Wide-Area Damping Control Proof-of-Concept Demonstration

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  – BPA Office of Technology Innovation – CTO: Terry Oliver
<table>
<thead>
<tr>
<th>Problem:</th>
<th>Solution:</th>
<th>Benefits:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Poorly damped inter-area oscillations jeopardize grid stability and can lead to widespread outages during stressed grid conditions</td>
<td>• Construct closed-loop feedback signal using real-time PMU data: 1st demonstration of this in North America</td>
<td>• Improved grid reliability</td>
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<tr>
<td>• Oscillation stability limits constrain power flows well below transmission capacity: Inefficient use of expensive infrastructure investments</td>
<td>• Modulate power flow on PDCI (up to +/- 125 MW)</td>
<td>• Additional contingency for stressed grid conditions</td>
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<td></td>
<td>• Implement a supervisory system to ensure “Do No Harm” to grid and monitor damping effectiveness</td>
<td>• Avoided costs from a system-wide blackout (&gt;&gt; $1B)</td>
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<td>• Reduced or postponed need for new transmission capacity: $1M–$10M/mile</td>
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<td>• Helps meet growing demand by enabling higher power flows on congested corridors</td>
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Damping Controller Strategy

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
Damping Controller Hardware

- Watchdog circuit module
- Key switch
- Heartbeat indicators
- E-Stop button
- Server for select supervisory functions
- Real-time Control platform
Supervisory System Ensures “Do No Harm”

**Watchdog Circuit:** Detects hardware failures, ensures smooth state transitions, and handles E-stop functions.

**Real-time Supervisor:** Monitors latencies and data quality, switching to other PMU sites if needed.

**Asynchronous Supervisor:** Estimates gain/phase margin, PDCI health, and slower-than-real-time tasks.
2016 Closed-Loop Tests Showed Significant Damping Improvements

Tests conducted at Celilo Converter Station on September 28-29, 2016

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.
May 16, 2017 Tests, CJB Pulse, Gain = 9 MW/mHz
May 16, 2017 Tests, CJB Pulse, Gain = 12 MW/mHz
May 16, 2017 Tests, 0.4 Hz Forced Oscillation

PDCI Estimated Power Flow, 0.4 Hz Forced Oscillation

PATH66 (COI)

- F1, Closed loop, K=12
- F2, Open loop
May 16, 2017 Tests, 1.0 Hz Forced Oscillation

PDCI Estimated Power Flow, 1.0 Hz Forced Oscillation

- PDCI Power Flow, No Control
- PDCI Power Flow, Control Enabled

PATH66 (COI)

- F4, Closed loop, K=12
- F3, Open loop
Time Delays in PDCI Damping Control

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Mean</th>
<th>Range</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_{\text{meas}}$</td>
<td>PMU Delay</td>
<td>50 ms</td>
<td>Assumed fixed at 50 ms</td>
<td>N. A.</td>
</tr>
<tr>
<td>$t_{\text{com}}$</td>
<td>Communications Delay</td>
<td>10 ms</td>
<td>[5,38]</td>
<td>Heavy Tail Normal</td>
</tr>
<tr>
<td>$t_{\text{del}}$</td>
<td>Signal Delay</td>
<td>60 ms</td>
<td>[55,88]</td>
<td>Heavy Tail Normal</td>
</tr>
<tr>
<td>$t_{\text{cont}}$</td>
<td>Control Processing Delay</td>
<td>11 ms</td>
<td>[3,17]</td>
<td>Bimodal Normal with peaks at 8 &amp; 15 ms</td>
</tr>
<tr>
<td>$t_{\text{tot}}$</td>
<td>Total Controller Delay</td>
<td>71 ms</td>
<td>[58,102]</td>
<td>Bimodal Normal with peaks at 66 &amp; 73 ms</td>
</tr>
<tr>
<td>$t_{\text{cmd}}$</td>
<td>Command Delay</td>
<td>Estimated at 11 ms</td>
<td>Assumed fixed at 11 ms</td>
<td>N. A.</td>
</tr>
<tr>
<td>$t_{\text{eff}}$</td>
<td>Effective Delay</td>
<td>82 ms</td>
<td>[69,113]</td>
<td>Bimodal Normal with peaks at 77 &amp; 84 ms</td>
</tr>
</tbody>
</table>

Conclusion: Round trip delays < 100 ms $\Rightarrow$ well within tolerances for robust feedback control
All Planned Tests Have Been Extensively Simulated

• Three WECC PSLF base cases: Heavy Summer 2016, Light Summer 2016, Dual Export 2014 are used to simulate controller performance in four test sequences:
  1. Negative Gain Testing
  2. Controller Limits with Large Gain Values
  3. Chief Joseph Brake Duration Comparison
  4. Forced Oscillations (30 MW probing at wide range of frequencies)

• Rare events are added to the simulations for the negative gain and controller limits tests:
  1. Double Palo Verde Trip
  2. BC-US Separation
  3. BC-Alberta Separation
  4. Chief Joseph Brake Pulse added to each of the above 3 events
2017 PDCI Testing Schedule

Phase 1: Active Short-Term Open & Closed-Loop Tests
• Completed on Tuesday, May 16, 2017

Phase 2: Active Medium-Term Closed-Loop Test
• Started on Tuesday, June 6, 2017, 10:33 a.m. PDT
• Ended on Wednesday, June 7, 2017, 12:00 p.m. PDT

Phase 3: Similar to Phase 1 to be Conducted Later in Season
• Scheduled Dates: TBD – Later in summer season preferably to coincide when Alberta is disconnected
• Phase 3 is very similar to Phase 1 except forced oscillations are induced from BPA-connected generators

Phase 4: Active Long-Term Closed-Loop Test
• Scheduled Dates: TBD – This will be a longer test than Phase 2 (several weeks in length)
Takeaways from PDCI Tests Conducted Thus Far

• Three phases of tests conducted on PDCI (Sept 2016, May 2017, and June 2017) have shown significant improvements in N-S B mode damping

• Test results have shown no degradations in damping of peripheral modes

• Test results have shown improved damping for forced oscillations < 1 Hz without worsening damping at > 1 Hz

• Test results have consistently confirmed the findings of simulation studies

• Time delays have been well within tolerances

• Supervisory system has performed exactly as expected
R&D Tasks Needed to “Operationalize” Controller

• **Testing & Network Characterization**
  – Long-term performance testing and analysis of results
  – Network latency characterization and mitigation strategies for bad data

• **Cyber Security**
  – Follow process used by RAS systems
  – Investigate time synchronization

• **Test Automation Unit**
  – Stand-alone unit to fully check out controller modes of operation
  – Needed for RAS consideration

• **Operation under PDCI Constraints**
  – Control design for PDCI flows at limits
  – Design for current limits (AC-VDCOL)

• **RTDS Studies**
  – Exercise controller for scenarios on DC side to analyze PDCI dynamics
  – Support studies of PDCI operation

• **Model Development**
  – Models needed to support wNAPS utilities and regulatory compliance
  – Pursue WECC approvals

• **Monitoring System**
  – Operator interface conveying current status, recent events, and other pertinent information
  – Incorporates ability to quickly retrieve more detailed information
Project Publications & Presentations in FY17


Impact of Project Results on Future Grid Controls

• First wide-area controller using real-time PMU feedback in North America ➔ Design expertise in using PMUs for control can be leveraged by other projects on a rapidly evolving network-enabled grid.

• Experience gained in networked controls will advance distributed control of networked assets (energy storage, smart inverters, DG, demand response).

• Supervisory system architecture and design process can be applied to real-time control systems for other grid functions.

• Extensive eigensystem analysis and visualization tools developed for simulation studies and analysis of test results.

• Model development and validation for multiple levels of fidelity to support analysis, design, and simulation studies.