# Supervisory System for a Wide Area Damping Controller Using PDCI Modulation and Real-Time PMU Feedback

Brian Pierre, Ryan Elliott, David Schoenwald, Jason Neely, Raymond Byrne
Sandia National Laboratories
Albuquerque, NM, USA

Dan Trudnowski, James Colwell
Montana Tech University
Butte, MT, USA

*Abstract* — **This paper describes a control scheme to mitigate inter-area oscillations through active damping. The control system uses real-time phasor measurement unit (PMU) feedback to construct a commanded power signal to modulate the flow of real power over the Pacific DC Intertie (PDCI) located in the western North American Power System (wNAPS). A hardware prototype was constructed to implement the control scheme. To ensure safe and reliable performance, the project integrates a supervisory system to ensure the controller is operating as expected at all times. A suite of supervisory functions are implemented across three hardware platforms. If any controller malfunction is detected, the supervisory system promptly disables the controller through a bumpless transfer method. This paper presents a detailed description of the control scheme, simulation results, the bumpless transfer method, and a redundancy and diversity method in the selection of PMU signals for feedback. This paper also describes in detail the supervisory system implemented to ensure safe and reliable damping performance of the real-time wide area damping controller.**

*Index Terms*—**Control systems, control, HVDC modulation, oscillations, Pacific DC Intertie, phasor measurement unit, power system stability, supervisory, synchrophasor, Smart Grid**

## I. INTRODUCTION

This paper presents preliminary results of a collaborative project to develop wide-area damping control methods, with project partners that include Sandia National Laboratories (SNL), Montana Tech University (MTU) and Bonneville Power Administration (BPA). The primary objective of this project is to design and demonstrate a prototype control system for damping inter-area oscillations in large-scale interconnected power systems. The damping control strategy relies on modulation of real power injections at strategically located points in the grid in response to real-time Phasor Measurement Unit (PMU) feedback. The damping controller prototype utilizes the Pacific DC Intertie (PDCI) as the actuator for real power flow modulation.

### A. Description of Control Method

The PMU feedback signal allows for the calculation of the frequency difference between two areas; the frequency difference is used to compute a differential power command which is provided to the power control system at Celilo, at the north end of the PDCI. The power command may be modeled as:

$$\Delta P_{cmd} = K\left(f_{North}(t - \tau_{d1}) - f_{South}(t - \tau_{d2})\right) \quad (1)$$

where $K$ is typically in units of MW/mHz, $f_{North}$ and $f_{South}$ are computed using appropriately selected PMUs in the north and south respectively, and $\tau_{d1}$, $\tau_{d2}$ are the network time delays of the system. This control strategy provides damping to the primary north-south oscillatory modes in the western interconnect without interacting with speed governor actions.

In practice, the controller samples the electrical bus angles $\theta_{North}(t)$ and $\theta_{South}(t)$ from real-time PMU feedback and applies a derivative filter $H(z)$ in (2) to the angle difference $\Delta\theta_{NS}(t)$ to attain a frequency difference between the north and south measurements $\Delta f_e(t)$. A gain $K$ and a saturation limit are then applied to define the final power command in MWs. The overall control strategy is depicted in Figure 1. The derivative filter was carefully designed such that the controller could effectively interact with inter-area oscillations between 0.2 and 1.0 Hz; oscillations outside this frequency are significantly attenuated. In single-precision floating-point form, the discrete-time transfer function is given by

$$H(z) = \frac{0.29192028 - 0.29192028z^{-2}}{1 - 1.55722597z^{-1} + 0.61839942z^{-2}} . \quad (2)$$

This is the 2nd-order Bessel filter cascaded with Tustin's approximation of a derivative. Additional detail in [1].
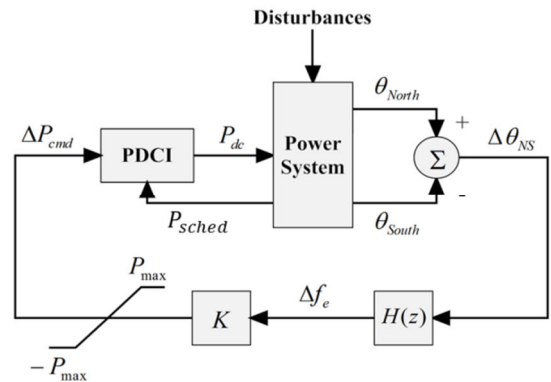


Figure 1. Diagram illustrating damping control scheme

### B. Active Damping of Inter-Area Oscillations

There are two main motivations to dampen inter-area oscillations. First, if damping is insufficient, oscillations may

grow causing a system breakup, which may lead to a series of cascading outages. Undamped oscillations have been implicated as a contributor to the infamous system break up and wide area blackout in 1996 0. Avoiding these large-scale power outages provides a significant financial incentive to damp inter-area oscillations. Second, power transfer through long transmission corridors in North America are often stability limited and limited by poorly damped electromechanical oscillations. Additional damping may increase the power transfer capacity along these transmission corridors.

Inter-area modes are described by frequency and shape. Several low frequency oscillation modes have been identified in the western interconnection, including 0,

- "North-South A" mode, nominally near 0.25 Hz
- "North-South B" mode, nominally near 0.4 Hz
- "East-West" mode, nominally near 0.5 Hz;
- "BC" mode, nominally near 0.6 Hz;
- "Montana" mode, nominally near 0.8 Hz

Figure 2 illustrates the primary oscillation mode shapes identified by the Western Electricity Coordinating Council (WECC) for the western interconnection. These modes have been significantly studied over the past 30 years [3, 4], and it has been established that damping these modes will improve system stability and may increase the transfer capability of the California Oregon Intertie (COI) corridor. This project focuses on damping the north – south modes as in Figure 2.
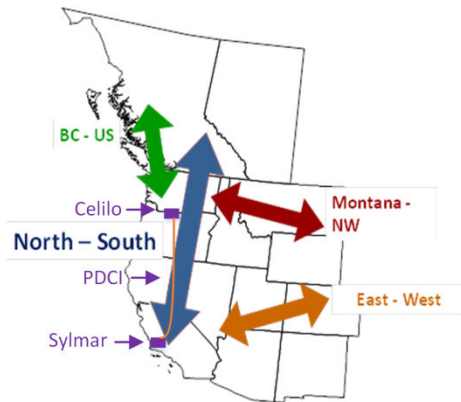


Figure 2. The primary modes of oscillation in the WECC

The next section illustrates the control operation in simulation. Section III provides a description of the hardware prototype and overview of the supervisor. Section IV the real-time supervisor functions. Section V describes higher level supervisor functions on the asynchronous platform. Section VI describes the hardware watchdog module. Finally, conclusions are presented in Section VII.

## II.  SIMULATION RESULTS

To illustrate the intended operation of the proposed control, dynamic simulations were done using General Electric's (GE) Positive Sequence Load Flow (PSLF) platform with WECC-developed models of the western interconnection. In particular, a custom transient stability model was developed for the PDCI to incorporate the control illustrated in Figure 1 and evaluate grid performance with and without the control

for a severe event. Figure 3 shows simulation results of a BC-Alberta separation event (disconnect of the Cranbrook – Langdon intertie) at $t$=1 sec; the WECC-developed PSLF model for the heavy summer 2013 case was used.
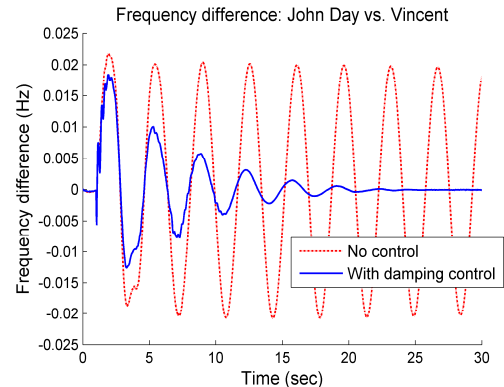


Figure 3. Simulation results of a BC-Alberta separation event, depicting frequency difference between John Day and Vincent with and without damping control

In simulation, the system exhibits a 0.25 Hz North-South oscillation, with a frequency difference amplitude of over 200 mHz, following the event. Without damping control, this response is nearly undamped, showing no noticeable attenuation after 7 cycles. With damping control, the electromechanical oscillation decays very quickly, attenuating by half after just 2 cycles. Additional simulation results are presented in [1]. Following an extensive simulation study, a prototype damping controller was developed to realize the control in hardware.

## III.  HARDWARE PROTOTYPE DESCRIPTION

The prototype damping controller is currently undergoing open-loop testing (i.e. not physically connected, but acting on real-time data and recording results as though it were) at the BPA Synchrophasor Laboratory. A photo of the prototype damping controller system hardware is shown in Figure 4. Therein, three key subsystems are shown, including the Watchdog module, Real-time controller, and the Asynchronous server. The KVM switch and monitor are for user interface.

The real-time damping controller and asynchronous monitor are implemented on National Instruments (NI) computer platforms. The damping controller software is run within a real-time operating system on the NI PXI-8135 which is housed in a NI PXI chassis with a NI PXIe-5341 multi-function I/O module. A +/-10V analog command signal is generated by this module to represent $\Delta P_{cmd}$. The asynchronous monitor is implemented onboard a NI RMC-8354 server. Both platforms generate a heartbeat signal that is monitored by the hardware interface. The hardware interface includes watchdog circuits, an E-stop circuit, and mechanical relays that connect the analog signal to the PDCI controller input.

The supervisory system includes a suite of functions implemented across the three platforms and designed to oversee the controller and ensure it does 'no harm' to the power system. The supervisory system can be categorized in three parts:

the real-time supervisor, the asynchronous supervisor, and the watchdog hardware supervisor as shown in Figure 5.
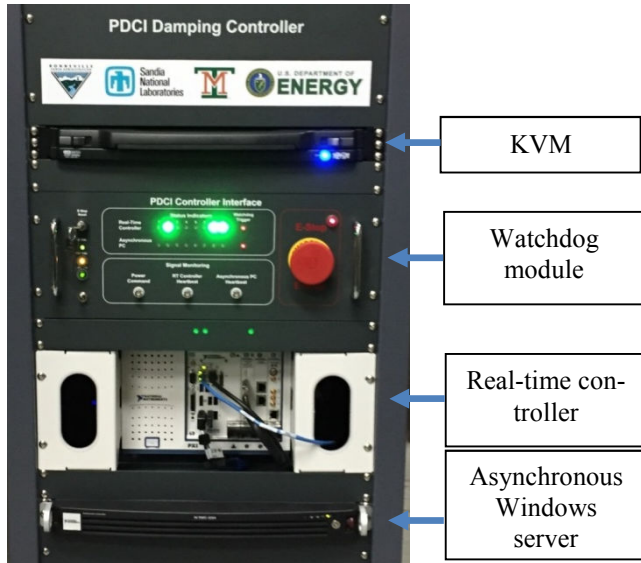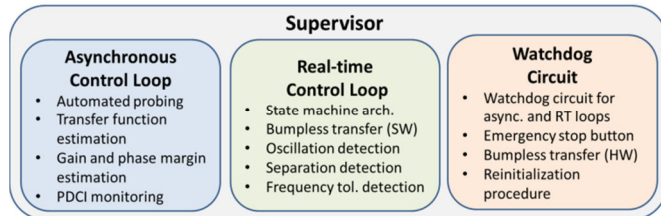


Figure 4. The prototype damping controller.



Figure 5. Supervisory system architecture

Several checks are performed in real-time inside the damping controller software to check: the PMUs' performance, the communication delays, and the network operating conditions. Additional checks that require more computation are done by the asynchronous supervisor, implemented in the windows server; this monitors the behavior of the PDCI. Finally, a hardware interface is included that incorporates watchdog and E-stop circuits. The watchdog circuit monitors the hardware of the controller. If either platform stops running (heartbeat stops), or if a malfunction or noncompliant behavior is detected by the watchdog circuit, or if the E-stop button is pressed by an operator, the analog signal from the damping controller is interrupted by opening a relay, and the voltage signal provided to the PDCI control is brought to zero through a hardware bumpless transfer. The objective of the bumpless transfer is to prevent large step functions injected into the system. The next sections describe the functions in more detail.

## IV. REAL TIME SUPERVISORY FUNCTIONS

The real-time supervisory system operates continuously, and it is embedded in the main control loop. PMU data is streaming to the controller in real-time at 60 Hz. With each packet of PMU C37.118 data, the controller acts on that data; however, real-time checks are also determining if the data is valid and if the system is operating correctly. To ensure relia-ble access to PMU data feedback, the damping controller utilizes a redundancy and diversity scheme. The damping controller utilizes a (software) bumpless transfer to eliminate step functions in the control signal. Finally, checks are performed to determine whether the controller should be disabled.

### A. Redundancy and Diversity

For purposes of this paper, redundancy is defined as multiple devices at a single point of measurement, e.g. redundant PMUs at a substation. Diversity is defined as multiple points of measurement in a common area, e.g. taking measurements at multiple nearby substations. To satisfy the redundancy and diversity method, four PMUs are utilized at the north location and four at the south location. For the controller to operate only one PMU data stream is needed from the north and one from the south. Redundant PMUs at each substation are used, and PMUs from two electrically close substations are used. With 8 PMU measurements, it allows the controller to run 16 parallel control instances that are prioritized by the best possible PMU pair. Each controller instance takes data from a single north PMU and a single south PMU and outputs a real power modulation signal ($\Delta P_{cmd}$). This redundancy and diversity scheme is shown in Figure 6. To allow for seamless switching between PMU pairs, the damping controller utilizes a bumpless transfer method.
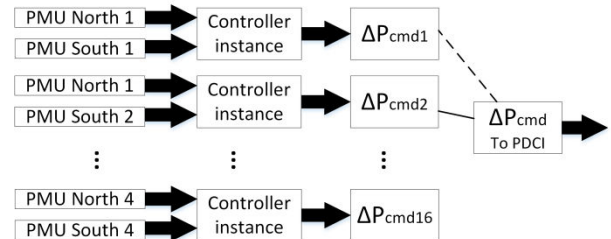


Figure 6. Sixteen controller instances operating in parallel with seamless switching between each

### B. Bumpless Transfer

When a change in system state is necessary, the damping controller utilizes a bumpless transfer to eliminate step functions in the control signal. The control signal cannot change by more than a user specified MWs per sample. The controller is operating at 60 Hz. For example, when the controller is disabled the command signal does not immediately go to zero, rather it ramps down to zero at a specified rate as in Figure 7. In addition, the controller looks for a zero crossing (or near zero) when connecting the command signal to the PDCI as in Figure 8. The bumpless transfer is also used when switching between PMU pairs.

Several real-time supervisory checks are done and may disable the damping controller. If any of these real-time supervisory checks flag, then that particular controller instance (16 controller instances operating in parallel), is disabled. If all 16 instances are disabled, the damping controller disables until it has a valid controller instance. These checks include the following.
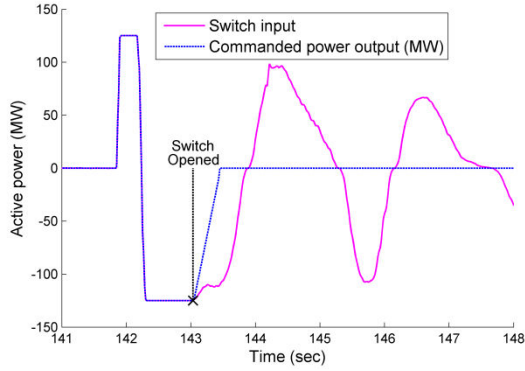
Figure 7. Controller ramps the command signal to zero when disabling the controller.
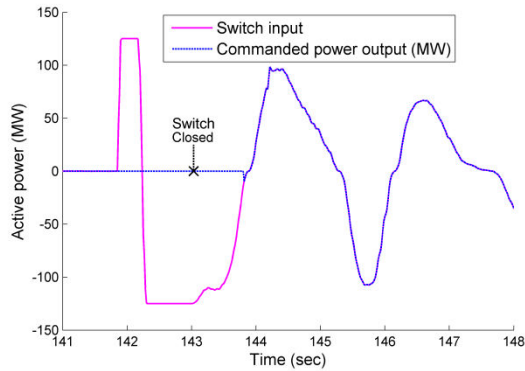


Figure 8. Controller looks for a near zero crossing to connect the command signal to the PDCI.

### C. PMU status and time quality flags

C37.118 PMU data includes a PMU status flag and time quality flag. If the status flag is non-zero, there is a problem with the PMU data, and the controller instance is disabled. The time quality number indicates how close the PMU is locked to the UTC traceable source (i.e. the GPS). If the PMU time quality number is greater than a specified threshold, the controller instance is disabled.

### D. Repeated data flag

If the controller instance receives the same data packet more than a specified number of samples, then the controller instance is disabled. If the controller instance stops receiving data from a PMU, the data is repeated. Therefore, if a PMU stops streaming data for more than a specified number of samples, the controller instance will disable.

### E. Delay flags

In real-time control, excessive delay is a significant problem. If the delay between the GPS time of measurement at the PMU location and the GPS time when controller is acting on that data is too large, that controller instance is disabled. This delay is mainly due to communication of the PMU data from the point of measurement to the controller. This communication must be routed from the PMU to a control center, and then to the damping controller at Celilo. It is emphasized that delay must be kept to a minimum, and past studies [1, 5, 6], have showed that a delay of 100 ms is tolerable.

In addition, the asymmetric delay is checked. This is the delay between the two PMU measurements. If this delay is greater than a specified value, that controller instance is disabled. Also, if the data received has a timestamp that is earlier than the previous data point, the controller instance is disabled.

### F. Abnormal operating conditions

If the system operating conditions are abnormal, the data is incorrect or the system conditions are so far removed from normal, it has been determined that controller instance will disabled. The absolute frequencies, the relative frequency, and the angle separation are checked in real time. If any of these values are very abnormal (e.g. absolute frequency less than 59.0 Hz), the controller instance is disabled.

### G. Emergency stop (E-stop) contacts flag

If a user pushes the E-stop button, or if there is a hardware failure and the E-stop contacts open (on the watchdog module in hardware), the command signal will ramp to zero with hardware. In addition, the command signal will also ramp to zero in software as a redundant measure.

### H. Forced oscillation detection flag

The goal of the feedback controller is to dampen oscillations in the inter-area electromechanical range (0.2 Hz to 1 Hz). The controller should NOT participate in oscillatoins outside this band. If significant sustained oscillations occur outside this band, the controller is disabled. Out-of-band oscillatons are detected in the feedback signals via RMS-energy filters. The filters are designed as described in [7]. RMS-energy filters calculate the total oscillation energy in a given frequency band. They operate in real-time and have been used extensively at BPA for oscillation detection. The RMS energy filters for the damping controller monitor oscillations above 1 Hz and alert the supervisor if the oscillation sustain for a specified amount of time [7].

## V. ASYNCHRONOUS SUPERVISOR FUNCTIONS

Supervisory actions that cannot be executed in real-time are assigned to the asynchronous supervisory system. This includes:

- monitoring the PDCI power flow to assure the requested $\Delta P_{cmd}$ has been properly added to the DC power flow
- monitoring the transfer-function phase of the feedback control loop to assure the phase margin remains within acceptable boundaries;

### A. PDCI monitoring

$\Delta P_{cmd}$ is calculated by the feedback control system and is to be added to the PDCI power flow. It is critical that $\Delta P_{cmd}$ is not delayed in time or scaled in any way prior to being added to the PDCI power flow. The actual PDCI power flow is established by a sophisticated converter control system where $\Delta P_{cmd}$ is simply an added input to this system. The goal of the PDCI monitoring system is to assure that the $\Delta P_{cmd}$ has been properly added to the power flow.

The PDCI monitoring is conducted via correlation analysis between $\Delta P_{cmd}$ and the actual power flowing on the PDCI. Two signals are calculated:

1. The coherency [8] between $\Delta P_{cmd}$ and the actual power flow is calculated. The coherence is a frequency-domain direct measure of correlation between the signals. For a given frequency, a coherence of zero indicates the signals are completely uncorrelated at that frequency, and a coherence of unity indicates the signals are 100% correlated at that frequency. The coherence is monitored within the bandwidth of the feedback controller (0.2 Hz to 1 Hz).

2. The relative cross-spectral-density phase [8] between $\Delta P_{cmd}$ and the actual power flow is the $2^{nd}$ signal calculated. The cross-spectral-density phase is a direct frequency-domain measure of delay between two signals at a given frequency [8]. A phase of 0° indicates the there is no delay.

System tests and simulations are done to establish thresholds for the coherency and cross-spectral-density phase. If the actual system exceeds these thresholds, the supervisor disables the controller.

Calculating the coherence and cross-spectral-density functions requires many seconds of time-synchronized measurements of the two signals. Welch's periodogram averaging is used to estimate the functions [8] on a continuous basis. The basic approach involves the averaging of a sliding Fast Fourier Transform (FFT) window. Typically, several windows of averaging are required to obtain convergence in the solution. An advantage of the approach is that measurement noise effects are averaged out of the process.

Estimating the phase angle of the open-loop transfer function yields valuable information regarding the control loop's ability to improve damping of desired modes. For controller robustness across the entire bandwidth of the controller, the open-loop phase must remain within a specified range [1].

Estimating the open-loop transfer-function phase while a controller is operating in closed-loop is very difficult. The approach utilized has its basis in [9]. A small sinusoid signal is added to $\Delta P_{cmd}$, which provides the required independence within the signals for estimating the open-loop transfer function. Spectral analysis via Welch's method [8] is then used to estimate the open-loop frequency-domain transfer function. Experiments are being conducted to determine the settings for the spectral analysis functions. Initial research suggests it requires one to three minutes of probing.

## VI.    Hardware Watchdog Module

The damping controller is overseen by the watchdog module. The purpose of this circuit is to monitor the hardware components of the controller and pass the command signal to the PDCI actuator. The controller will cease operation through a (hardware) bumpless transfer in the event of hardware failure. The watchdog is continuously monitoring heartbeat signals from each platform. If the watchdog does not see a falling edge from each platform within a specified time, a relay opens and the command signal ramps to zero.

The watchdog module also includes LED status indicators which indicate whether the controller is operating, what state the controller is in, whether the heartbeats are on, and whether power is supplied to the controller. The watchdog module also has output channels for the command signal and heartbeats for monitoring and development. The watchdog module includes a large emergency stop button, which may be pushed by a user if needed. The module also includes a physical key switch, therefore, to turn on the controller and have it connect to the PDCI, a user needs a physical key.

## VII.    Conclusions and Future Work

This paper described a control scheme to mitigate inter-area oscillations through active damping. It has been shown through simulation that active damping utilizing real-time PMU feedback can significantly dampen inter-area oscillations. The initial prototype controller hardware to implement this scheme has been presented. The supervisory system designed for this control scheme has been detailed, including: the real-time supervisory checks, the hardware supervisory watchdog circuit, and the asynchronous supervisory system. In addition, the bumpless transfer method, and the redundancy and diversity methods incorporated in the supervisory system have been described. The prototype damping controller is currently operating open-loop at the BPA Synchrophasor Laboratory. Future work will report on the results from the analysis of open-loop testing data. The prototype is scheduled to begin closed-loop testing in 2016.

### References

D. Trudnowski, D. Kosterev, J. Undrill, "PDCI Damping Control Analysis for the Western North American Power System," Proceedings of the IEEE Power & Energy Society General Meeting, July 2013.

D. N. Kosterev, C. W. Taylor, and W. A. Mittelstadt, "Model Validation for the August 10, 1996 WSCC System Outage," IEEE Trans. On Power Systems, vol. 14, no. 3, pp. 967-976, Aug. 1999.

D. Trudnowski, "Baseline Damping Estimates," Report to Bonneville Power Administration, September 2008.

D. Trudnowski, "Transfer Function Results from the 2009 and 2011 PDCI Probing Tests," Year 4 report of BPA contract 37508, Sep. 2011.

D. Trudnowski, "2012 PDCI Probing Tests," Year 6 report of BPA contract 37508, Sep. 2012.

D. Trudnowski, "Modal and Controllability Analysis of the MinniWECC System Model," Year 2 report of BPA contract 37508, Sep. 2009.

D. Trudnowski, "Observability Analysis of the MinniWECC System Model," Year 3 report of BPA contract 37508, Sep. 2010.

M. Donnelly, D. Trudnowski, J. Colwell, J. Pierre, and L. Dosiek, "RMS-Energy Filter Design for Real-Time Oscillation Detection," Proceedings of the IEEE Power & Energy Society General Meeting, July 2015.

J. S. Bendat and A. G. Piersol, Engineering Applications of Correlation and Spectral Analysis, 2nd Ed., John Wiley & Sons, New York, 1993.