DOE/OE Transmission Reliability Program

HVDC and Load Modulation for Improved Dynamic Response using Phasor Measurements (GM0073)

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Project Overview

- Objective
  - develop a universal wide-area damping control that can use a mix of different fast-acting resources to effectively mitigate inter-area oscillations
- Impact:
  - Manage power grid stability in a much more flexible manner by utilizing different resources
  - Improve system damping of inter-area oscillations for higher power transfer capacity
  - Enhance robustness of damping controllers to wide-area communication network effects

Project Team

- Pacific Northwest National Laboratory (lead)
  - Eric Andersen (PM), Jamie Lian (PI)
  - Shaobu Wang, Renke Huang
  - Marcelo Elizondo, Rui Fan, Harold Kirkham
  - Jacob Hansen, Laurentiu Marinovici, Qian Zhang
- Sadia National Laboratory
  - David Schoenwald, Felipe Wilches-Bernal
- Arizona State University
  - Vijay Vittal, Weili Yi
- Penn State University
  - Minghui Zhu, Hunmin Kim

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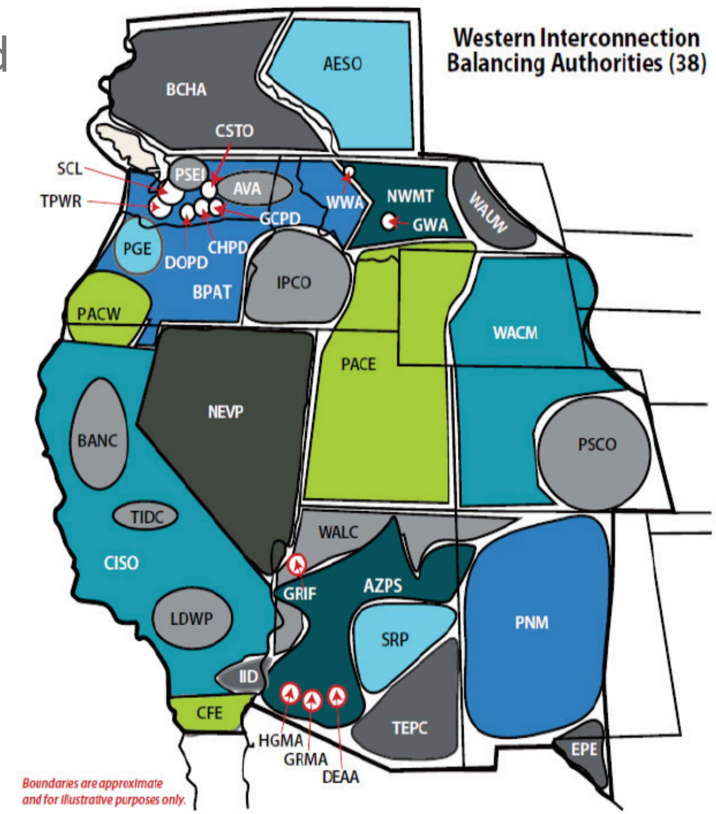
FY16 Planned Activities

Task	Deliverables	Due Date
1	Develop a decoupled modulation control approach based on wide-area PMU measurements • Decouple different oscillation modes from PMU measurements • Design decoupled damping control using PSS/FACTS devices	8/30/2017
2	Design decoupled damping control for multiple HVDC lines • Perform literature survey on HVDC line/network modeling • Propose test systems with three or more HVDC lines • Extend decoupled modulation control to HVDC lines	8/30/2017
3	Design decoupled damping control for controllable loads • Perform literature survey on controllable load modeling • Design load control strategies for aggregated power modulation • Extend decoupled modulation control to controllable loads	8/30/2017
4	Complete proof-of-concept testing and validation of different control strategies on the WECC system	8/30/2017

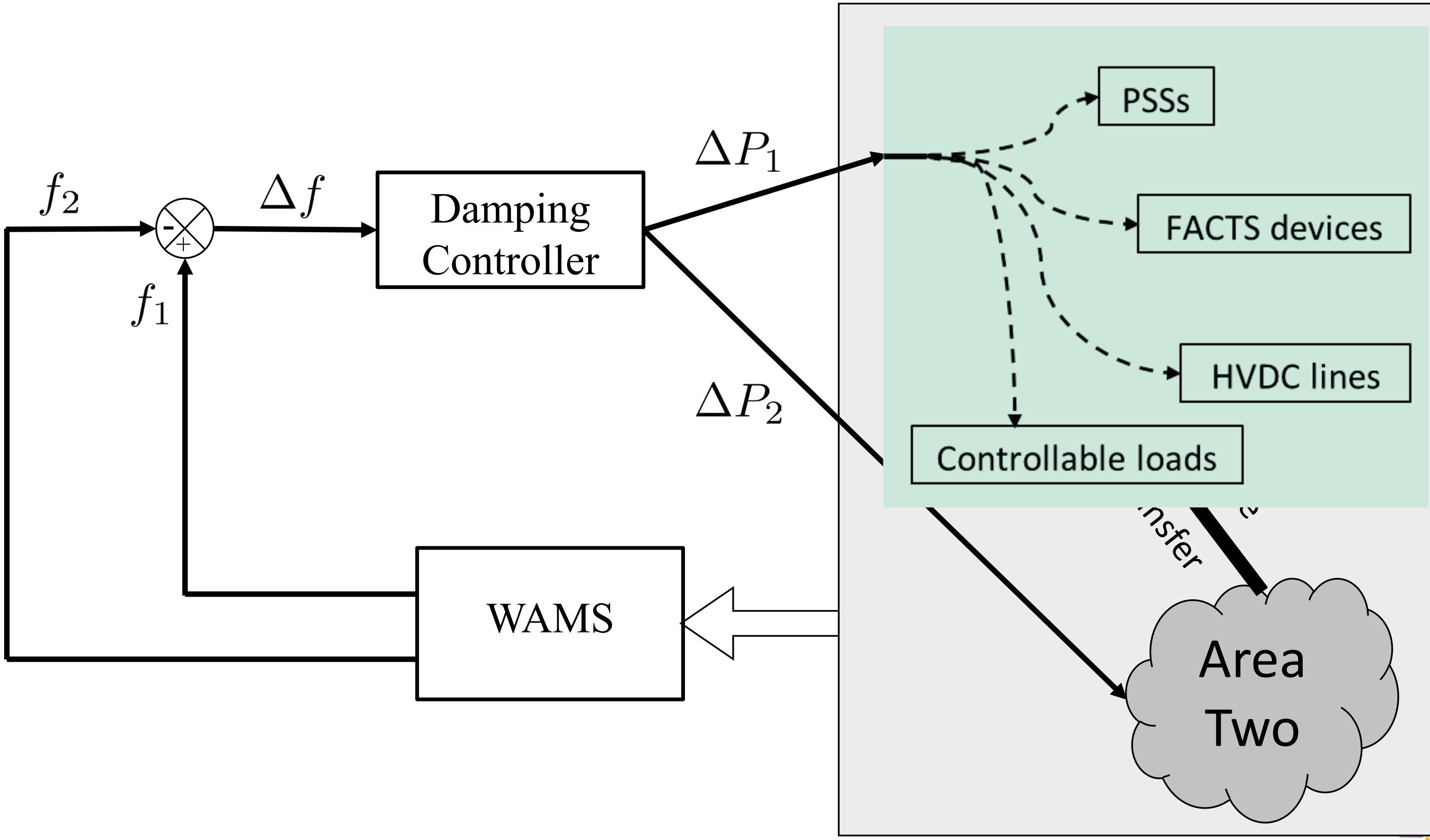
WECC System

- WECC has multiple inter-area oscillation modes and suitable for testing proposed damping control technologies
- Major inter-area oscillation modes*:
  - "N-S" (~0.13 Hz)
  - "Alberta" (~0.29 Hz)
  - "BC" (~0.62 Hz)
  - "Montana" (~0.55 Hz)
  - "E-W South 1" (~0.53 Hz)
  - "E-W South 2" (~0.69 Hz)
  - "E-W middle" (~0.71 Hz)



*D. Trudnowski, "The MinniWECC System Model," Appendix 2 of J. Undrill and D. Trudnowski, "Oscillation Damping Controls," Year 1 report of BPA contract 37508, Sep. 2008

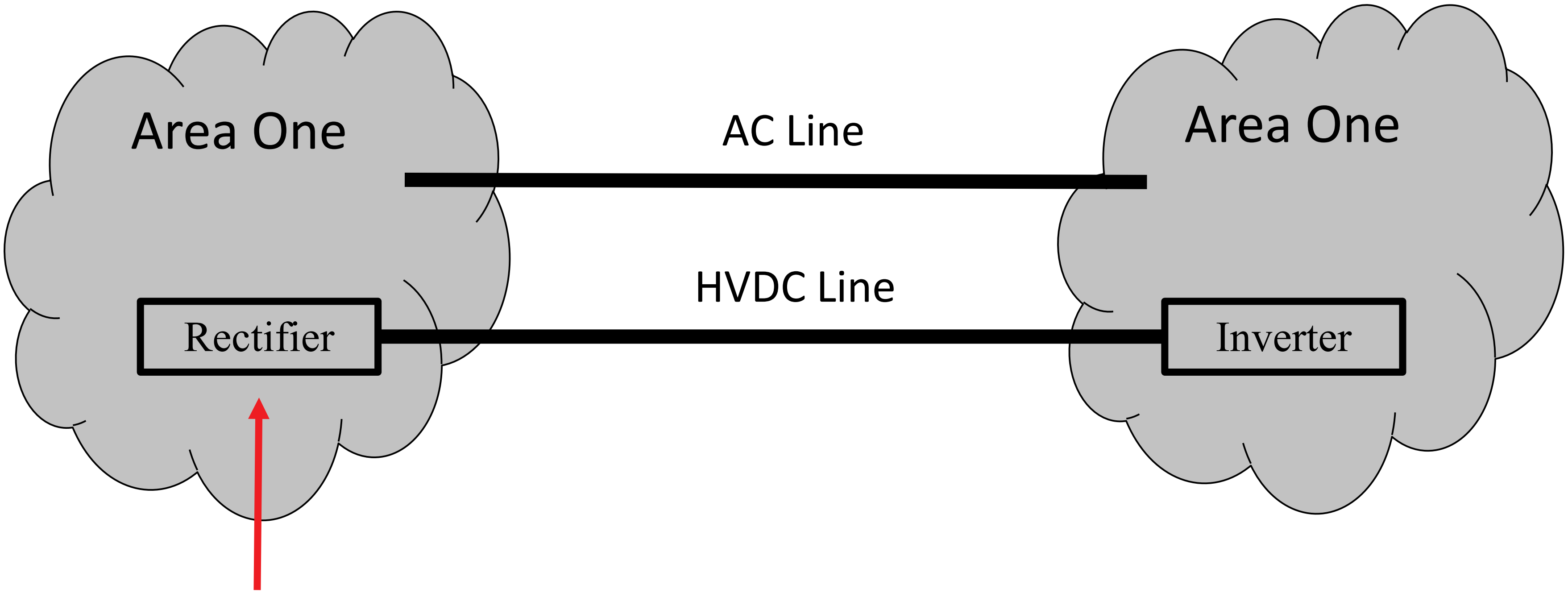
Wide-area Damping Control



Damping Control

HVDC Lines

Damping Control using HVDC Line

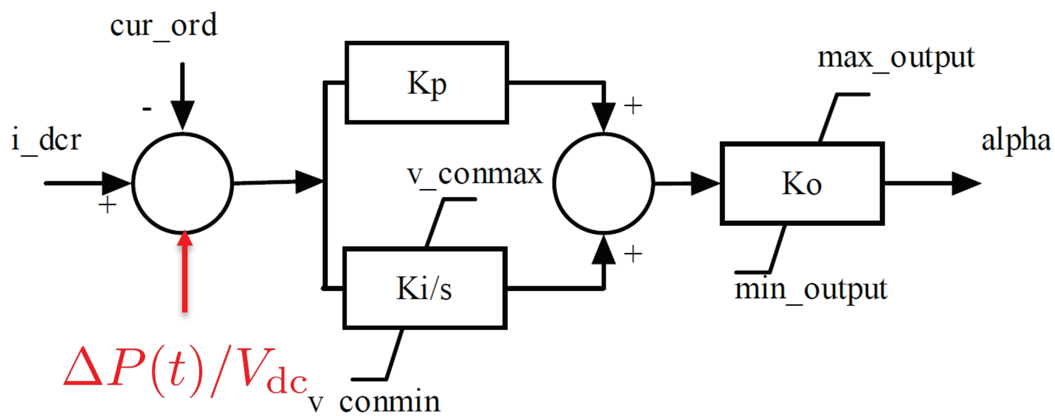


$$\Delta P \qquad \Delta P = K(f_1 - f_2)$$

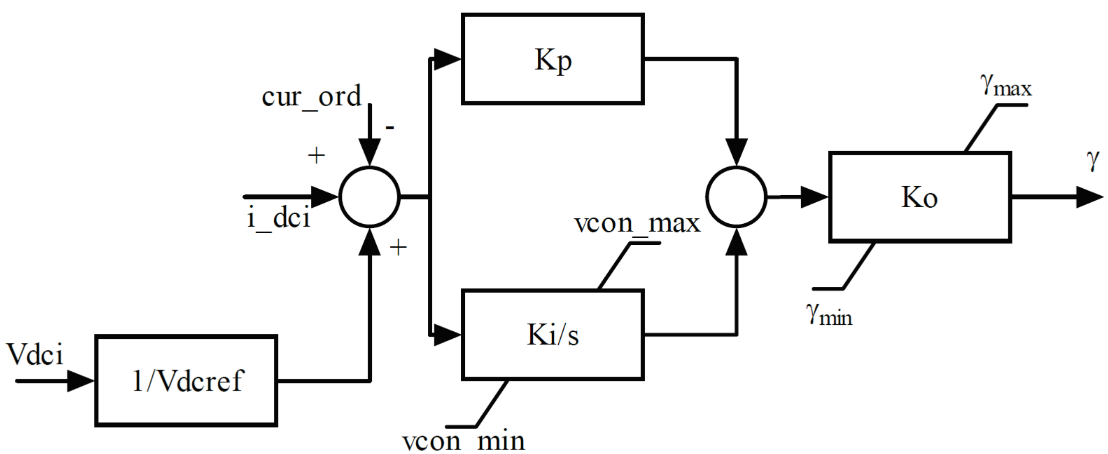
$$K < 0$$

HVDC Line Control

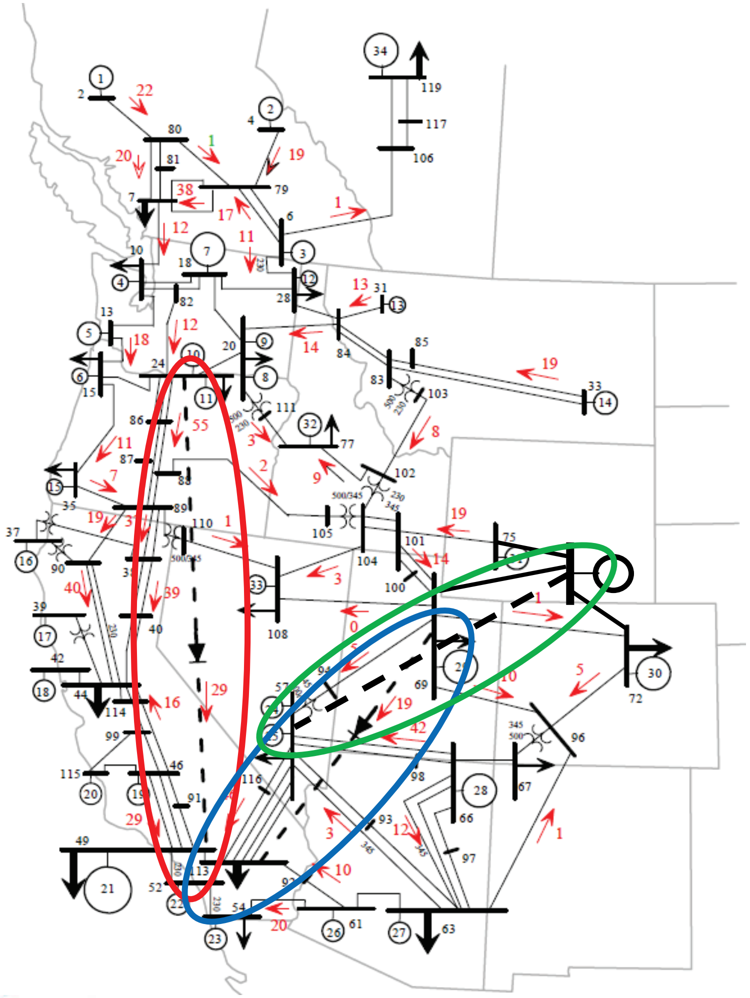
Rectifier Control



Inverter Control



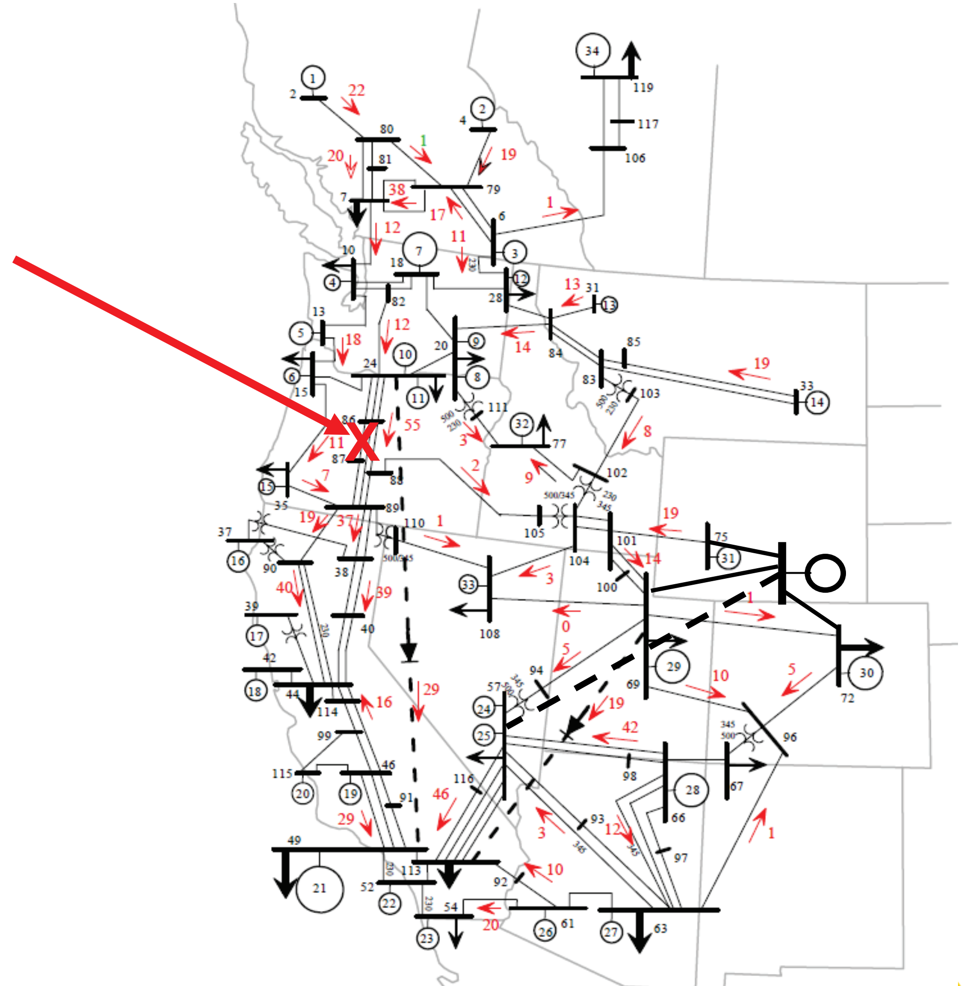
Minni-WECC Test System



- Pacific DC Intertie (PDCI)
  - From Celilo converter station at Dalles, Oregon, to the Sylmar converter station north of Los Angeles, California
- Intermountain Power Project (IPP)
  - From Intermountain converter station near Delta, Utah, to the Adelanto Converter Station in Adelanto, California
- TransWest Express Transmission Project (TWE, in operation by 2020)
  - From Rawlins, Wyoming, to Las Vegas, Nevada

Case Study

- Three-phase fault occurrs on line 86-87 (AC tie-line)
- Line 86-87 recloses after fault cleared



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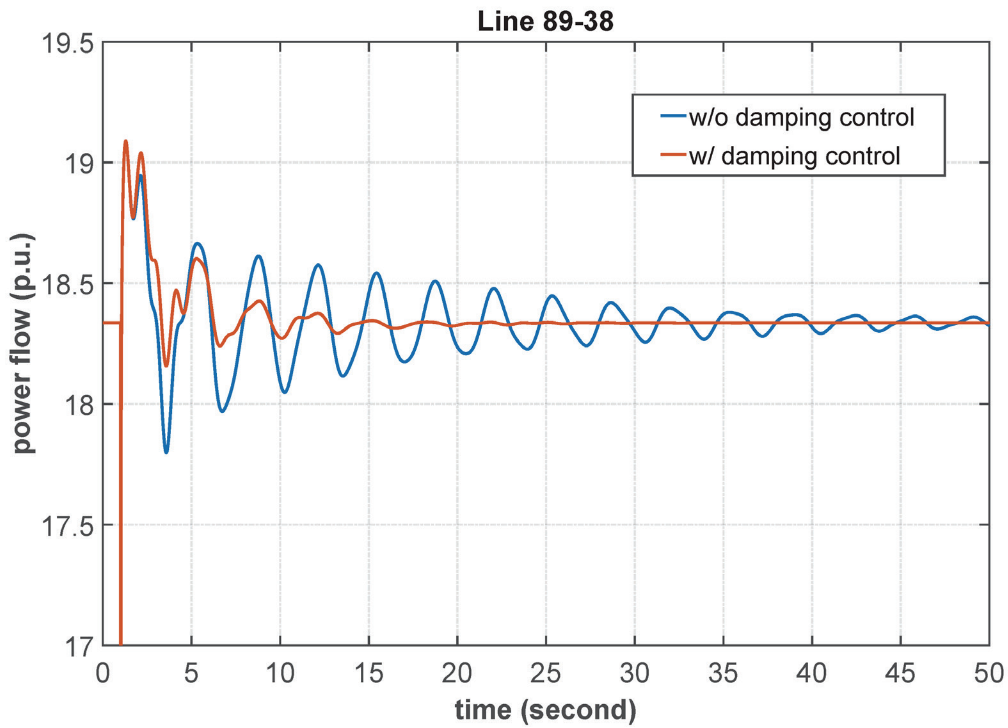
Simulation Results

- Control in each line responds to frequency difference at its terminals



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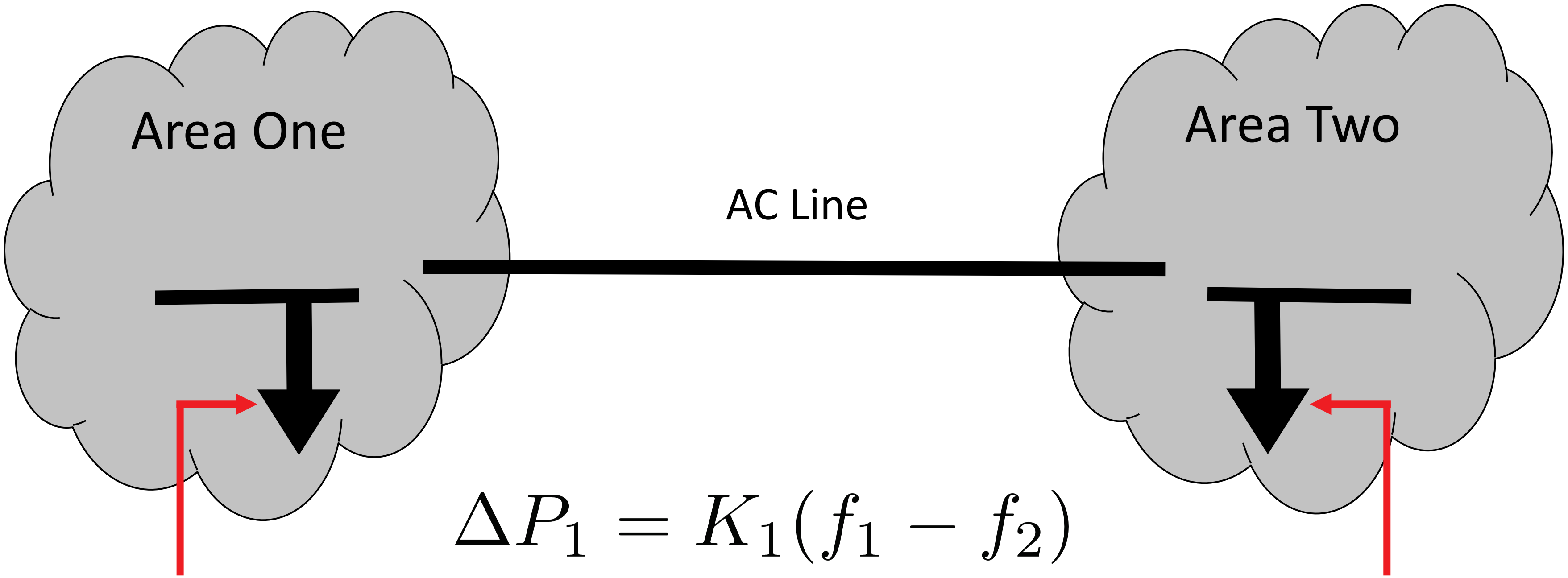
Damping Control

Controllable Loads

Damping Control using Loads



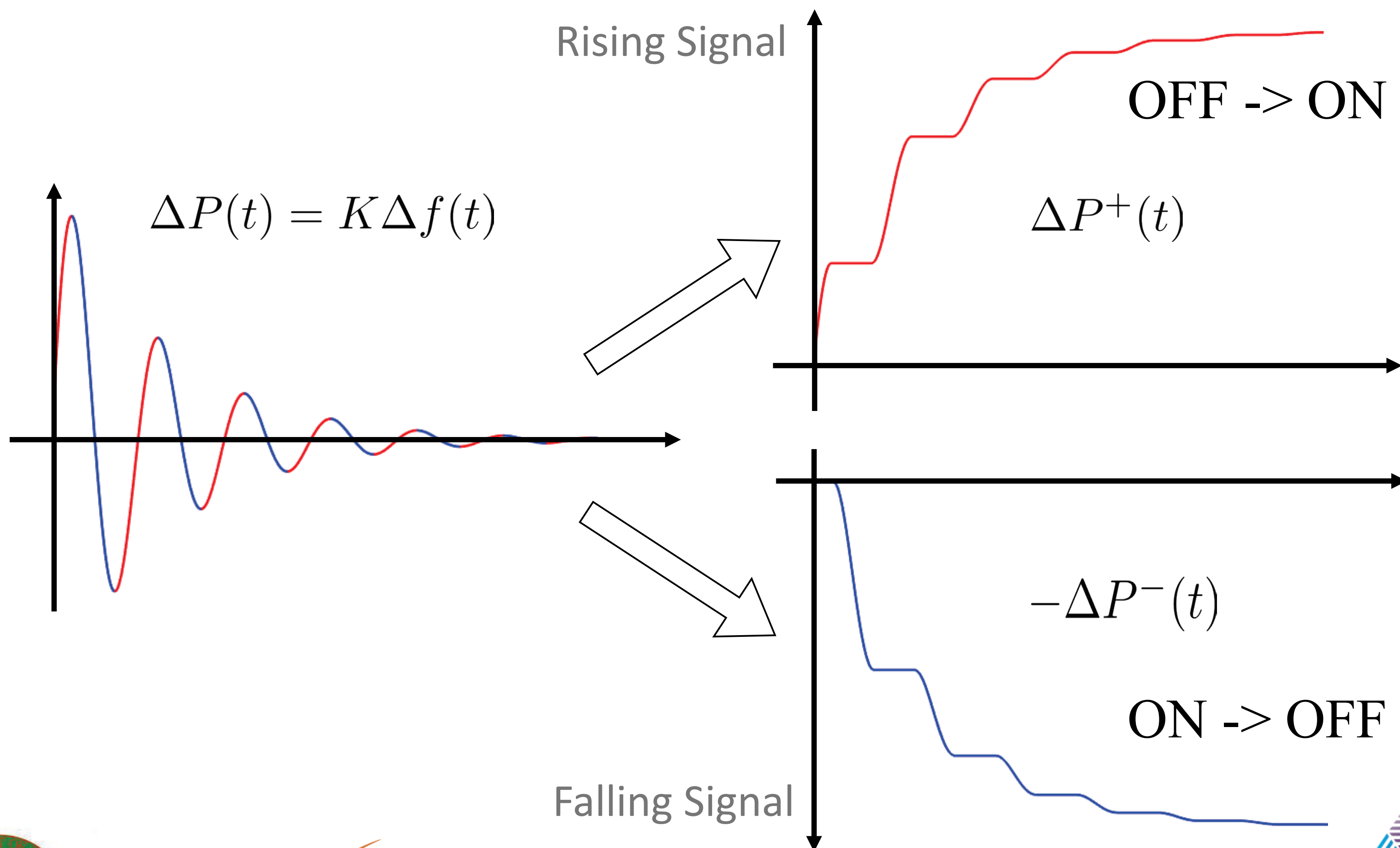
ΔP_1 ΔP_2

$$\Delta P_1 = K_1(f_1 - f_2)$$

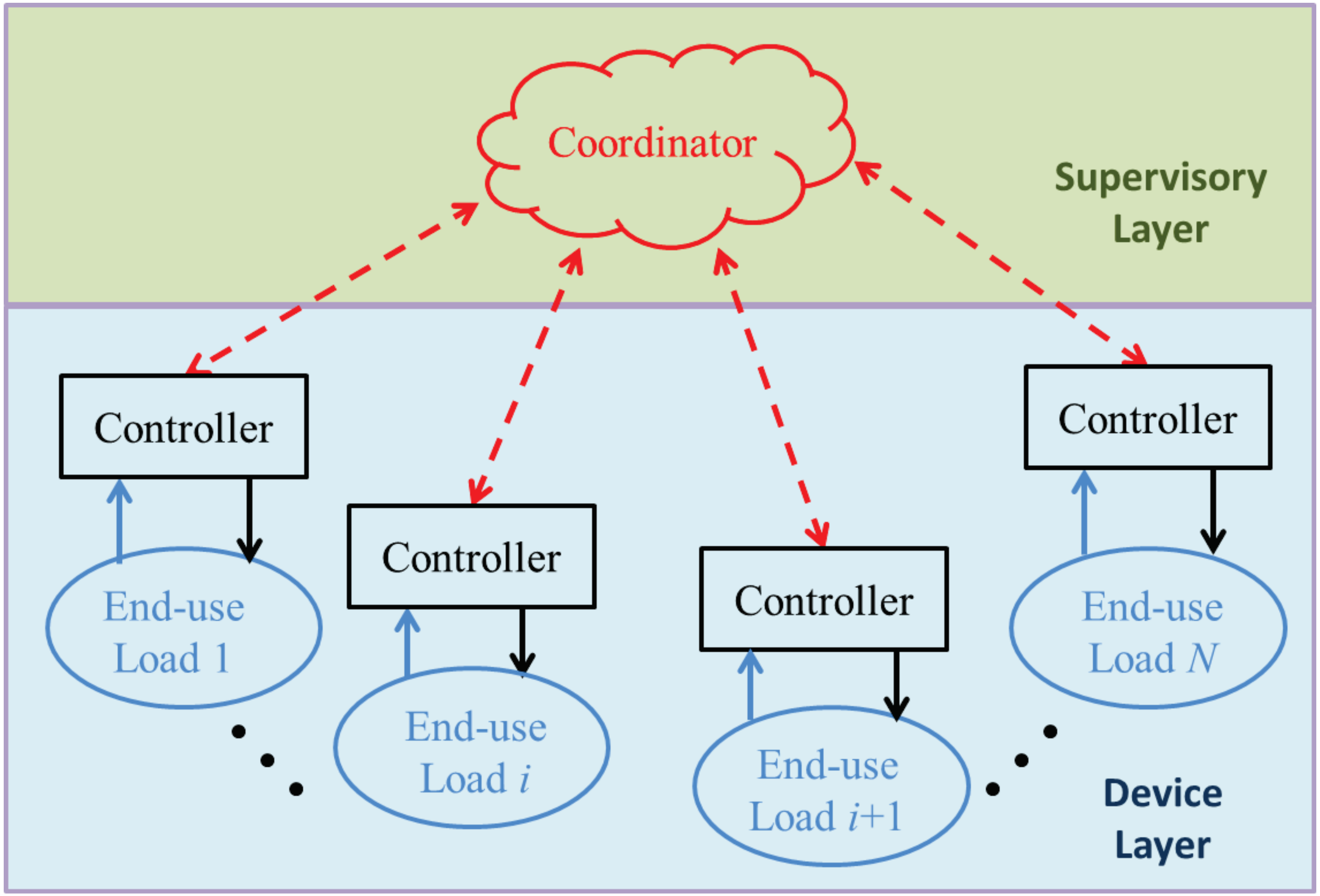
$$\Delta P_2 = K_2(f_1 - f_2)$$

$$K_1 > 0 \quad K_2 < 0$$

Load Power Modulation Signal

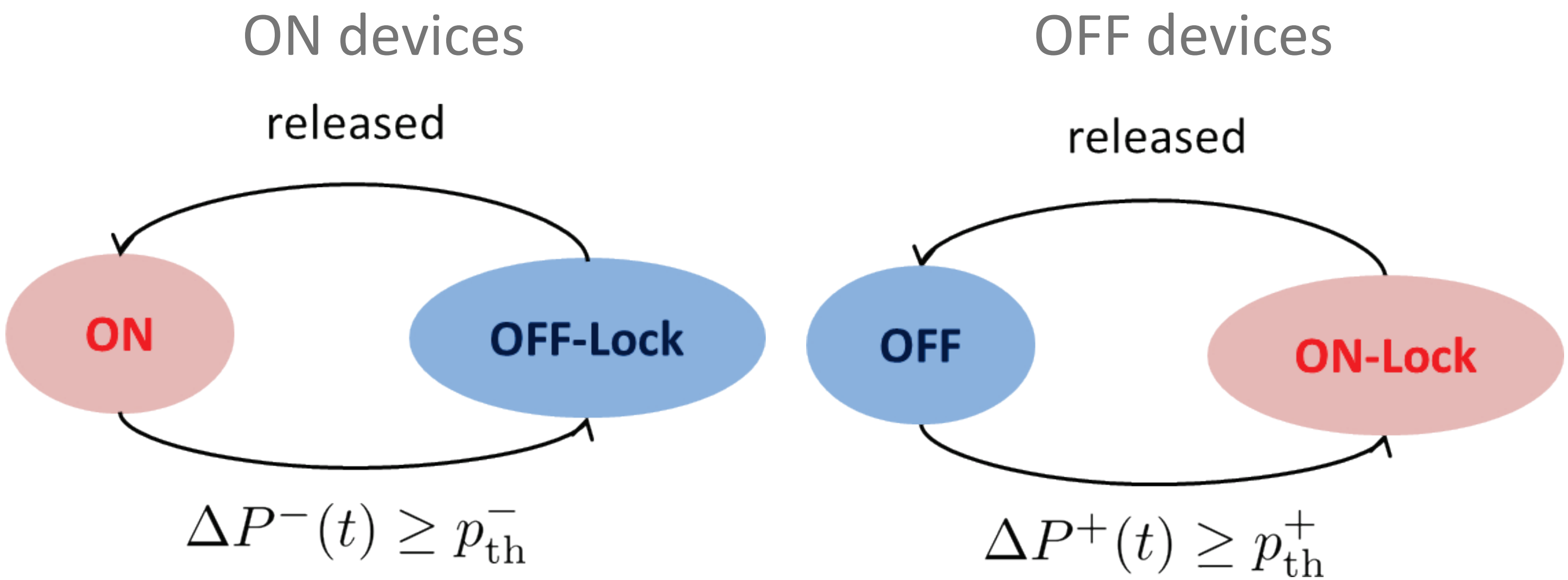


Load Control Strategy



Device-level Control

- Autonomous response based on local thresholds



$\Delta P^+(t)/\Delta P^-(t)$	Broadcasted rising/falling signals
$p_{\text{th}}^+/p_{\text{th}}^-$	Local thresholds for turning ON/OFF

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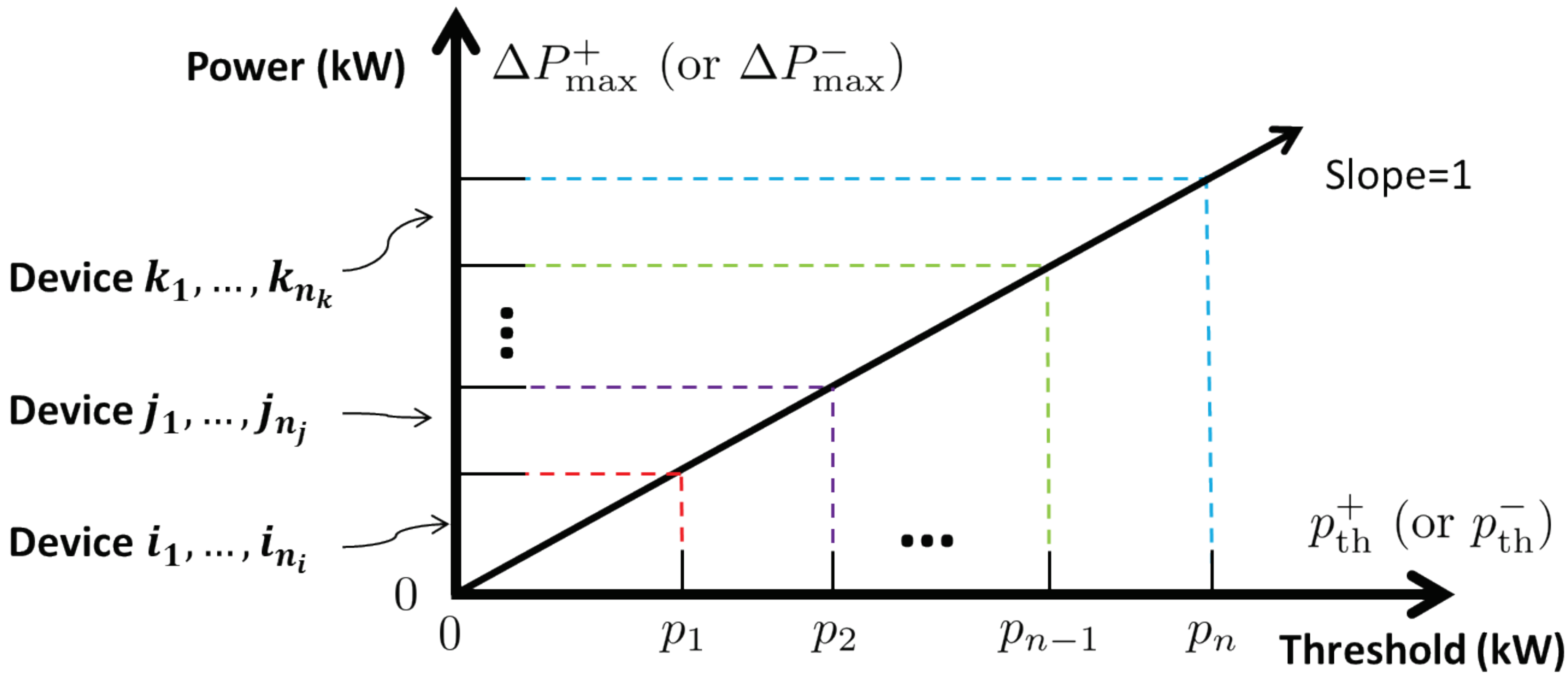
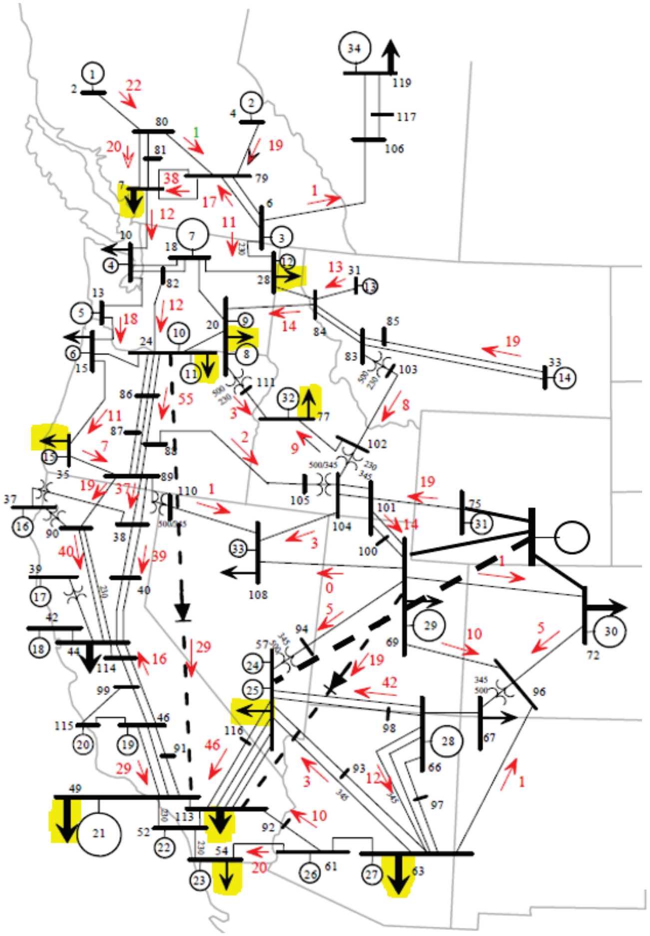
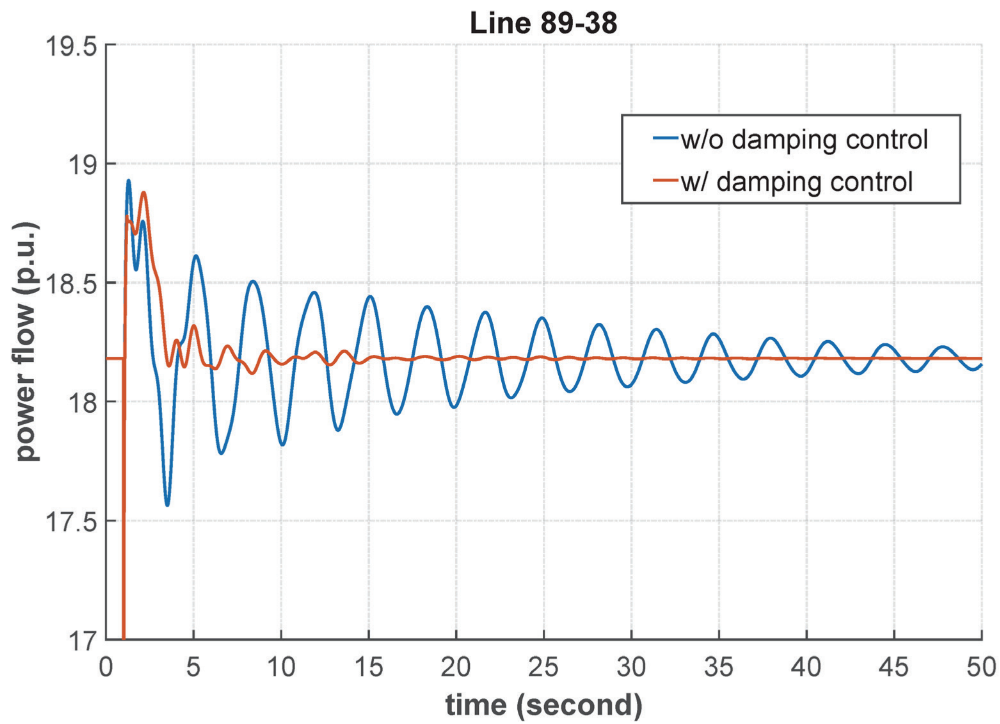
Supervisor-level Coordination

- Threshold determination in a hierarchical manner at a slow time scale (e.g., every 15 minutes)



Simulation Results





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Damping Control

Decoupled Modulation

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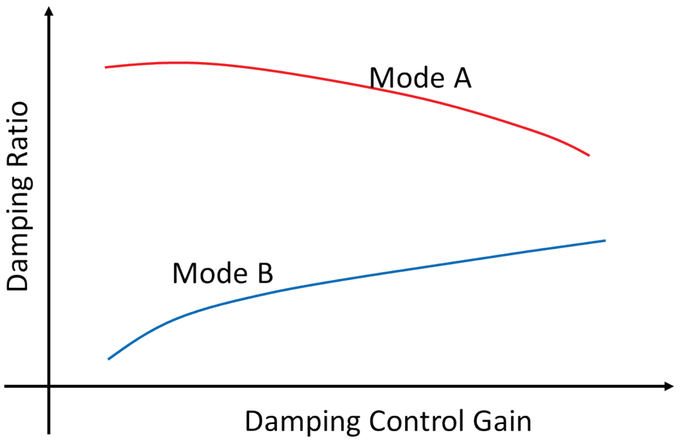
Motivation

- Large-scale power grid usually has multiple inter-area oscillation modes
- Damping controller based on real-time feedback of directly measured signals may not be effective for damping all the oscillation modes
- In the worst case, the damping of two modes could be affected in the opposite directions, which is undesirable



Mode Decomposition

- Solution: Design damping controller based on the real-time feedback of single mode
  - More effective due to minimum interference among different oscillation modes
- Existing technique: Band-pass filter
  - Require a prior knowledge on the frequency
  - Very difficult to obtain a pure oscillation mode
- Proposed rigorous method for real-time mode decomposition by using remote measurements provided by PMUs

Proposed Method

- Offline study of the system property
  - Select a chunk of historical data collected by *n* PMUs
  - Apply Prony's analysis to identify modal signals

$$m_j(t) = e^{\alpha_j t}\cos(\omega_j t + \phi_j), \quad j = 1, \dots, q$$

  - Determine the system matrix *C* that relates identified modal signals to the given PMU measurements

$$\begin{cases} v_1(t) = \sum_{j=1}^{q} C_{1j} m_j(t) \\ \quad \vdots \\ v_n(t) = \sum_{j=1}^{q} C_{nj} m_j(t) \end{cases} \Longleftrightarrow \begin{bmatrix} v_1(t) \\ \vdots \\ v_n(t) \end{bmatrix} = C \begin{bmatrix} m_1(t) \\ \vdots \\ m_q(t) \end{bmatrix}$$

$\Rightarrow$ C Left-invertible, uniquely determined by system topology and operating point

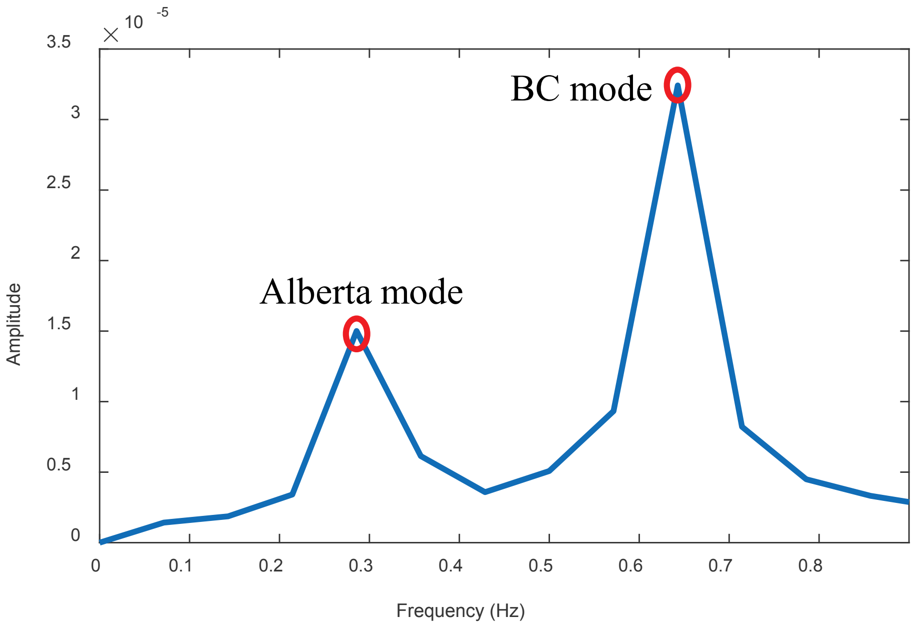
Proposed Method

- Offline study of the system property
  - Select a chunk of historical data from *n* PMUs
  - Apply Prony's analysis to determine modal signals
  - Determine the system matrix *C* that relates identified modal signals to the given PMU measurements
- Online mode decomposition
  - Collect measurements from pre-determined *n* PMUs
  - Determine real-time modal signals based on matrix *C*

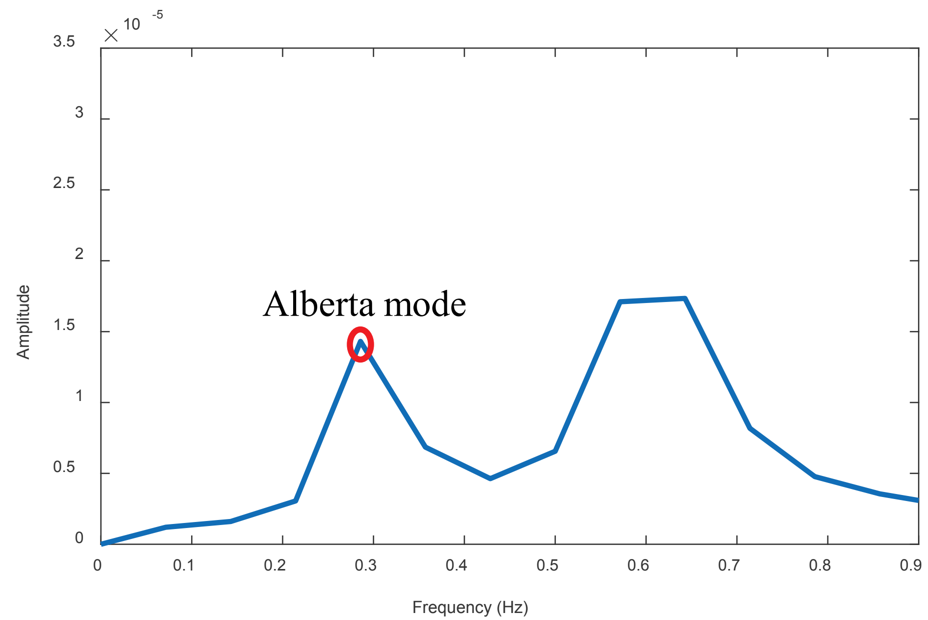
$$\begin{bmatrix} m_1(t) \\ \vdots \\ m_q(t) \end{bmatrix} = C \backslash \begin{bmatrix} v_1(t) \\ \vdots \\ v_n(t) \end{bmatrix}$$

Simulation Results on PSS

Before Control



After Control



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FY16 Remaining Activities

- Extend proposed decoupled modulation to HVDC lines and controllable loads
- Connect proposed load control strategy with damping controller
- Perform initial investigation of the impacts of communication delay to control performance
- Submit planned journal and conference papers

Publications

Journal articles:

- S. Wang, R. Fan, R. Huang, J. Lian, R. Diao and Z. Huang, "Enhanced power system damping with decoupled modulation," *IEEE Transactions on Power Systems*, 2017.
- R. Fan, S. Wang, R. Huang, J. Lian, M. Elizondo, "A decoupled HVDC control strategy for power system inter-area oscillation damping," *IEEE Transactions on Smart Grid*, 2017.
- M. Elizondo, R. Fan, H. Kirkham, F. Wilches-Bernal, D. Schoenwald and J. Lian "Oscillations damping control using high voltage DC transmission: A review," *IEEE Transactions on Smart Grid*, 2017
- H. Kim, M. Zhu and J. Lian, "Distributed robust adaptive frequency regulation of power grid with variable renewable integration," *IEEE Transactions on Automatic Control*, 2017.

Conference proceedings:

- R. Fan, M. Elizondo, H. Kirkham, F. Wilches, D. Schoenwald and J. Lian "Oscillations Damping Control Using Multiple High Voltage DC Transmission Lines: Controllability Exploration," *2018 Transmission and Distribution Conference and Exposition*, April, 2018.
- F. Wilches-Bernal, D. Schoenwald, R. Fan, M. Elizondo, and H. Kirkham, "Analysis of the impact of network-induced latencies in feedback signals on HVDC damping controllers," *2018 Transmission and Distribution Conference and Exposition*, April, 2018.
- J. Lian, Q. Zhang, L. Marinovici, R. Fan, R. Huang and J. Hansen, "Hierarchical decentralized load control strategy for inter-area oscillation mitigation" *2018 Transmission and Distribution Conference and Exposition*, April, 2018.

FY17 Proposed Activities

- Investigate the impacts of communication effects (delay, packet loss, etc.) to control performance
- Study the interactions among damping control realized by HVDC lines, controllable loads, PSS through integrated testing
- Validate damping control strategies on the full WECC system model using commercial tools
- Improve the resilience of wide-area monitoring and control systems to cyber-physical attacks

Questions?

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HVDC Expansion Plans

Several lines could be potential candidates to participate in damping modulation because of their alignment with typical oscillations modes in the WECC.

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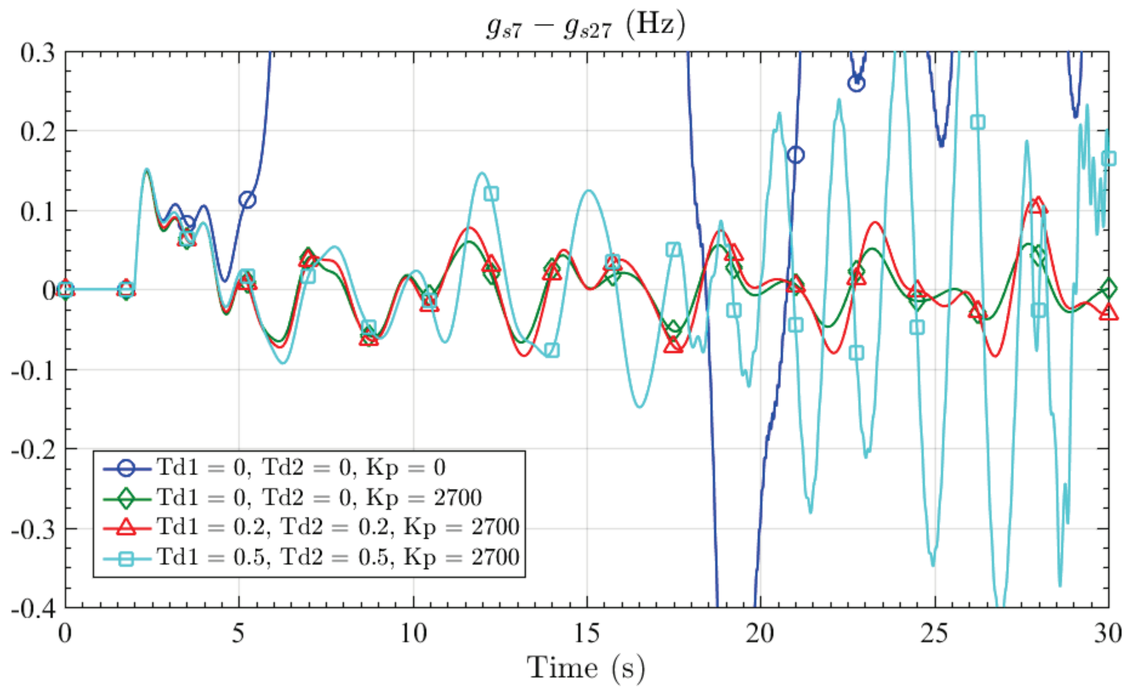
Initial Tests on Delays

- System w/o control is unstable (blue line in Fig).
- The controller brings the system back to stability.
- When delay is added to the feedback measurements, the system becomes unstable once again.
- The system still shows acceptable performance for latencies as high as 200 ms.



Event considered: trip of Palo Verde unit (imbalance in the south). **Power lost** is about **2.2 GW**.