows
- Future implementations may not have proprietary, fiber-based communication network.



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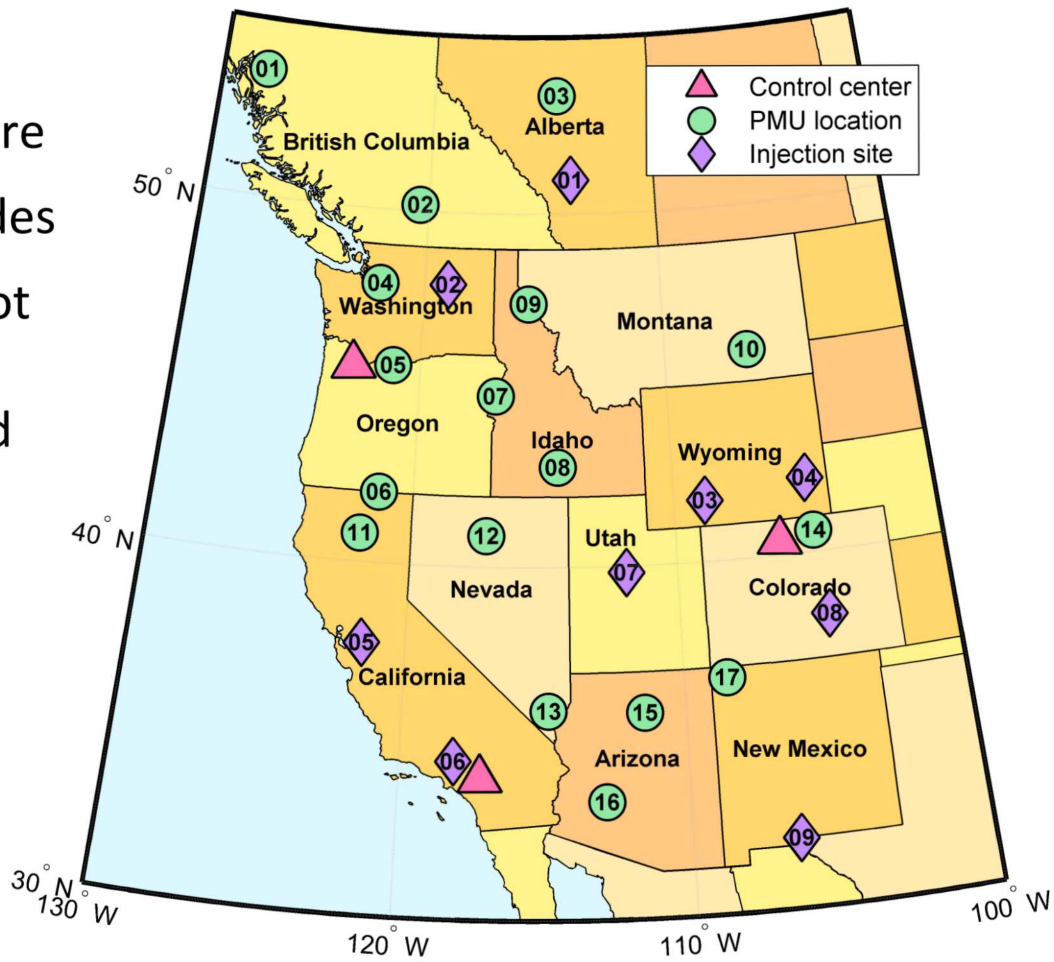
What about multi-node distributed control?

Advantages:

- Robust to single points of failure
- Controllability of multiple modes
- Size/location of a single site not as critical as more distributed energy resources are deployed

Challenges:

- Siting and sizing multiple resources
- Communication
- Distributed algorithms



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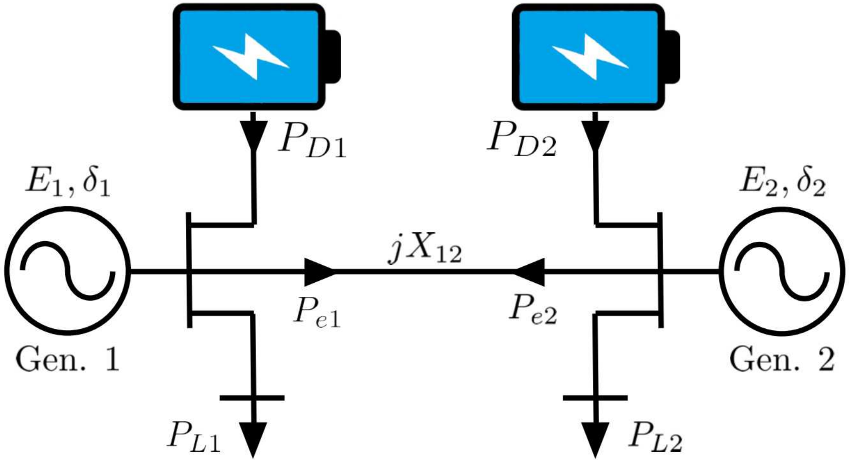
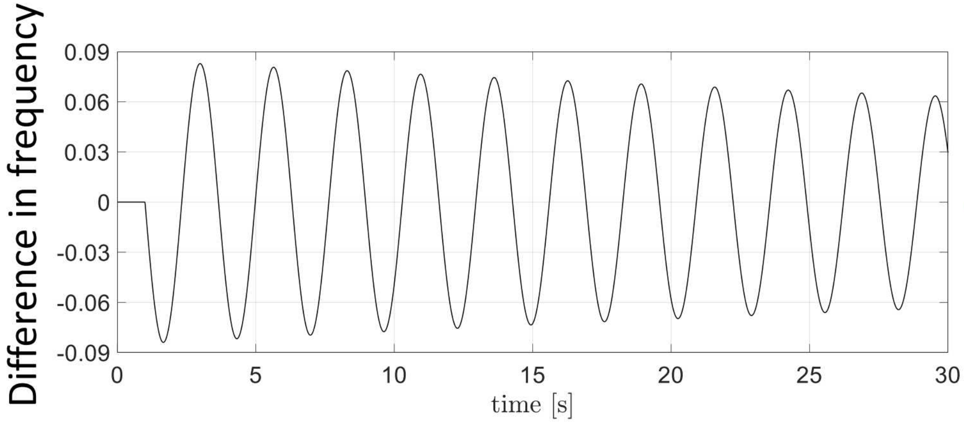
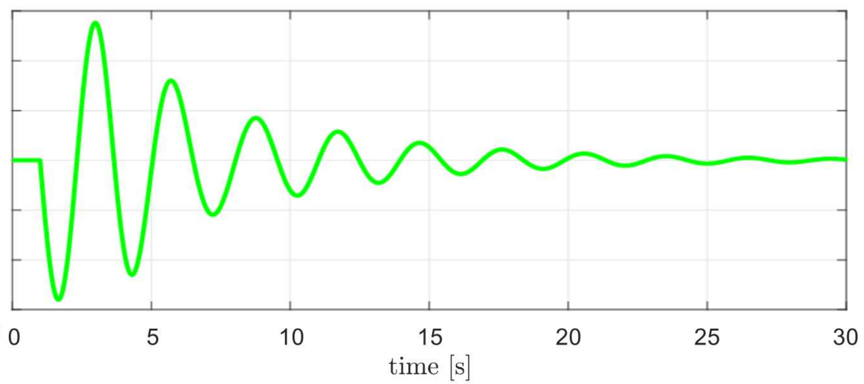
Multi-node distributed control

Objective:

- Damp oscillations using power injections from multiple distributed resources.
- Wide-area measurements (e.g. from PMUs) can be used for feedback.

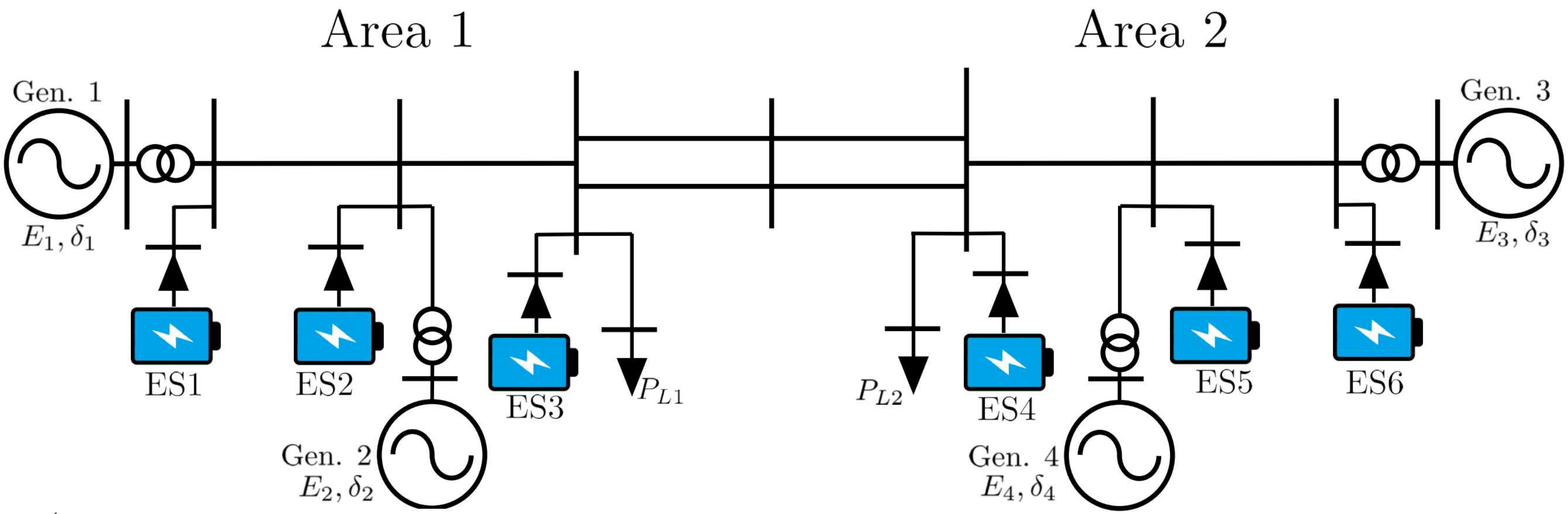


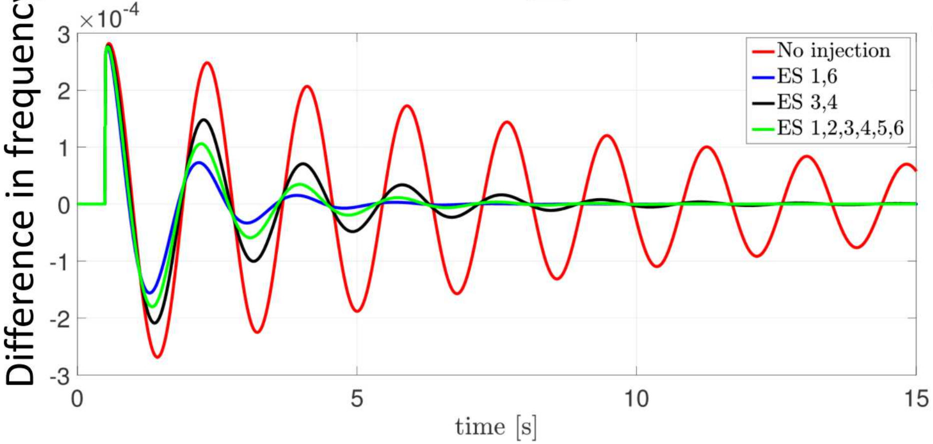


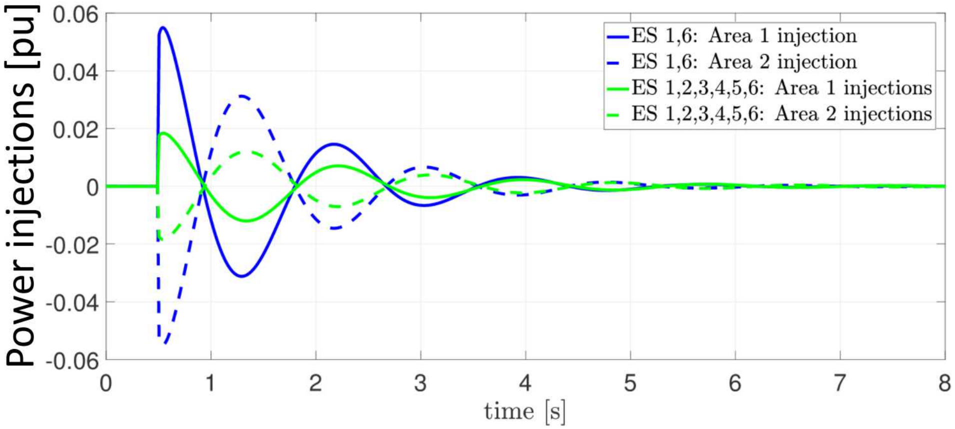


Siting and Sizing

Where to locate the resources, and how large should they be?







Siting and Sizing

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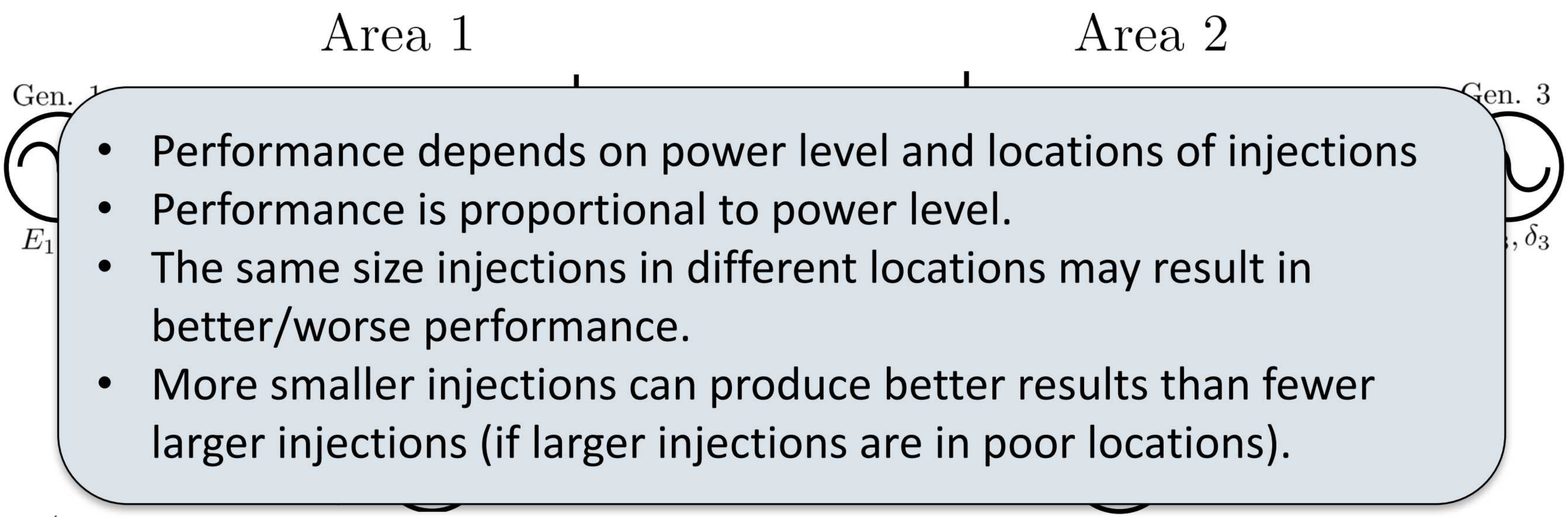
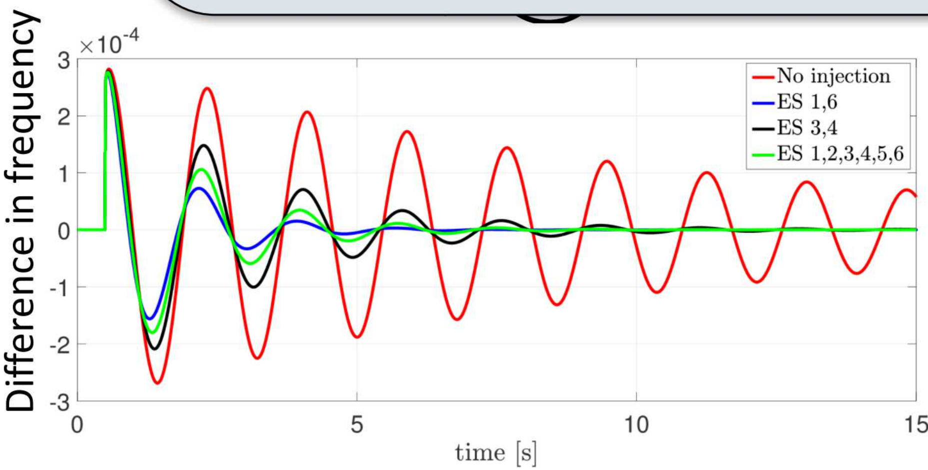
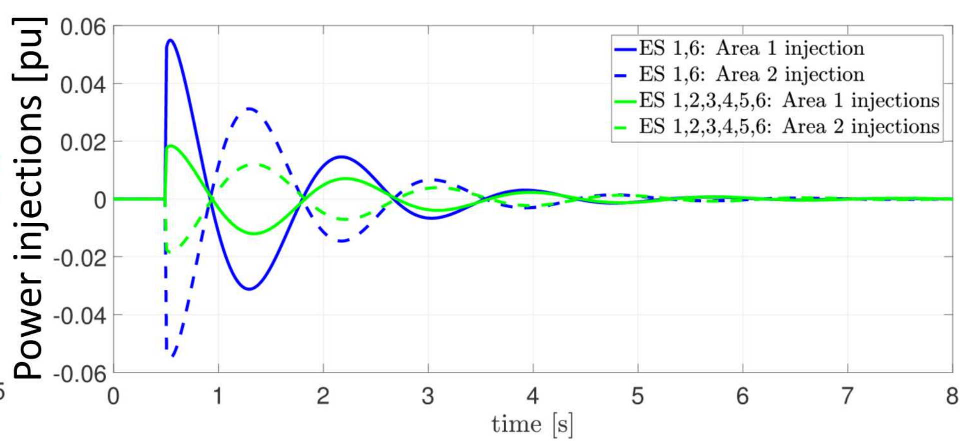


- Performance depends on power level and locations of injections
- Performance is proportional to power level.
- The same size injections in different locations may result in better/worse performance.
- More smaller injections can produce better results than fewer larger injections (if larger injections are in poor locations).





Communication Network Considerations

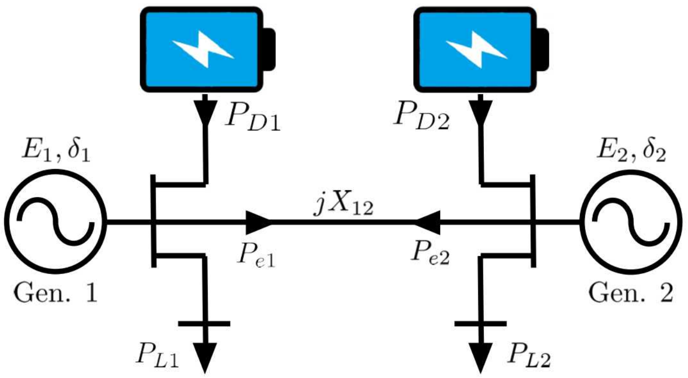
Future implementations will not be on secure, resilient, efficient networks.

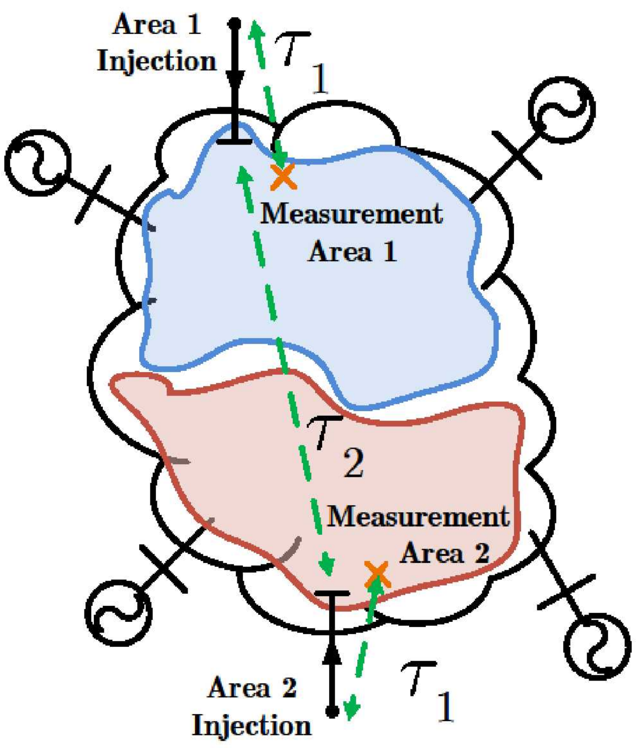
Need to accommodate:

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

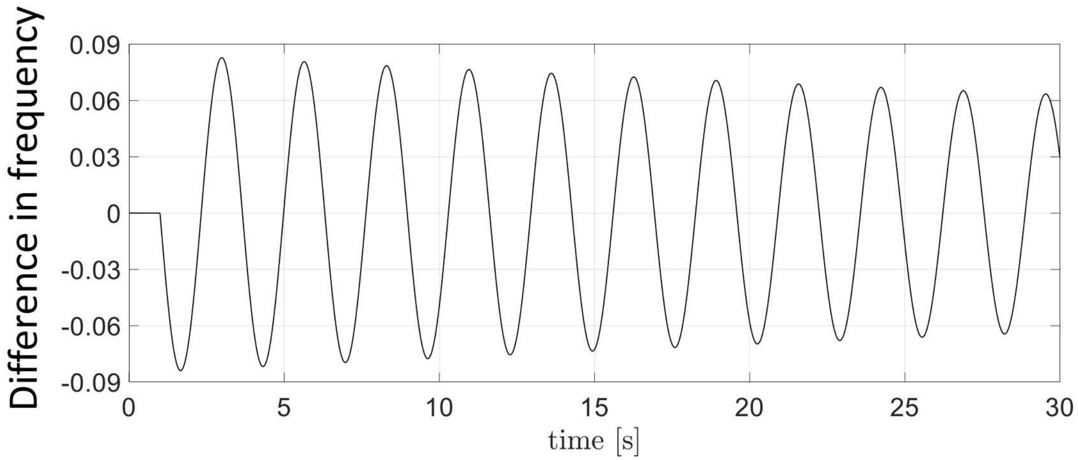
How much delay can the system handle?

How does the distributed control action affect stability in the presence of delays?

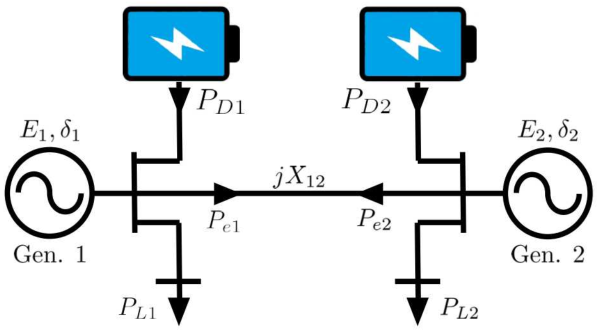


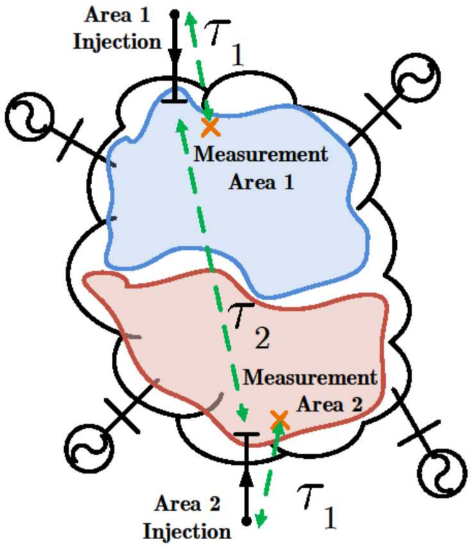


Stability Criterion

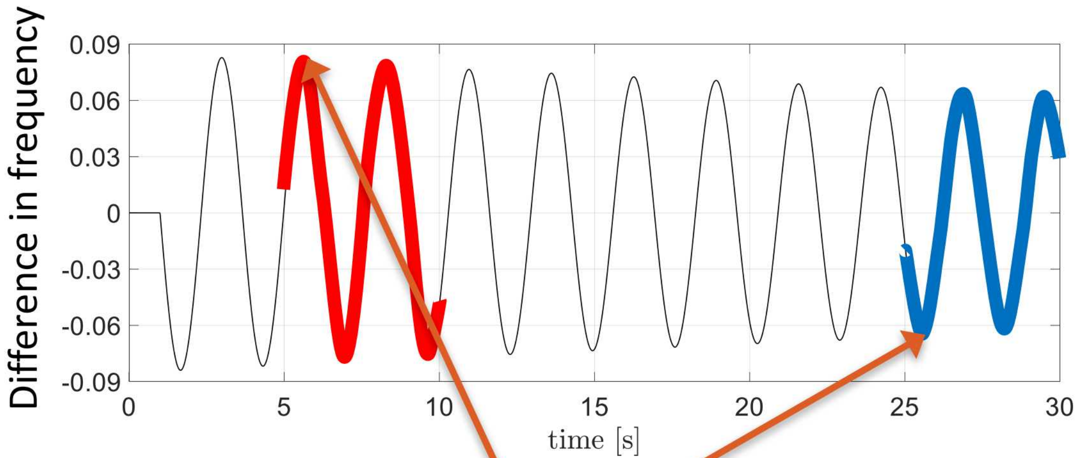


Natural system response after sudden change in load.





Stability Criterion



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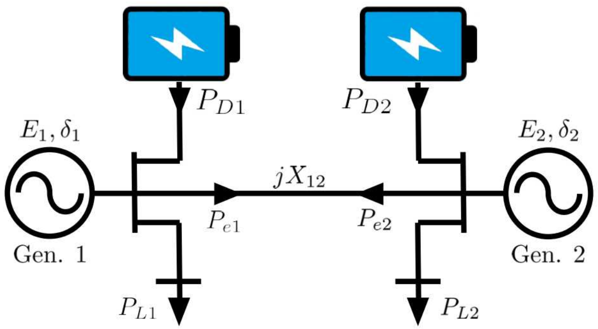
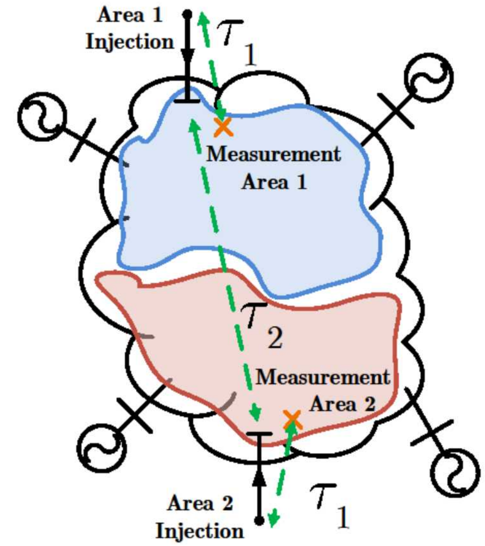
Largest amplitude in red > largest amplitude in blue

➡ stable



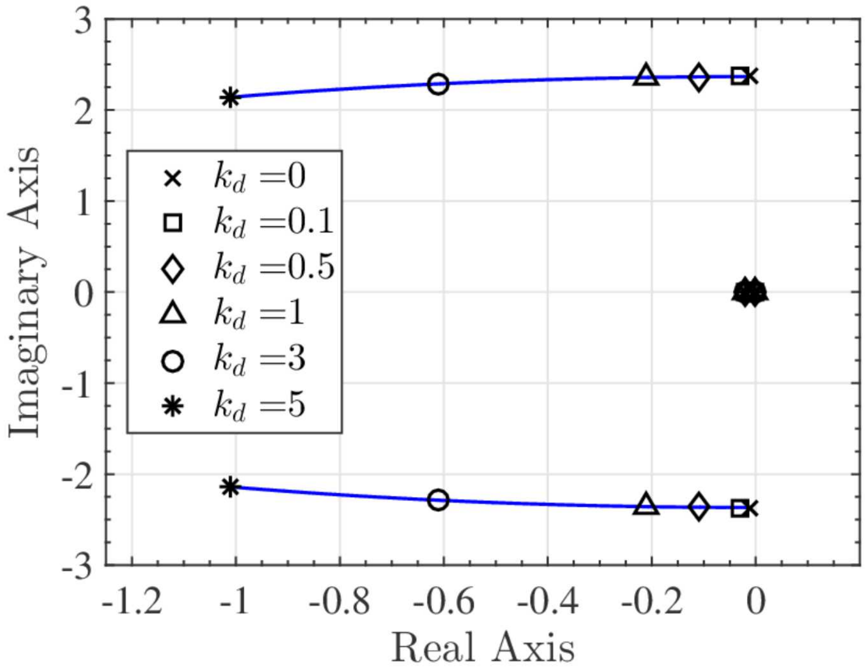


Using this criterion, determine regions of stability that depend on time delays τ_1, τ_2 and damping gain k_d.

Eigenvalues and Regions of Stability

Eigenvalues

Without delays, increasing damping improves stability (eigenvalues move to the left).

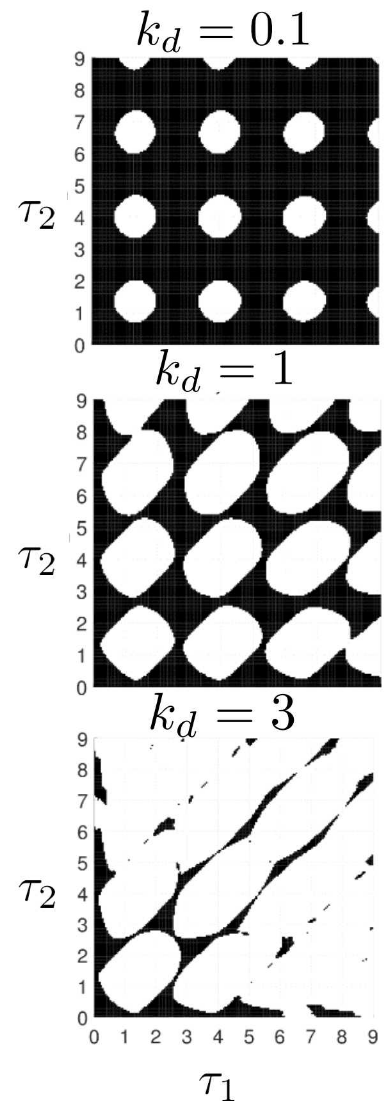


Regions of stability

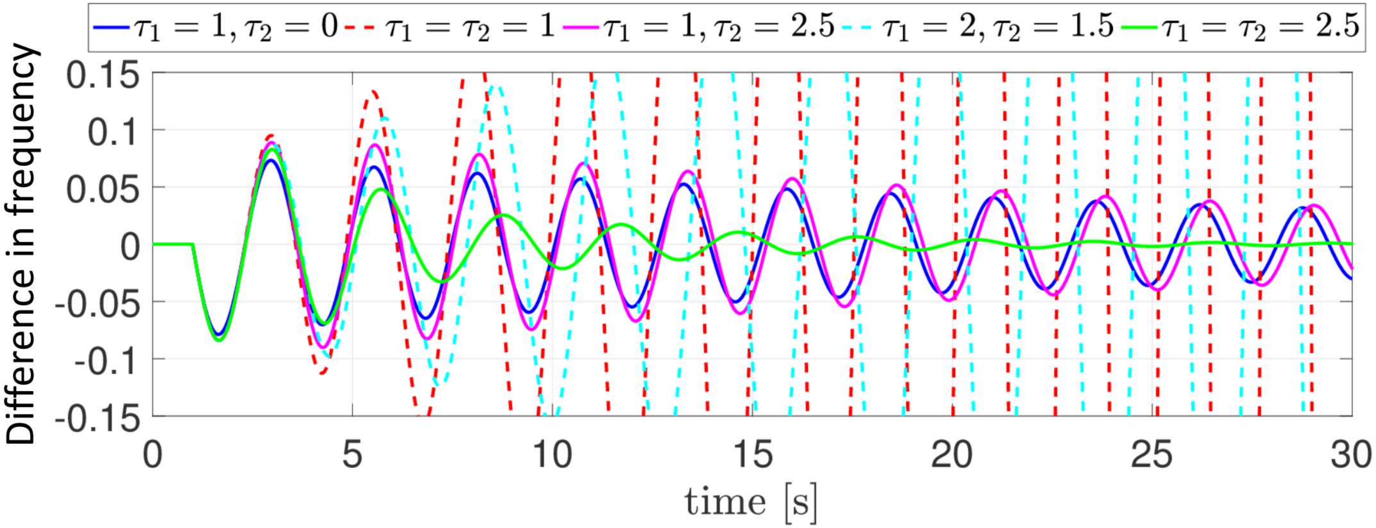
Black: Stable

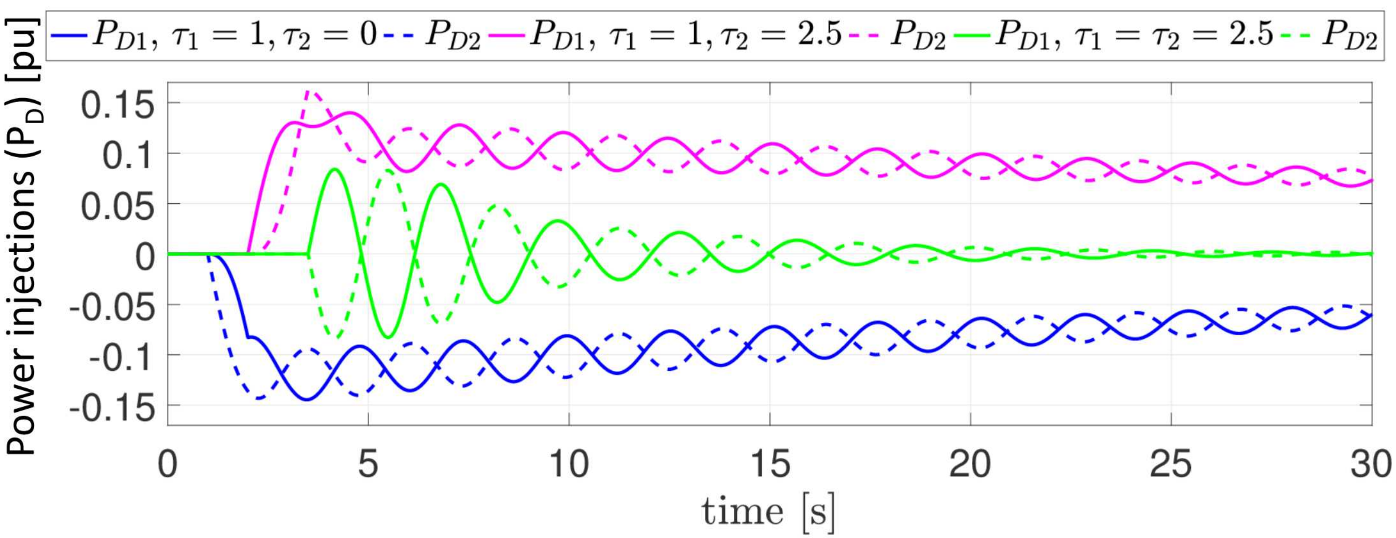
White: Unstable

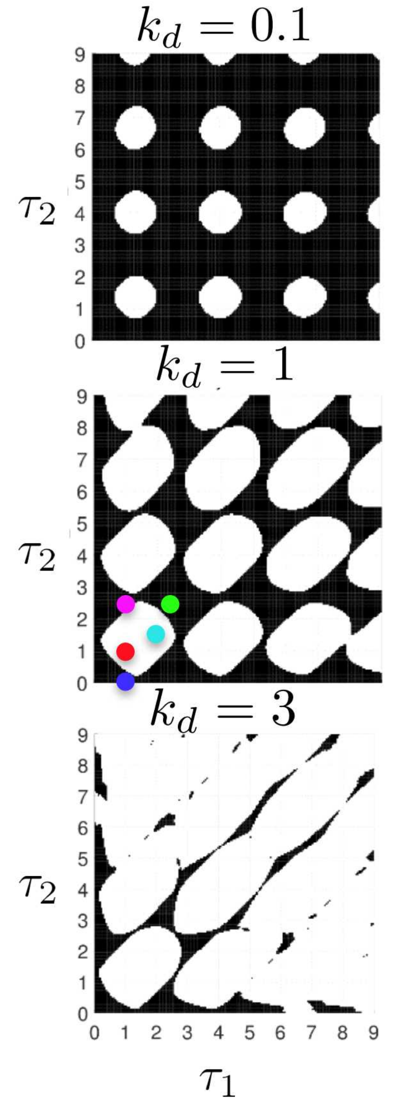
In the presence of delays, increasing damping may lead to instability.



Time Domain Simulations







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Conclusions

- Grid conditions are changing
- Need flexible and controllable resources with the right operational characteristics in the right locations.
- All interconnected power systems experience oscillations.
- Wide-area damping control can be used to damp inter-area oscillations.
- Wide-area measurements (e.g. from PMUs) can be used for feedback.
- Oscillations can be damped with power injections.
- Several challenges considered:
  - Choose locations and sizes of resources.
  - Time delays in the feedback signals can cause the damping control to destabilize the system, and stability depends on the size of the delays as well as the size of the control gain.

Future Challenges

- (Optimal) distributed and networked approaches to wide-area damping control
- Big data methods to handle thousands of sensor measurements
- Simulation tools for studying transient stability of both transmission and distribution grids
- Addressing cyber-security and privacy (intellectual property) concerns related to networked systems

Acknowledgements

Dr. David Schoenwald
Dr. Raymond Byrne
Dr. Felipe Wilches-Bernal
Dr. Tu Nguyen
Dr. Babu Chalamala

Sandia National Laboratories

U.S. DEPARTMENT OF ENERGY

Funding for Sandia related work provided by US DOE Energy Storage Program managed by Dr. Imre Gyuk of the DOE Office of Electricity Delivery and Energy Reliability.

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QUESTIONS?

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