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Open-Loop Testing Results for the Pacific DC Intertie Wide Area Damping Controller

Brian J. Pierre, Felipe Wilches-Bernal, David A. Schoenwald, Ryan T. Elliott, Jason C. Neely, Raymond H. Byrne
Sandia National Laboratories
Albuquerque, NM, USA

Daniel J. Trudnowski
Montana Tech University
Butte, MT, USA

Abstract — **This paper describes the initial open-loop operation of a prototype control system aimed at mitigating inter-area oscillations through active DC power modulation. The control system uses real-time synchrophasor feedback to construct a commanded power signal added to the scheduled power on the Pacific DC Intertie (PDCI) within the western North American power system (wNAPS). The control strategy is based upon nearly a decade of simulation, linear analysis, and actual system tests. The control system must add damping to all modes which are controllable and "do no harm" to the AC grid. Tests were conducted in which the damping controller injected live probing signals into the PDCI controls to change the power flow on the PDCI by up to ±125 MW. While the probing tests are taking place, the damping controller recorded what it would have done if it were providing active damping. The tests demonstrate that the dynamic response of the DC system is highly desirable with a response time of 11 ms which is well within the desired range. The tests also verify that the overall transfer functions are consistent with past studies and tests. Finally, the tests show that the prototype controller behaves as expected and will improve damping in closed-loop operation.**

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

I. Introduction

This paper describes open-loop test results from a project whose primary objective is to design and demonstrate a prototype control system for damping inter-area oscillations in large-scale interconnected power systems. The damping control system utilizes real-time Phasor Measurement Unit (PMU) feedback to modulate real power injections at specific points in the grid based on frequency difference. The damping controller prototype utilizes the Pacific DC Intertie (PDCI) as the actuator for real power flow modulation. The PDCI is the largest DC transmission line in the U.S. It is ±500 kV, 846 miles long, with a capacity of 3,220 MW. The damping controller prototype modulates the power flow by up to ±125 MW.

The strategy employed by the control system is based upon nearly a decade of analysis and testing [1]-[4]. This paper describes the results of recently connecting the control system to the PDCI and conducting a battery of tests. Primary findings of these tests show that the DC system response is highly favorable with a quick response time of 11 ms, that the measured open-loop transfer functions are consistent with past measurement in [3], [4], and that the controller operated as expected with indications that closed-loop operation would provide significant damping. This includes testing the use of several parallel PMU feedback paths.

A. Control Strategy

The control strategy is a proportional action on the frequency difference of two separate areas of the western North American Power System (wNAPS), one in the north-west and the other in the south-west. For this paper, the local measurement is from the north part of the wNAPS and the remote measurement is from the south part of the wNAPS. The power command, which is sent to the PDCI controls at the north terminal of the PDCI, can be modeled as

$$P_{command} = K\left(f_{local}(t-\tau_d) - f_{remote}(t-\tau_d)\right) \quad (1)$$

where f_{local} and f_{remote} are computed using appropriately selected PMUs in the north and south respectively, K is the gain typically in units of MW/mHz, and τ_{d} is the network time delay of the system (with the data from the north and south time-aligned). In practice, the controller receives sampled bus angle measurements $\theta_{\text{local}}(kT_{\text{s}})$ and $\theta_{\text{remote}}(kT_{\text{s}})$ from real-time PMU feedback with time step $T_{\text{s}} = 1/60$ second and applies a derivative filter, $H(z)$, to attain the frequency measurements at the north and at the south respectively [2]. The overall control strategy is depicted in Fig. 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 above 1.0 Hz are significantly attenuated by $H(z)$ and oscillations below 0.2 Hz are attenuated by using relative frequency. This control strategy provides damping to the primary north-south oscillatory modes in the wNAPS without interacting with speed governor actions. Additional background can be found in [1], [2].

B. Motivation to Damp Inter-Area Oscillations

The first motivation to damp inter-area oscillations is for stability reasons. If damping is insufficient, these oscillations can grow and contribute to large scale blackouts, which have occurred in the past [5]. The second motivation is that power transfer through long transmission corridors is often limited by poorly damped electromechanical oscillations. Additional damping may increase the power transfer capacity along these transmission corridors.

Specific modes of oscillation have been identified in the wNAPS, including [2]-[4]:

- "North-South A" (NSA) mode, nominally near 0.25 Hz

Brian J. Pierre is a senior member of technical staff in the power systems research group at Sandia National Laboratories, bjpierr@sandia.gov.

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- "North-South B" (NSB) mode, nominally near 0.4 Hz
- "East-West" (EW) mode, nominally near 0.5 Hz;
- "BC" mode, nominally near 0.6 Hz;
- "Montana" mode, nominally near 0.8 Hz

These modes have been a topic of research [3]-[8] and wide area damping control has been a topic of research [1], [2], [10], [11] over the past 30 years. This project primarily focuses on damping the NSB mode. Improved damping of this mode will improve system stability and may increase the transfer capability of the California Oregon Intertie (COI), which has significant financial incentives. The control should also improve damping for the other modes; or, at a minimum have no degrading effect on them.

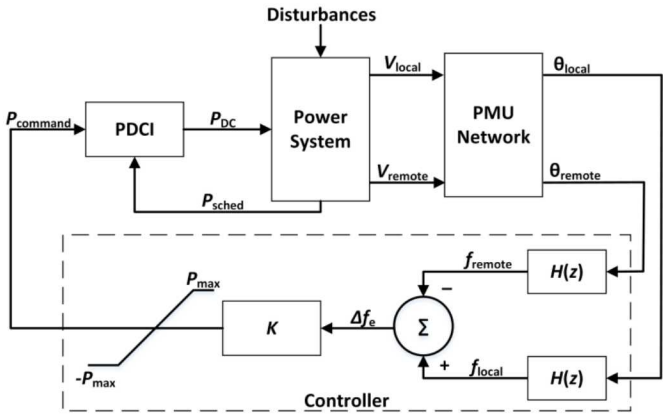

Figure 1. Diagram illustrating the damping control scheme

C. Robust Design with Minimal Delays

The damping controller uses four PMUs in the north and four PMUs in the south for redundancy and diversity purposes. This allows for 16 control instances operating in parallel. If the active control instance has an issue, the controller can seamlessly switch to another control instance through a bumpless transfer. A large focus of this project is to "do no harm," and therefore a suite of supervisory functions was developed over three hardware platforms to provide reliable and robust performance [2]. The supervisory functions "flag" and disable individual control instances during specific situations. When the controller instance in use is disabled, a bumpless transfer in software occurs between it and the other instance the controller is transitioning to. A bumpless transfer, in both hardware and software, is also used when all 16 controller instances are disabled and the entire controller is disarmed.

Extensive delay in real-time control cannot be tolerated. The system delays were subject to extensive study in this project. The final results show the overall delay (from time of measurement, the PMU data timestamp, to the timestamp as the $P_{command}$ is sent out of the controller) is on average 71 ms with the worst case showing 103 ms. The PDCI control action introduces an additional ~11 ms of lag, which will be further discussed in Section III.

D. Simulation results

Before any physical tests took place, an extensive simulation study was completed using the GE dynamic simulation platform, Positive Sequence Load Flow (PSLF). All the physical tests were simulated along with a suite of major events that are often simulated as some of the worst contingencies in North America. The simulations used Western Electricity Coordinating Council (WECC) developed models of the wNAPS and a custom transient stability model developed by Sandia National Labs for the PDCI to incorporate the control illustrated in Fig. 1. Fig. 2 shows simulation results of a double Palo Verde unit outage. The double unit outage causes a loss of ~2.8 GW in the south-western U.S. Fig. 2 shows the frequency difference between Los Angeles, California and the Oregon/Washington border with no control, north – central control (using feedback signals in the north-west and central-west U.S.), and north – south control (using feedback signals in the north–west and south–west U.S.). Using the proposed damping controller the electromechanical oscillations damp faster than in the no control case. Additional simulation and analysis results are presented in [1], [2].

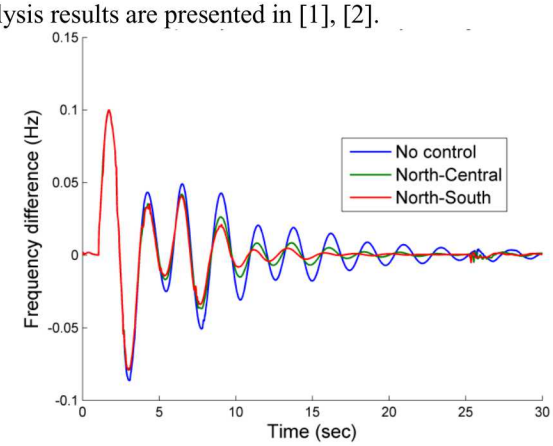

Figure 2. Simulation results of a double Palo Verde unit outage event, depicting frequency difference between Los Angeles, CA, and the Oregon / Washington border with and without damping control

Once the controller was developed in hardware, it was tested in three stages:

- Open-loop tests – receiving real live data and acting on the data, but not physically connected to the PDCI,
- Open-loop probing tests – physically connected to the PDCI controls and sending probing signals to excite the wNAPS, then determining how the controller would act if it were actively damping.
- Closed-loop tests – The controller provides active damping to the system while tests are taking place to excite the system.

The controller was in open-loop testing for nearly two years. The first open-loop probing tests were separated in three phases all carried out in September 2016. The two phases of closed-loop testing were also performed in September 2016.

E. Nomenclature

The power command ($P_{command}$) that is sent to the PDCI in Fig. 1 is shown in more detail in Fig. 3. This nomenclature helps explain the figures in subsequent sections. The controller has two modes of operation: control mode and probe mode. Control mode is normal operation and if the controller is physically connected to the PDCI, it would provide active damp-

ing. Probe mode allows the controller to send a predetermined probing signal to the PDCI.

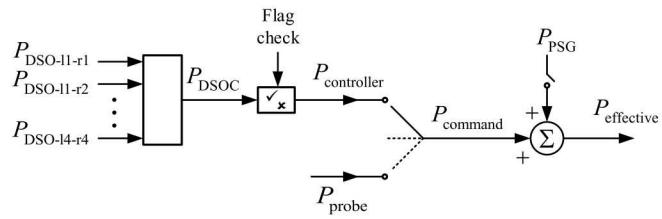

Figure 3. The flow chart of the power commands for nomenclature purposes.

$P_{DSO-lx-ry}$ - There are 16 power commands from the 16 control instances. The 'lx' and 'ry' are the internal IDs used to identify each of the 8 PMUs, e.g. l1 is PMU local one, r1 is PMU remote one. The abbreviation DSOC is used for deadband saturation output command.

P_{DSOC} - the selected power command out of the 16 possible instances. The selection is based on priorities and the flag statuses.

$P_{controller}$ - The output of the damping controller if the damping controller is in control mode. It is the same as P_{DSOC}, except in the case where all controller instances are disabled in which it takes a value of 0 MW.

P_{PSG} - The power command sent by the external Probing Signal Generator (used to excite the system).

P_{probe} - The output of the damping controller if the damping controller is in probe mode (similar to the Probing Signal Generator, except directly from the controller).

$P_{command}$ - The damping controller final output sent to the PDCI controls. It takes the values of either P_{probe} or $P_{controller}$ depending on the controller mode of operation.

ΔP_{DC} - The change in power flow on the PDCI.

The remainder of this paper is organized as follows, Section II presents the transfer function estimation history for this project. Section III presents the results of the open-loop probing tests. Finally, Section IV presents the conclusions and future work for the damping controller.

II. Transfer Function Estimation

The control strategy defined by equation (1) is based upon extensive simulation and past PDCI probing tests. Nearly 100 PDCI open-loop probing tests have been conducted on a routine seasonal basis since 2009 [3], [4], [8]. As related to damping controls, the objectives are to provide comparative information to model-based studies [1], and to evaluate controllability, observability, and robustness properties. The concluding results of these past studies and tests are: 1) verification that the control strategy in (1) performs as desired; 2) test filter settings for estimating the frequency components in (1) from multiple PMU phasors; 3) determination of limitations on the acceptable time delay (τ_d) of the communication system; 4) selection of desired PMU locations for use as feedback signals; and 5) selection of the control gain K.

The tests described in this paper have two unique characteristics differing from past tests. First, a major PDCI upgrade was completed at the end of 2015. This included replacement and upgrade of all converter components ranging from controls to power electronic components to transformers. An expected benefit of this upgrade is a faster and more accurate response to power commands of which modulation control is part of.

The second characteristic is that the damping controller prototype is fully developed and installed to include time stamping of all relevant signals. All past probing tests provided the ability to analyze the transfer function of the "Power System" component in Fig. 1 but not the "PDCI" dynamics.

With these two characteristics in mind, the primary contributions of this paper relate to the wide area damping controller and are:

- characterization of the PDCI dynamics;
- verification that the Fig. 1 "Power System" dynamics are consistent with past tests; and,
- demonstration and test results of the complete control system and PMU networking system.

III. Open-Loop Probing Results

The damping controller includes the capability to inject custom probing signals into the PDCI controls for testing purposes (probe mode, P_{probe}). Fig. 4 shows the system configuration during probing.

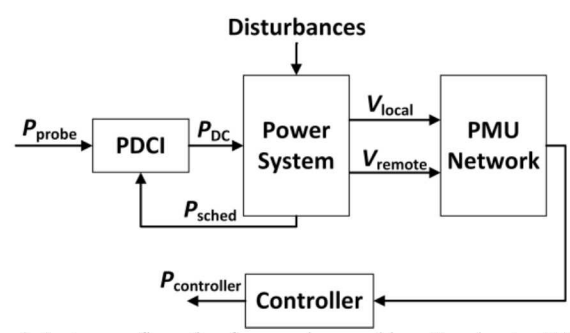

Figure 4. System configuration for open-loop probing. V_{local} denotes PMUs used to estimate f_{local}, and V_{remote} denotes PMUs used to estimate f_{remote}.

The following tests were completed:

- +20 MW (10 seconds) followed immediately by -20MW (10 seconds),
- ±20 MW multi-sine fitted (MSF) function for 100 seconds (1 period, 6 periods, & 12 periods) [11],
- ±135 MW sine wave at 0.025 Hz for 4 cycles,
- ±135 MW sine wave at 0.1 Hz for 4 cycles,
- ±125 MW sine wave at 0.3 Hz for 4 cycles,
- ±125 MW sine wave at 1.0 Hz for 4 cycles,
- ±125 MW square wave at 0.4 Hz for 3 cycles.

All tests were completed multiple times. Results for these tests are shown in the next sections.

Fig. 5 shows the power flow on the PDCI for approximately 3 hours during which 13 of the previously described tests were completed in Sept. 2016. The power flow on the PDCI varied from 1715 MW to 1600 MW. The system was in open loop, but the power command was computed as if it were in closed loop with a gain of 9 MW/mHz. The following sections A-E will provide analysis on each specific test.

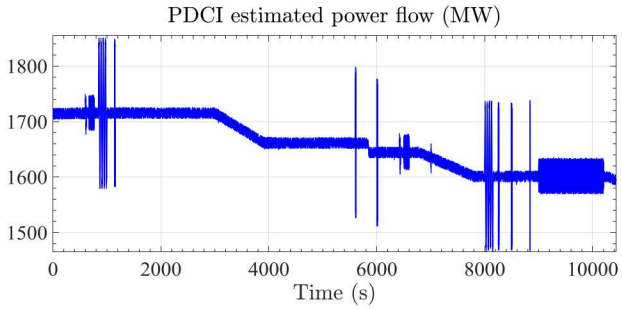

Figure 5. The PDCI power flow during open-loop probing tests.

A. ±20 MW multi-sine fitted (MSF) function

This is the primary test signal used to estimate the desired open-loop transfer functions. It is a multi-sinusoid signal designed using the algorithm in [11] which is optimized to minimize the peak-to-peak swings in the AC system. The probe signal consists of 6 or 12 cycles (one cycle shown in Fig. 6) of a 100-sec. signal and is scaled to ±20 MW and contains frequency content up to 10 Hz. The resulting signal is the same as the one used in [4] and has slightly wider frequency bandwidth than the one in [9]. Fig. 6 shows the probing signal overlaid with the PDCI power flow.

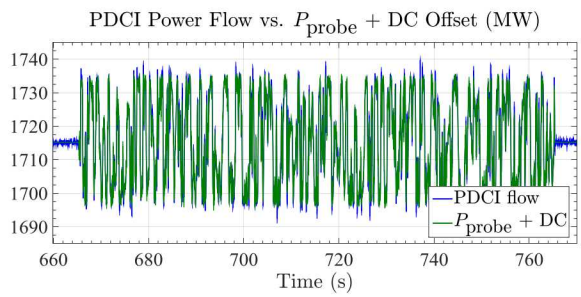

Figure 6. The multi-sine fitted function probing signal overlaid on the actual flow of the PDCI during the probing test.

Spectral analysis based upon Welch's periodogram averaging [12] is used to estimate key transfer functions. All spectral plots that follow were calculated using the following settings: FFT length = 50 sec., FFT window = Hanning; and FFT overlap = 80%.

1. PDCI Dynamics

Fig. 7 shows the estimated open-loop transfer function of the PDCI based upon 4 different probing tests, specifically the transfer function from P_{probe} to ΔP_{DC} in Fig. 4. The output ΔP_{DC} is the real power change measured from the PDCI on the AC side of the converter and represents the actual power injected into the AC system. Each test is represented with a different color. The results are nearly identical for each test. The results in Fig. 7 show several ideal properties described here.

First, the gain of the PDCI is nearly flat with a bandwidth of nearly 7 Hz, which is higher than the dynamics bandwidth of electromechanical oscillations. The gain does increase slightly near 5 Hz as seen in Fig. 7, indicating a slight underdamped response. However, since this underdamped response is much faster than the expected modal oscillations, it is of minimal concern.

Second, the response time is very fast. The response of the PDCI is calculated from the slope of the phase in Fig. 7. In the control band (0.1 Hz to 1.0 Hz), the lag is approximately 11 ms. This is well within the limitations [1], [3], [4].

Third, the system is not corrupted by any noise. This is demonstrated in the third "Coh" subplot in Fig. 7 which shows the coherency between P_{probe} and ΔP_{DC} [12]. The coherency is a measure of correlation between two signals; a coherency of zero indicates no correlation and a coherence of unity indicates 100% correlation [12]. This plot indicates that 100% of the damping controller modulation will pass to the AC system.

Lastly, the response is very consistent. This is expected as the dynamics are governed by the PDCI converter controls and electronics, which are very predictable.

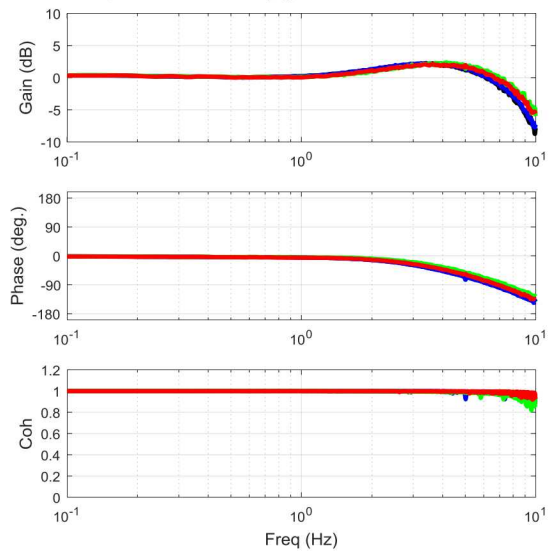

Figure 7. Estimated PDCI transfer function for 4 different independent identical tests over a range of two weeks. Subplot 1 is the gain of the transfer function, subplot 2 is the transfer-function phase, and subplot 3 is the coherency between the input and output.

2. Loop Transfer Function

Fig. 8 shows the estimated open-loop transfer function of the entire loop for the four probing tests using a control gain K of 9 MW/mHz. Fig. 8 represents the transfer function from P_{probe} to $P_{controller}$ in Fig. 4. For all tests, the 1st priority PMUs were used for the f_{local} and f_{remote} calculations. The results are very consistent with all the past probing tests described in [3], [4], and [8] and indicate improved damping for all modes controllable during the tests.

A mode is indicated by a peak in the gain plot below 1 Hz in Fig. 8. The plots show three primary peaks near 0.25 Hz (NSA mode), 0.35 Hz (NSB mode), and 0.7 Hz (BC mode). As typical of the wNAPS, the modal properties change depending on the particular operating conditions. The dynamics above 1 Hz are primarily due to the PDCI physics.

Damping is added to a given mode if the phase is transitioning thru 0° near the peak frequency of the mode [1], [3]. If the phase is outside ±90°, the controller will destabilize the mode. Note that damping is added to all modes for all four tests. This is consistent with the nearly 100 tests conducted since 2009 [3], [4], [8].

A gain of 9 MW/mHz assures a gain margin of 10 dB at a crossover frequency of 4 Hz. This certainly represents good robustness properties. A gain margin less than 6 dB is unacceptable, and the 4 Hz crossover is well outside the electromechanical frequencies.

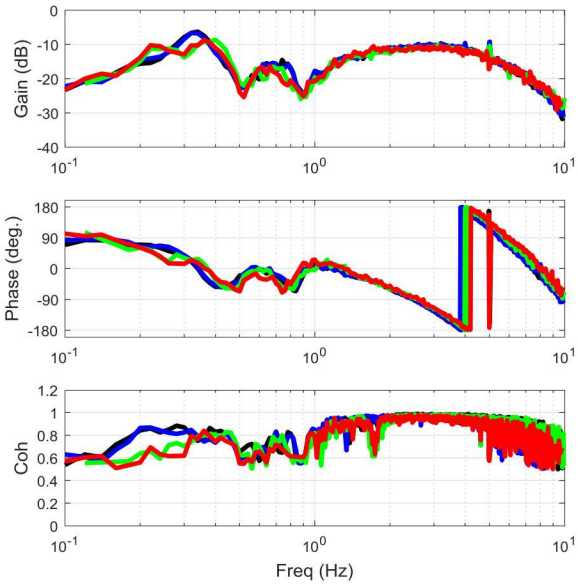

Figure 8. Estimated loop transfer function for 4 different independent identical tests over a range of two weeks with a gain of 9 MW/mHz. Subplot 1 is the gain of the transfer function, subplot 2 is the transfer-function phase shifted by 180°, and subplot 3 is the coherency between the input and output.

B. ±125 MW sine wave at 0.3 Hz for 4 cycles

The north-south modes of oscillation in the wNAPS are near 0.3 Hz; the controller is designed to significantly damp these oscillations. A sine wave of 0.3 Hz at ±125 MW for four cycles was injected into the PDCI using the controller in probe mode. The response of the system and the open-loop control output is indicated in Fig. 9 – 11.

Fig. 9 indicates the PDCI followed the controller command signal closely. Fig. 10 shows the absolute frequency at the local (north) and remote (south) measurements.

Fig. 11 shows the probing signal vs. the probing signal added to the open-loop command signal (P_{DSOC}). This shows the controller significantly interacts with oscillations at 0.3 Hz. Fig. 11 indicates a strong likelihood of improved damping if the controller were connected in closed loop. This is indicated by the decrease in amplitude with the probing signal added to the P_{DSOC}.

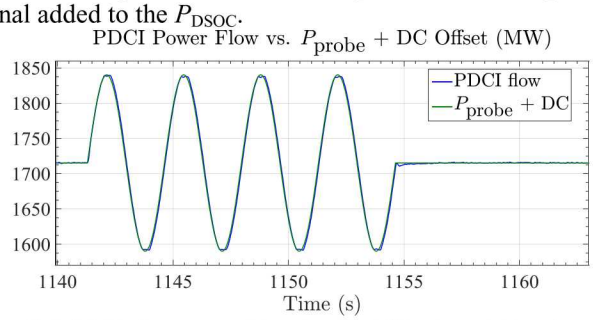

Figure 9. A 0.3 Hz sine wave probing signal test (P_{probe}) overlaid on top of the power flow on the PDCI. PDCI flow followed the command signal closely.

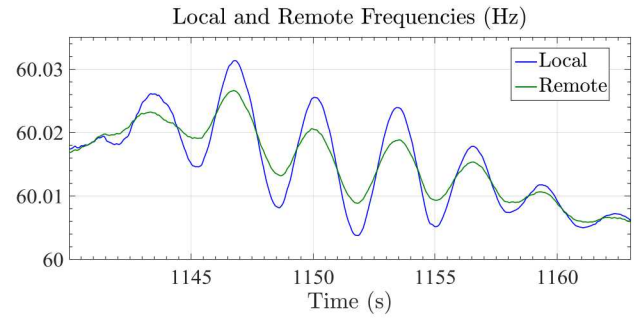

Figure 10. The frequencies at the local and remote measurements during a 0.3 Hz sine wave probing signal test.

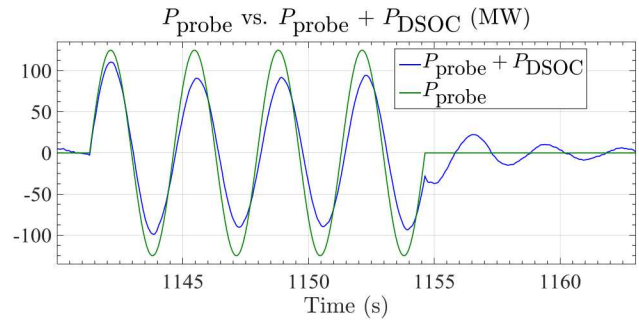

Figure 11. The 0.3 Hz sine wave probing signal test vs. the probing signal test added to the damping controller command signal in open-loop (P_{DSOC}). Decreased amplitude indicates improved damping.

C. ±125 MW sine wave at 1.0 Hz for 4 cycles

A sine wave at 1.0 Hz ±125 MW was injected into the PDCI to test the controller interaction with oscillations at 1.0 Hz. The PDCI responded as expected and tracked the command signal very closely. The controller moderately interacts with a 1.0 Hz oscillation; however, as anticipated, the interaction is not as strong as during a 0.3 Hz oscillation. Fig. 12 shows the controller moderately interacts with the 1.0 Hz oscillation and would have provided modest damping.

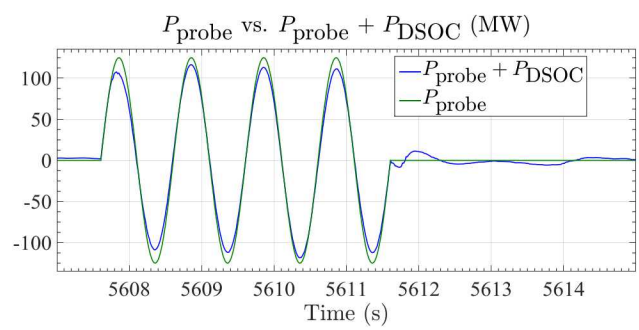

Figure 12. The 1.0 Hz sine wave probing signal test vs. the probing signal test added to the damping controller command signal in open loop (P_{DSOC}). Decreased amplitude indicates imrpoved damping.

D. ±135 MW sine wave at 0.025 Hz for 4 cycles

A sine wave at 0.025 Hz and amplitude of ±135 MW is requested from the controller (P_{probe}) during this test. The purpose of this test is two-fold: first to demonstrate the limits of the controller (±125 MW), and second to ensure the controller has little interaction with this low frequency oscillation. The controller was designed to interact with frequencies between 0.2 and 1.0 Hz. As anticipated, the controller had

almost no interaction with the 0.025 Hz oscillation. Fig. 13 indicates the probing signal (P_{probe}), and the probing signal added to the open-loop command signal (P_{DSOC}). The P_{DSOC} is ~0 MW (noise near 0 MW) as expected since there is little interaction with a 0.025 Hz oscillation; this is noticeable in Fig. 13 since the traces are nearly identical. In addition, the controller clips at ~±125 MW. Similar results were found for the 0.1 Hz sine wave tests.

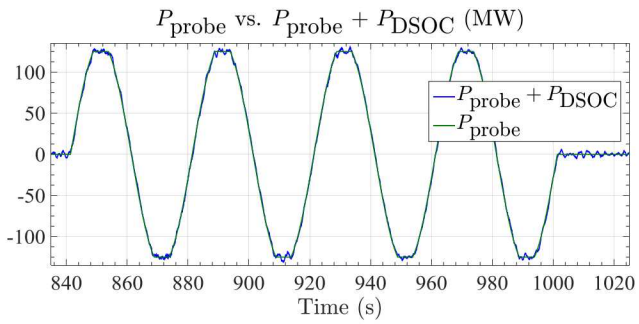

Figure 13. The 0.025 Hz sine wave probing signal test vs. the probing signal test added to the damping controller command signal in open loop (P_{DSOC}). Traces on top of each other indicate almost no controller interaction with such a low frequency oscillation.

E. ±125 MW square wave at 0.4 Hz for 3 cycles

The purpose of this test is to excite the wNAPS enough to see the north-south modes oscillate. A ±125 MW square wave at 0.4 Hz for 3 cycles was injected into the PDCI by an external probing signal generator (P_{PSG}). The controller responded as expected, and if it were in closed-loop, it would have improved damping. Fig. 14 shows the flow on the PDCI vs. the controller command signal in open loop (P_{DSOC}). The injected square wave causes the PDCI flow to change as anticipated with little overshoot. The controller would have provided damping as indicated by the opposite phase injections of P_{DSOC} noticed in Fig. 14. Also note the slightly under-damped response at the immediate switching times; this is consistent with the results in Section III.A.1.

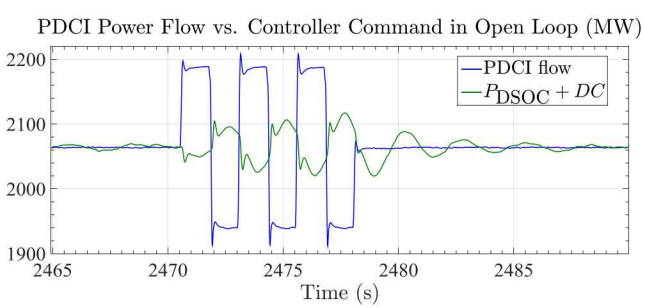

Figure 14. The PDCI power flow during a ±125 MW square wave at 0.4 Hz for 3 cycles vs. the damping controller command signal in open loop (P_{DSOC}). Oposite phase indicates improved damping.

IV. Conclusions and Future Work

This paper describes the open-loop probing results of a prototype controller to mitigate inter-area oscillations through active damping. Multiple open-loop probing tests are presented to assess the damping controller and the feedback network in place. The response time of the PDCI control system is favorable and measured at approximately 11 ms. The controller performed according to previous testing and simulations, and had around 10 dB of gain margin at approximately 4 Hz using a gain that provides improved damping. The overall transfer functions seen by the damping controller are consistent with the past 92 transfer functions from previous tests with an external probing system. Test results show the controller significantly interacted with 0.3 Hz oscillations, had moderate interaction with 1.0 Hz oscillations, and minimal interaction with 0.1 and 0.025 Hz oscillations. Through analysis of the open-loop tests the controller has shown it will provide damping during closed-loop operation. Forthcoming papers will present the closed-loop testing results, latency analysis, and communication network issues encountered in the controller development. Testing of the controller will continue in 2017.

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