SAND2015-0400C

Technology Innovation

TIP 289: Wide Area Damping Control Proof-of-Concept Demonstration

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Project Team

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  - Prof. Matt Donnelly
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  - Dr. John Undrill

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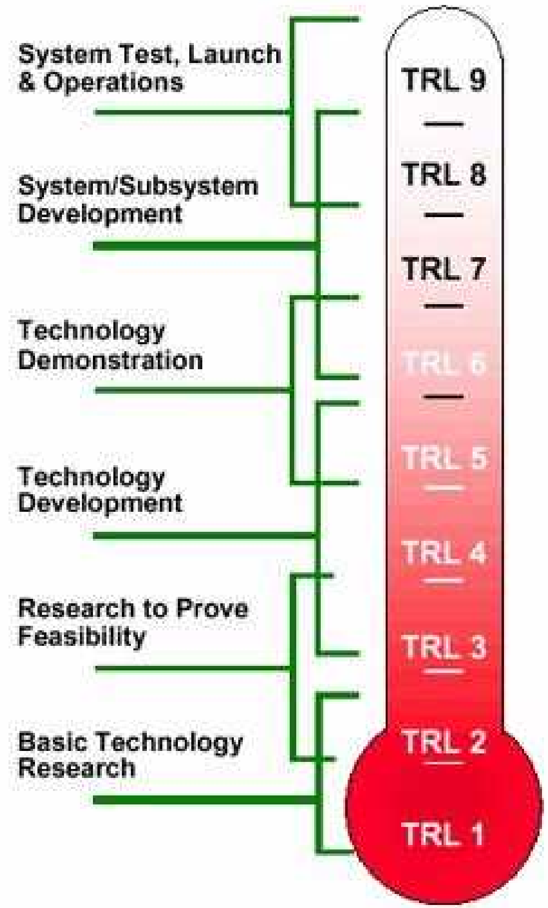
  - BPA Technology Innovation Program – TIP 289
  - DOE-OE Grid Reliability Program (PM: Phil Overholt)
  - DOE-OE Energy Storage Program (PM: Dr. Imre Gyuk)

Project Synopsis

- **Overall Project Goal:**
  - **Significantly increase the TRL** (Technology Readiness Level) of wide area damping control systems so that **next phase is deployment** oriented
  - **TRL = 2 at start of project (Summer 2013)**
  - **TRL = 6 currently (end of Phase I)**
  - **TRL = 9 planned by end of Phase II**
- **Primary Phase I Deliverables**:
  - Constructed and installed a **prototype PDCI-based damping control system** that is being tested and validated in the BPA Synchrophasor Laboratory
  - Provided analysis and modeling tools to assess the capabilities of **energy storage** for damping control
- **Control Design Features:**
  - **Real-time PMU** (Phasor Measurement Unit) feedback to dampen inter-area oscillations
  - **Supervisor controller** to monitor damping effectiveness and enforce **“Do No Harm”**

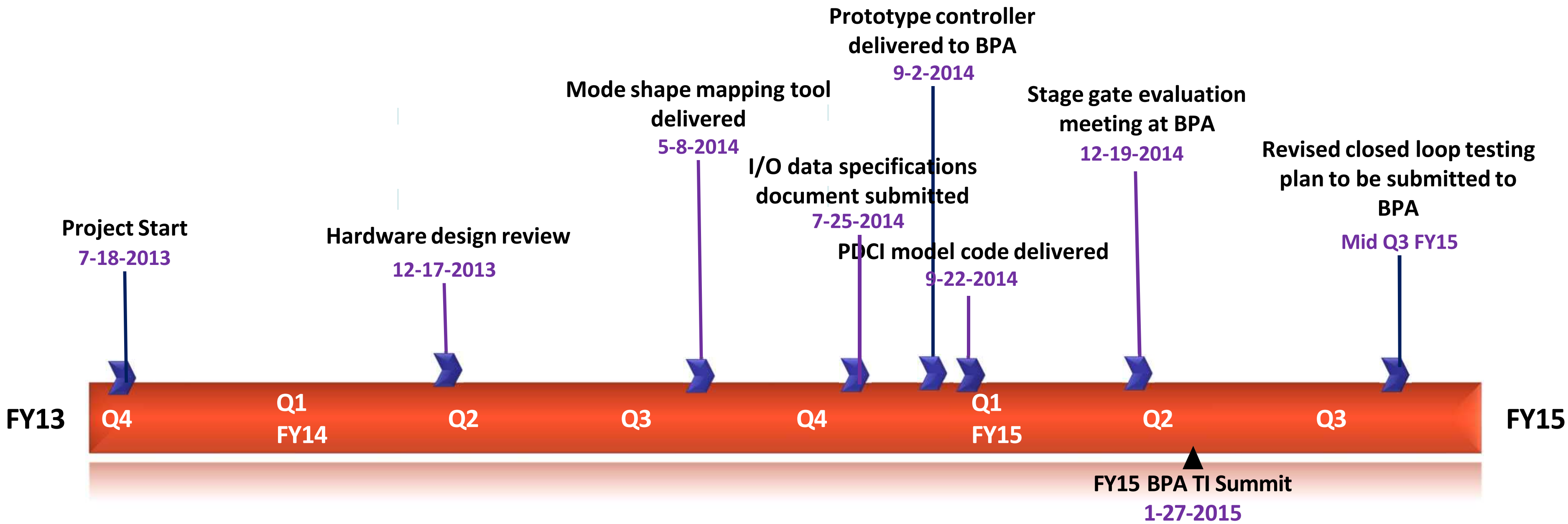


Expected Benefits

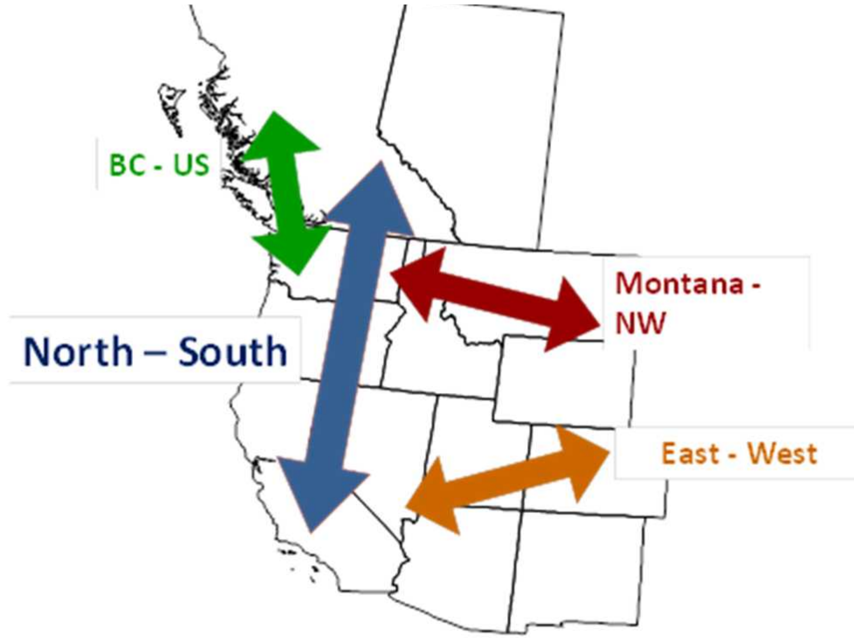
Detailed simulation studies have demonstrated these benefits:

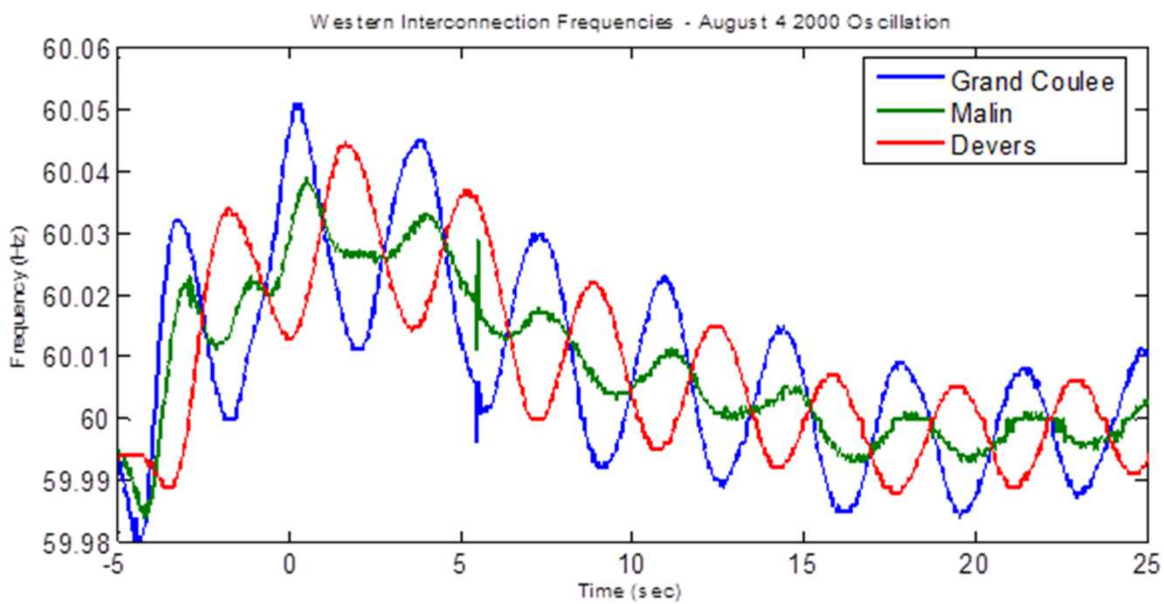
- Improved system reliability
- Additional contingency in a stressed system condition
- Potential economic benefits:
  - Avoidance of costs from an oscillation-induced system breakup (1996 outage costs: > $1B overall impact)
  - Reduced or postponed need for new transmission capacity (capital cost savings in excess of $1M/mile)

Project Timeline



Western Interconnect Oscillation Modes

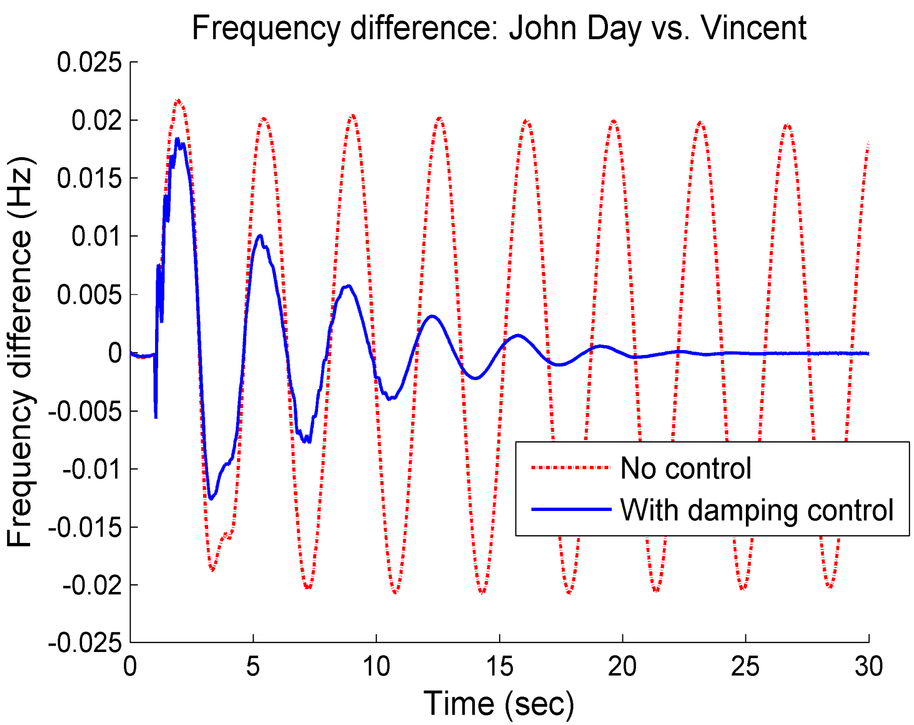


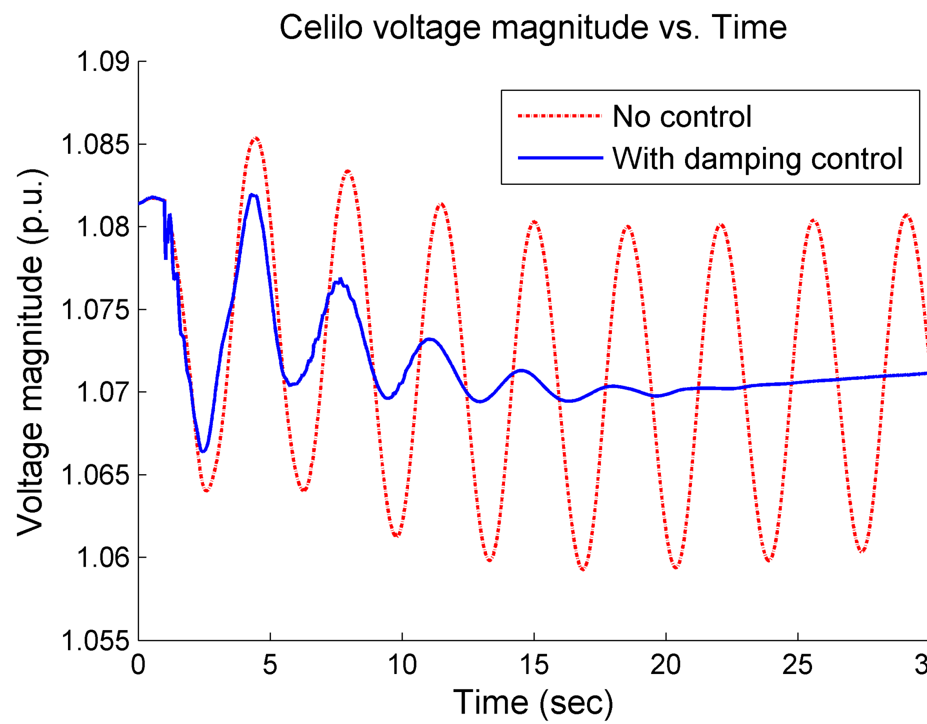


Benefits of PDCI Damping Control

Simulation Details

- 2013 Heavy Summer base case
- BC-Alberta separation (Cranbrook-Langdon intertie)
- The primary objective is to improve the damping of inter-area modes
- A secondary benefit is voltage support near the terminals of the PDCI





Project Accomplishments: FY13 - FY15

- **Development of prototype hardware and real-time software:**
  - Prototype has been installed and operating at BPA Synchrophasor Lab
  - Damping control design based on real-time PMU feedback
  - Supervisor control design to monitor:
    - System operation to assure all control settings are correct
    - Real time stability monitoring
- **Damping control strategies incorporating energy storage:**
  - Optimal allocation of distributed energy storage for active damping
  - PDCI modulation augmented with energy storage to mitigate E-W mode

Project Accomplishments: FY13 – FY15

- **Award:**

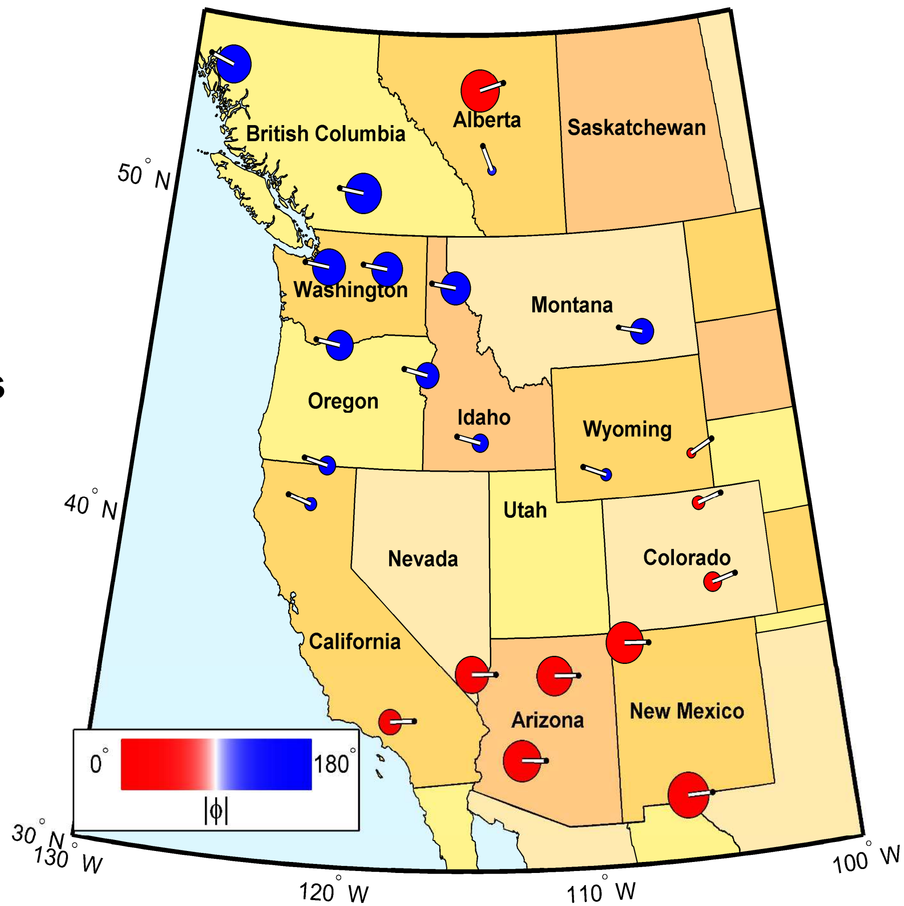
  Dan Trudnowski, Dmitry Kosterev, and John Undrill
  "PDCI Damping Control Analysis for the Western North American Power System," Proceedings of the 2013 *IEEE Power & Energy Society General Meeting*
  awarded as one of four "Best of the Best" papers

- **Publications:**
  - 2013 & 2014 IEEE Power and Energy Society General Meeting (PESGM)
  - 2013 Electrical Energy Storage Application and Technology (EESAT)

- **DOE Program Reviews:**
  - **Highly rated** by DOE-OE Transmission Reliability Program internal review meeting – June 2014
  - **Strong support** from DOE-OE Energy Storage Program peer review meeting – Sept 2014

Technology Transfer/Application to BPA

- **BPA end user is Transmission Operations**
  - Delivered prototype control system to BPA PMU Lab
  - Submitted PDCI I/O requests to ABB for Celilo upgrade
  - Rack space has been allocated for damping controller
  - Ensuring hardware compatibility for transition to Celilo
  - Closed loop testing plan in review (phased testing)
  - I/O data specifications document submitted FY14
  - Hardware architecture diagrams and wiring schematics delivered for FY14 prototype hardware design review
- **Analysis, modeling, and simulation capabilities**
  - PDCI Probe testing analysis reports
  - Revised mapping software delivered May 2014
  - Open loop testing of prototype controller began in late FY14 with regular briefings on performance analysis
  - Report summarizing options for BPA feedback signals delivered in January 2015
  - Characterization of PMU latencies and data quality
  - PDCI model (in PSLF)
  - PSLF simulation studies
  - Tools for oscillatory mode analysis (Prony method, Eigensystem Realization Algorithm – ERA)
  - Simplified models to study distributed damping schemes



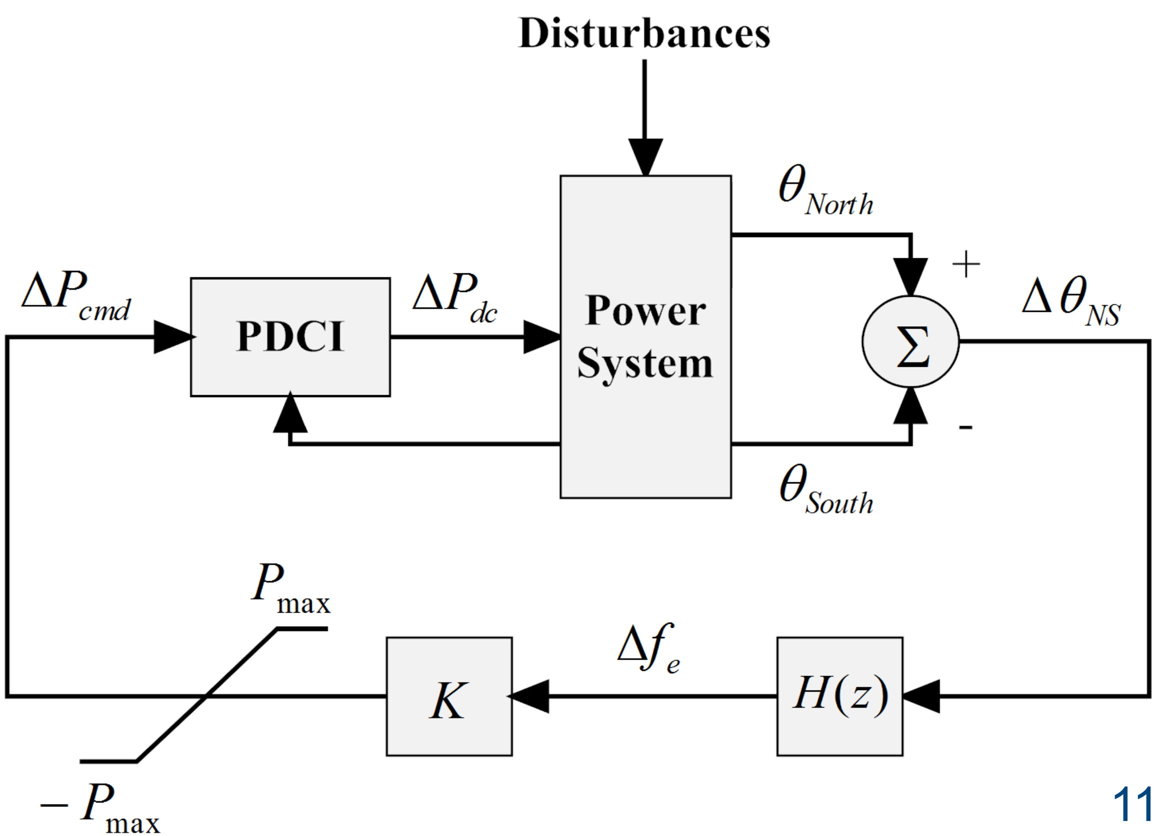
Damping Control Strategy

Control Objectives:

- Dampen all modes of interest for all operating conditions without destabilizing peripheral modes
- Do NOT worsen transient stability (first swing) of the system
- Do NOT interact with frequency regulation (e.g. speed governors)

➔ **Feedback control signal should be proportional to the frequency difference between two areas**

PDCI Modulation:



Supervisor Control Design Philosophy

Design was driven by the need to detect and respond to certain system conditions in real-time as well as asynchronous monitoring functions at slower than real time

Supervisor

Asynchronous Control Loop

- Automated probing
- Transfer function estimation
- Gain and phase margin estimation
- PDCI monitoring

Real-time Control Loop

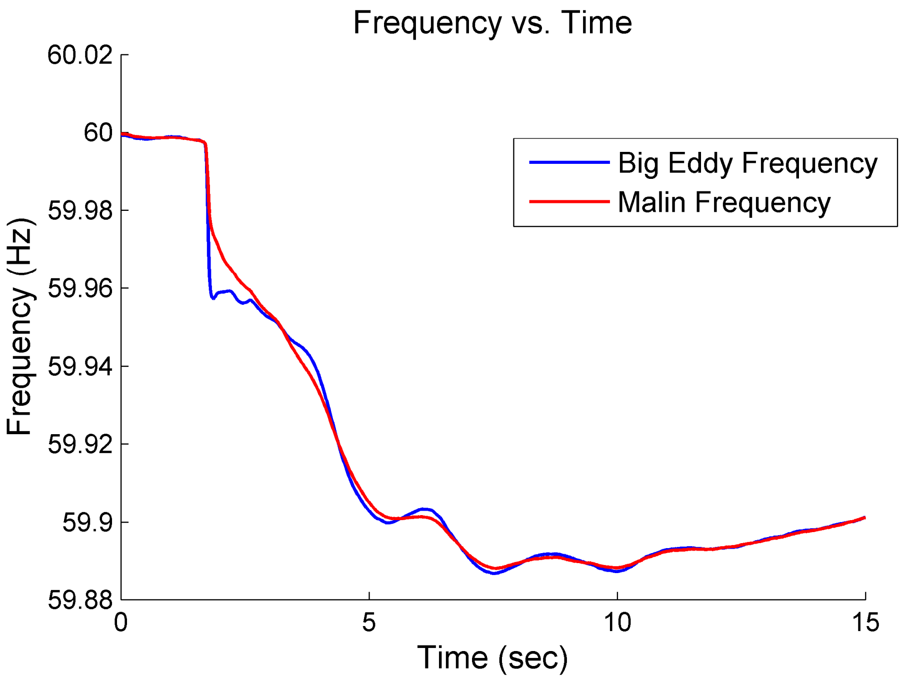
- State machine arch.
- Bumpless transfer (SW)
- Oscillation detection
- Separation detection
- Frequency tol. detection

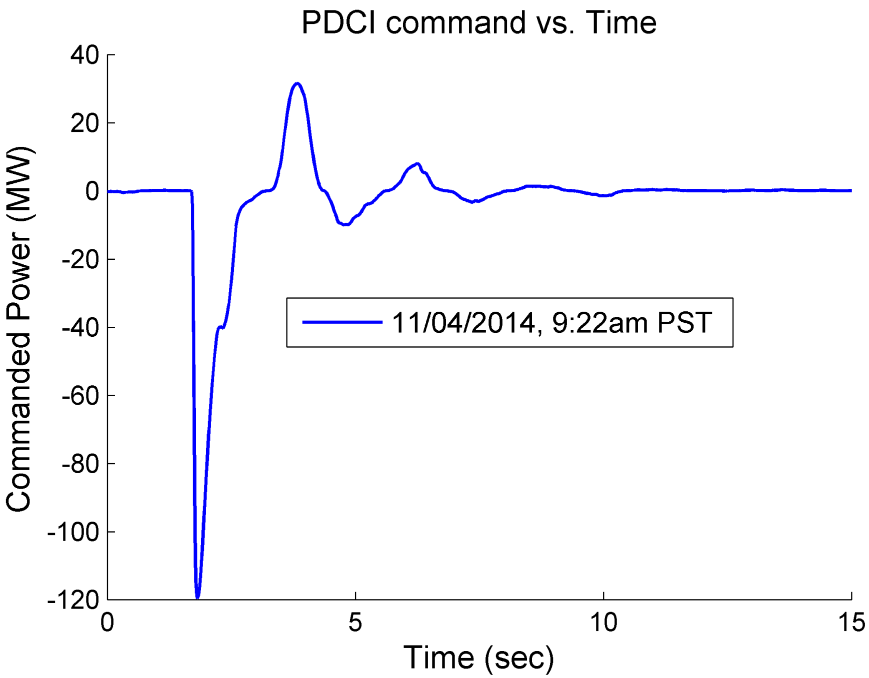
Watchdog Circuit

- Watchdog circuit for async. and RT loops
- Emergency stop button
- Bumpless transfer (HW)
- Reinitialization procedure

Open Loop Testing of Prototype

- Continuously operating (24/7) since mid-October 2014 in BPA Synchrophasor Lab
- Acquires live PMU data from multiple sites (e.g. John Day, Big Eddy, Malin)
- Constructs real-time feedback control signal from acquired data
- Control signal is not sent to PDCI (goes to log file for analysis)
- System event: morning of November 4th, 2014
  - An apparent generation outage led to a 120mHz decline in system frequency (moderate inter-area deviation = 18mHz).
  - Control system performance is precisely as expected



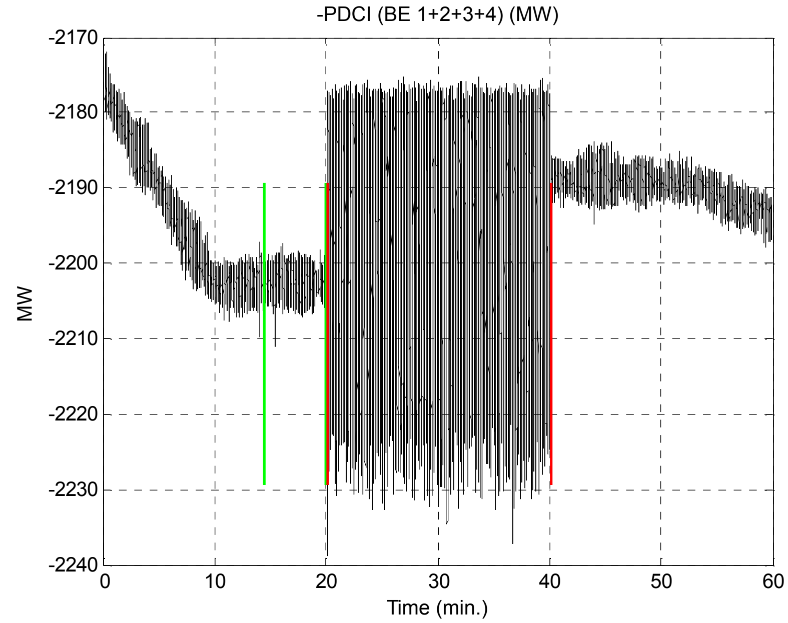


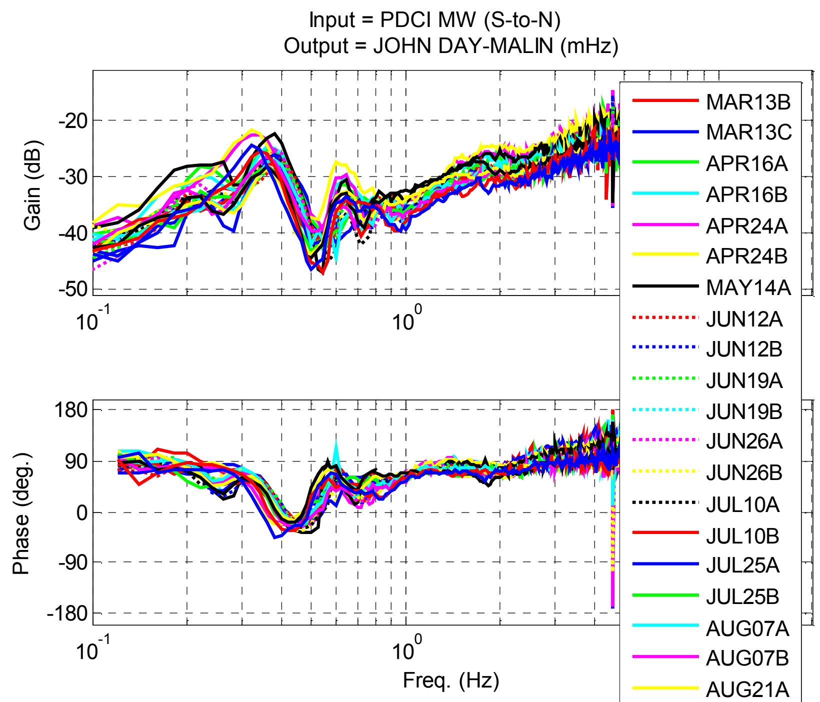
Project Direction/Next Steps

- Phase II of project will transition from **proof-of-concept** to **deployment:** TRL = 6 → TRL = 9
  - Draft of Phase II statement of work is being iterated upon by BPA and SNL/MTU (includes closed loop testing plan)
  - Phase II is proposed as a 2 year project: FY2016 – FY2017
- Analysis of open loop testing
- Refinement of control system based on above
- Assess PMU data quality and latency issues
- Resolve hardware issues for transition to Celilo
- Address cyber security issues for closed loop testing

PDCI Probing Tests

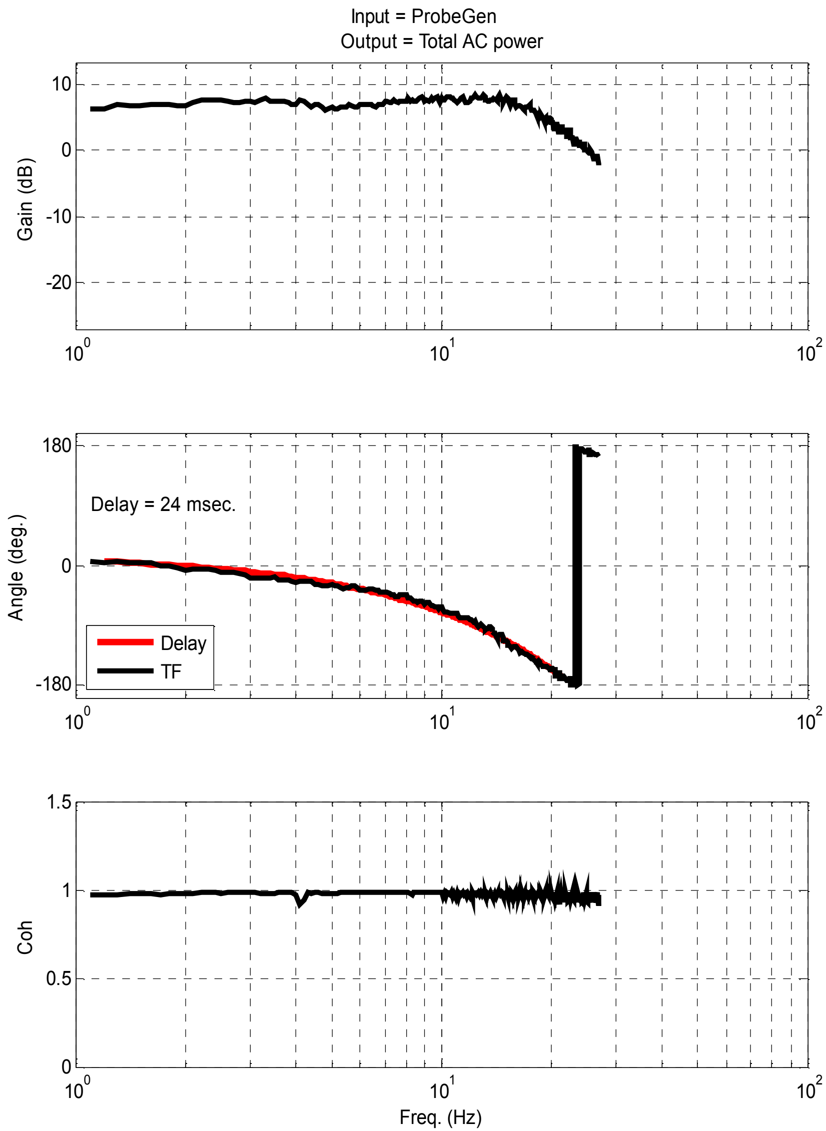
- Probing signal added to PDCI reference
  - Over 100 tests conducted since start of project
  - In 2014, 36 tests conducted
    - Includes 4 high-freq probe tests
- Testing benefits
  - Monitor western interconnect dynamics
  - Damping control data and testing
    - Evaluate control-system robustness
    - Compare to model-based studies
    - Test PDCI performance
- What we've learned
  - Why control didn't work in 1970s
  - New theory supported by tests
  - Candidate Feedback Signals
    - JohnDay – Malin
    - JohnDay – Sylmar
    - ChiefJoe – Malin
  - Feedback gain of 5 to 10 MW/mHz will provide SIGNIFICANT damping
  - PDCI has adequate bandwidth
  - Optimal design of feedback filter
  - We need to further test and fine-tune PMUs



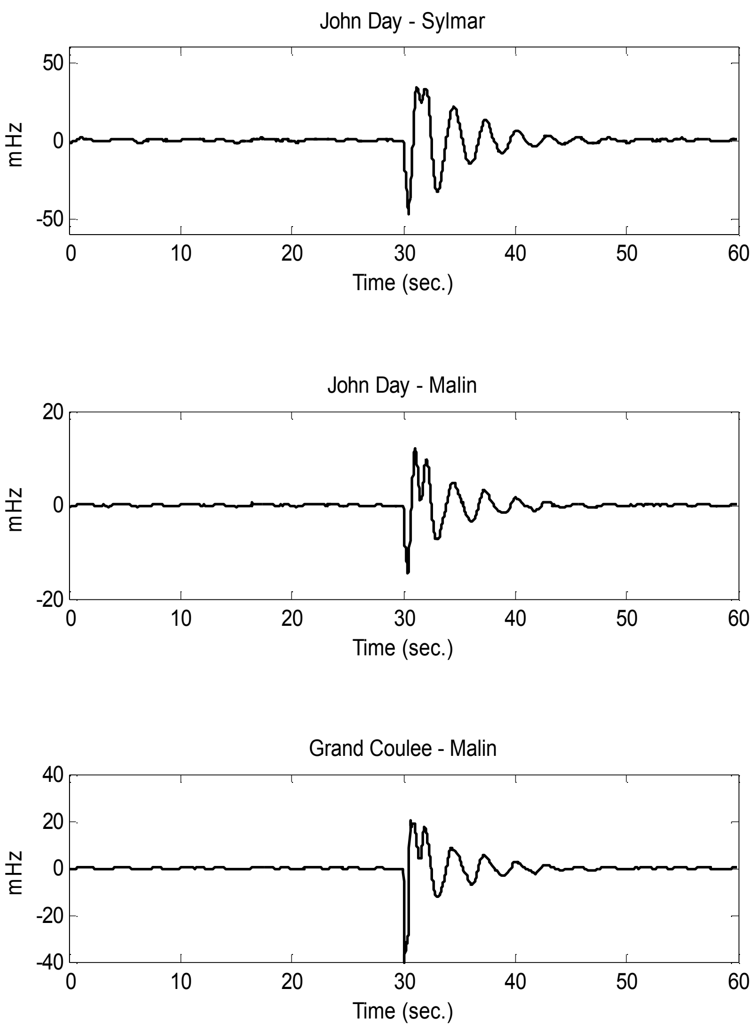


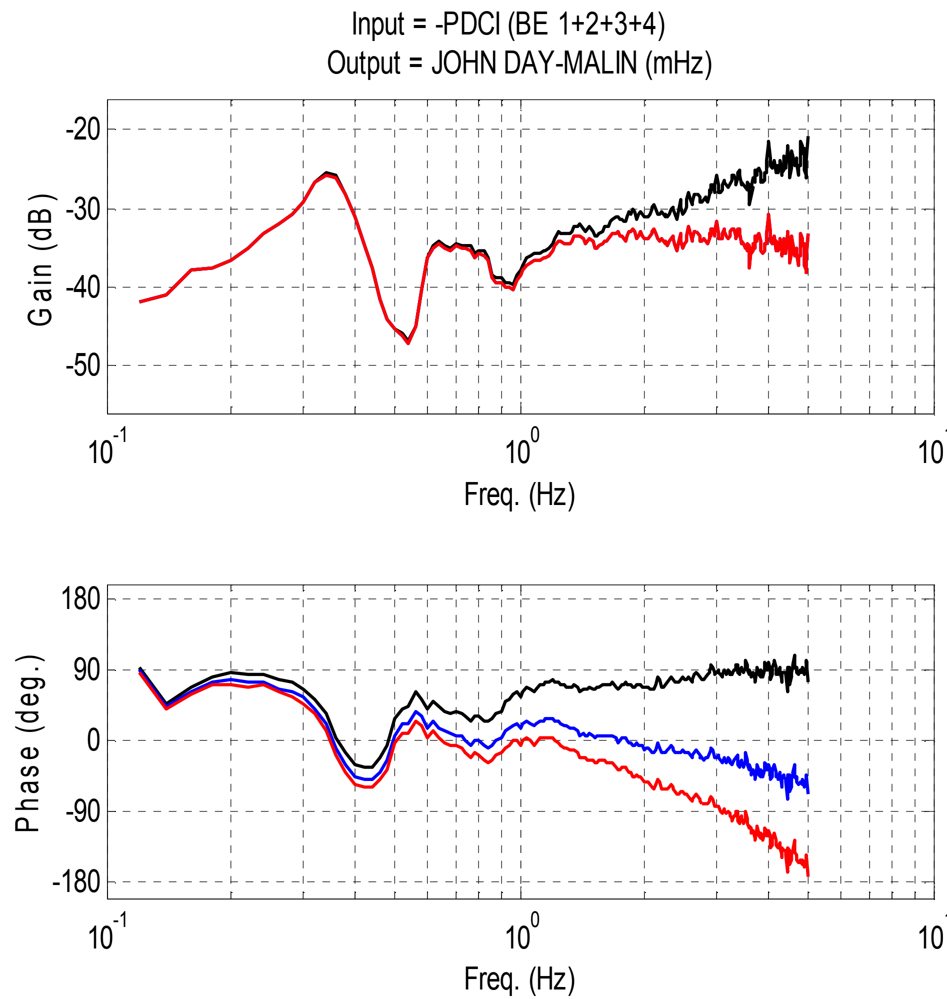
PDCI Bandwidth Testing

- PDCI bandwidth well above 10 Hz
- Delay is constant and about 25 msec
- Gain is linear and “flat”
- PDCI system upgrade
  - Includes injection point for damping controller
  - Signal communication compatible with damping controller



Candidate Feedback Signals





Conclusions

- Theory → working prototype < 2 years
- Transition to deployment well underway
- Demonstrated success in implementation issues

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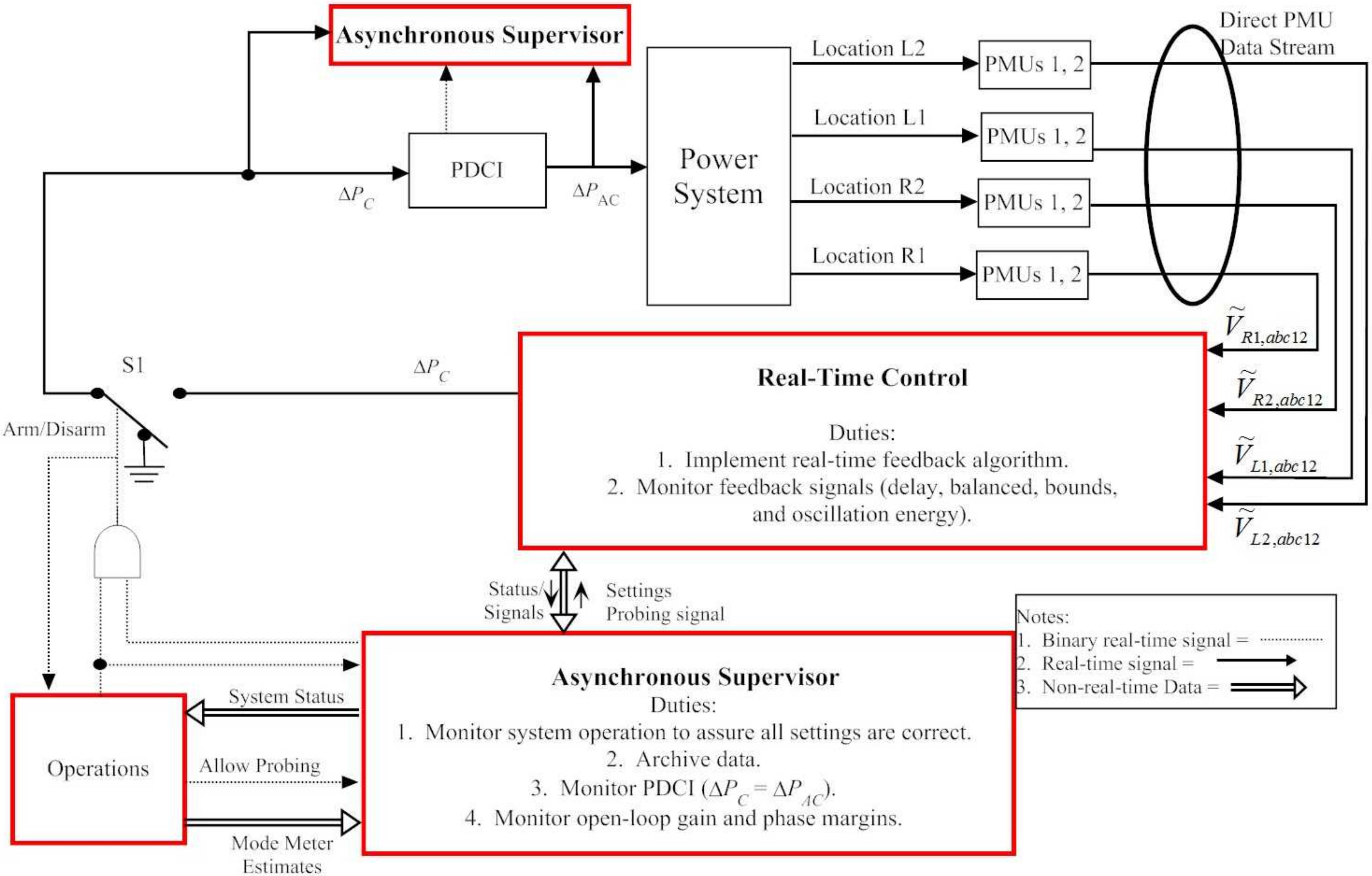
- Likelihood of continued success is very promising

Additional Slides

Control System Overview



State Machine Architecture

- Supervisor incorporates a state machine to enable the control system to transition smoothly between modes of operation.
- Ensures the system starts up, shuts down, and reinitializes safely.

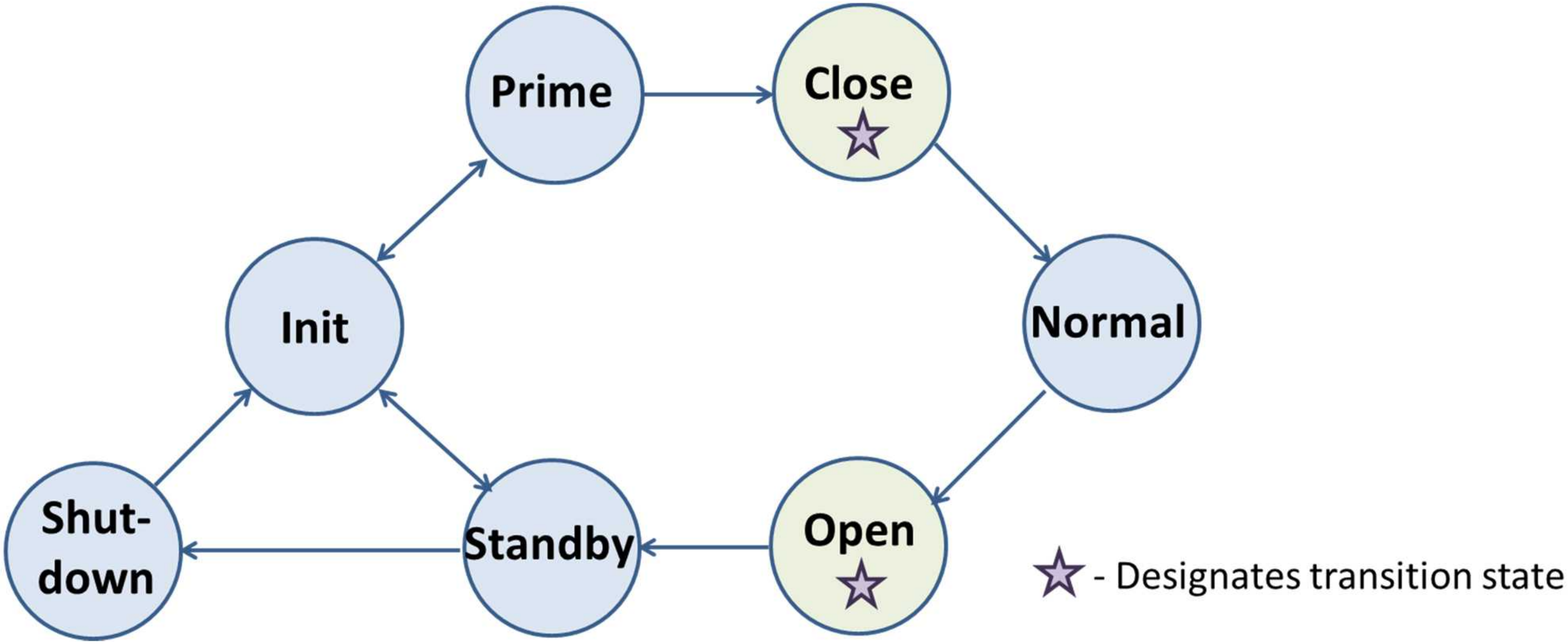
  Init: Set initial values to ensure a flat-start condition

  Prime: Play data through the calculations while holding the command signal to zero

  Standby: Compute the commanded power, but ground the controller output

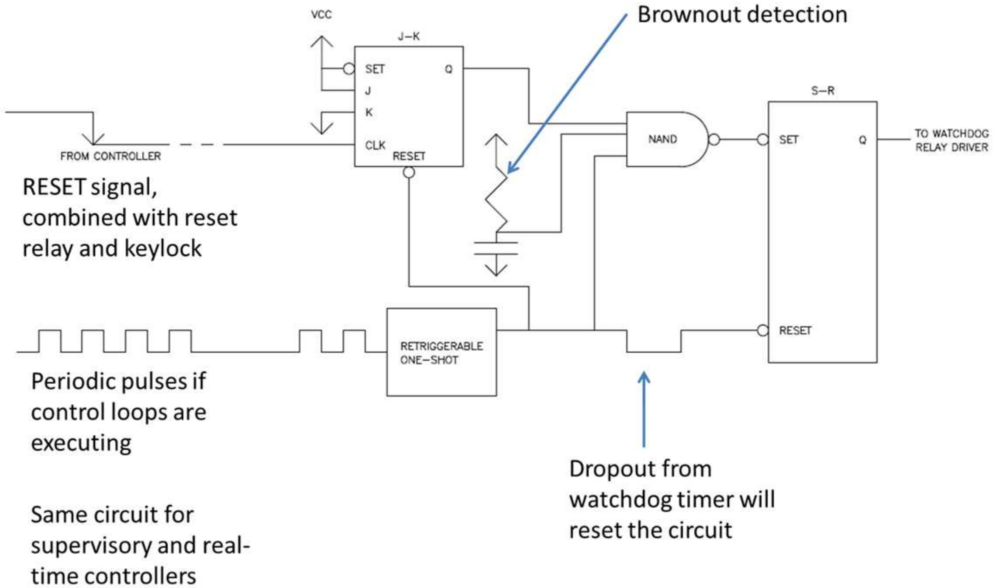
  Normal: Update the command signal as dictated by the control scheme

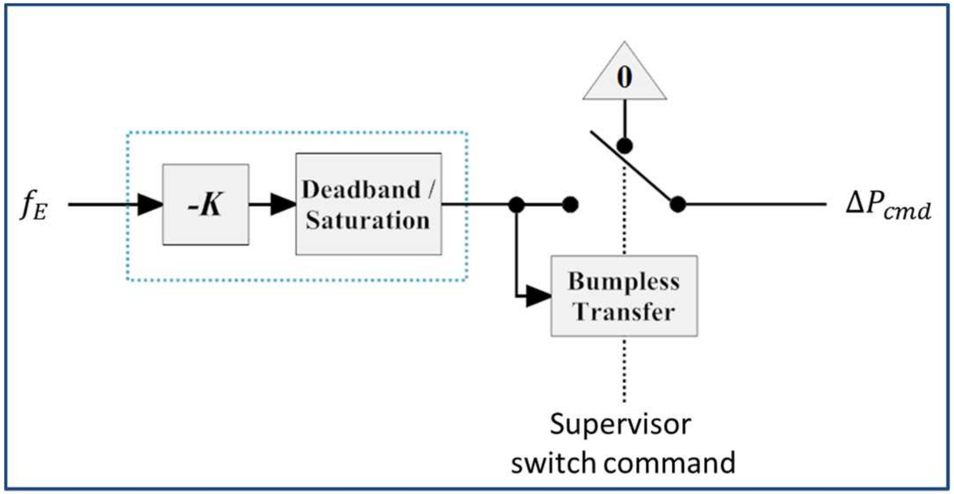
  Shutdown: Ground the controller output and wait for further instructions



Watchdog Circuit

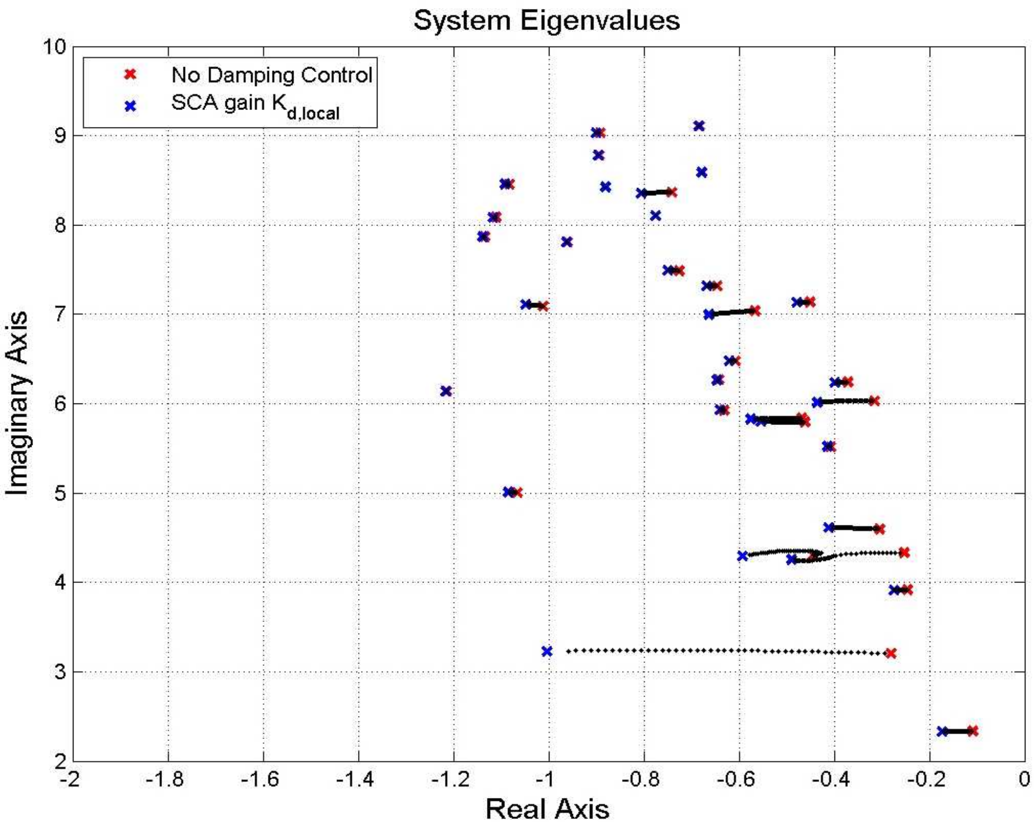
- The watchdog circuit monitors the following:
  - Emergency Stop button on the chassis
  - Supervisory controller watchdog circuit
  - Real-time controller watchdog circuit
- The overriding design philosophy was to make the circuit "failsafe" – failure of any component would safely disconnect the control system
- Bumpless transfer describes the seamless transition *between* modes of operation
- Ensures that the controller never injects a step function into the system
- Additionally ensures smooth start-up and re-initialization procedures

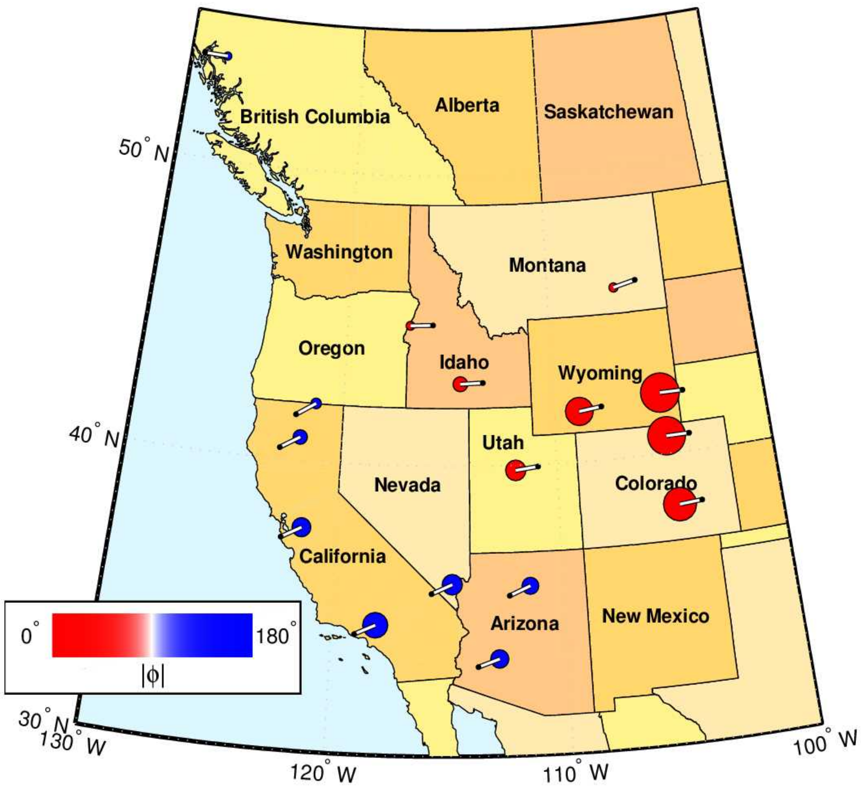




Energy Storage Based Damping Control

- A Structured Control Algorithm (SCA) is under development for designing damping controls using *distributed energy storage*
  - Distributed damping provides improved controllability of multiple modes
  - Mode shapes may be specified or prioritized through control design
  - Example – Algorithm provides selective damping of East-West Mode





Three Node Damping Control Scheme: PDCI augmented with Energy Storage

Addition of energy storage reduces amplitude of East-West A mode