Active Damping of Power System Oscillations Using Distributed Energy Storage

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Project Overview

Project Deliverables:
1. **Prototype PDCI-based damping control system**
   - Open-loop testing in BPA’s PMU Lab
   - Transition to Celilo for closed-loop testing
2. **Implementation strategy for ESS-based damping**
   - Control algorithms employing distributed storage
   - Implementation strategies for deployment

Innovative Features of Project:
1. **Real-time PMU measurements** for frequency feedback to dampen inter-area modes
2. **Supervisor controller** to monitor damping effectiveness and ensure “Do No Harm”
Western Interconnect Oscillation Modes

North-South Mode

North – South

BC - US

Montana - NW

East - West

North-South Mode

- British Columbia
- Alberta
- Saskatchewan
- Washington
- Idaho
- Montana
- Oregon
- Nevada
- Utah
- New Mexico
- Arizona
- Colorado
- California

0° – 180° |φ|
Inter-Area Oscillations Jeopardize Grid Stability

- Large generation and load complexes separated by long transmission lines can develop inter-area oscillations
- Present approach to mitigate this scenario is maintaining large headroom in power flow
- More efficient mitigation strategy is active power injection using energy storage or PDCI modulation
Expected Benefits of Damping Control

- Improved system reliability
- Additional contingency in a stressed system condition
- Economic benefits:
  - Avoidance of costs from an oscillation-induced system breakup (1996 outage costs: > $3B)
  - Reduced need for new transmission capacity (capital cost savings > $1M/mile)
  - Potential for increased power flows through congested transmission corridors

Frequency difference: John Day vs. Vincent

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Frequency difference (Hz)</th>
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<tbody>
<tr>
<td>0</td>
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<tr>
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<tr>
<td>25</td>
<td>-0.005</td>
</tr>
<tr>
<td>30</td>
<td>-0.025</td>
</tr>
</tbody>
</table>

- No control
- With damping control
Advantages:

- Robust to single points of failure
- Controllability of multiple modes
- Size/location of a single site not as critical as more storage is deployed
Algorithmic Approach to Multi-Node Distributed Damping

- A scalable $N$-node damping control scheme using distributed energy storage
- Each node modulates power based on local PMUs and multiple remote PMUs

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

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

![Diagram showing the Algorithmic Approach to Multi-Node Distributed Damping with nodes connected through network topology, model estimate, cost function, and feedback gain values.](image)
An Optimization Problem is Formulated

- To attain the control law \( u_d = -K_d y \)

\[
\min_{K_d} \quad J = \int_0^{T_f} \left( x^T Q x + u_d^T R u_d \right) d\tau
\]

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 recent journal paper:

Example of Damping Control using Distributed Storage

- Total storage capacity on order of 50 MW is sufficient
- With 10s of sites deployed, individual ESS capacity ≈ 1 MW is sufficient
- Control strategy uses ESS primarily serving other applications → very little additional cost for very large benefit

![Graph of System Eigenvalues](image)

Improvement in Damping of East-West Mode

![Map of East-West Mode](image)
Project Direction: FY16 – FY17

- Energy storage component of project will focus on distributed damping:
  
  **Implementation of algorithms** ➔ Design strategies will account for communication network issues and likely ESS penetration levels

- PDCI modulation component of project will focus on deployment with the goal of demonstrating closed-loop operation:

  **Phased approach** ➔ Gradual increases of both magnitude and duration of closed-loop testing with go/no-go decisions between phases
Planned Phase II Timeline

**PDCI:**
- **Start Phase II**
- **Open-loop PDCI probe testing using prototype**
- **Closed-loop PDCI probe testing using prototype under benign conditions**
- **Closed-loop testing for extended periods under ambient conditions**
- **Closed-loop testing under Chief Joseph brake test**
- **Closed-loop testing for increasing power levels under ambient conditions**

**ESS:**
- **Start Phase II**
- **Design distributed damping strategies**
- **Characterization of PMU Data and Network Performance**
- **Conduct PSLF simulation studies of distributed control designs on wNAPS**
- **Analyze performance of control designs via simulations**
- **Assess performance differences between distributed and centralized damping**
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Questions?

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