SAND2020-1052C

Forced Oscillations in the Western Interconnection with the Pacific DC Intertie Wide Area Damping Controller

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***Abstract*—Forced oscillations in power systems are of particular interest when they interact and reinforce inter-area oscillations. This paper determines how a previously proposed inter-area damping controller mitigates forced oscillations. This paper illustrates how a previously proposed inter-area damping controller mitigates forced oscillations. The damping controller modulates active power on the Pacific DC Intertie based on PMU frequency measurements. The primary goal of the controller is to improve the small signal stability of the north south B mode in the North American Western Interconnection. The paper presents small signal stability analysis in a reduced order system, time-domain simulations of a detailed representation of the WI and actual system test results to demonstrate that the PDCI damping controller provides effective damping to forced oscillations in the frequency range below 1 Hz.**

***Index Terms*—Forced Oscillations; Inter-area Oscillations; HVDC modulation; Pacific DC Intertie; Power system oscillation control; Wide Area Measurement Systems.**

NOMENCLATURE

BC	British Columbia
BPA	Bonneville Power Administration
COI	California-Oregon Intertie
PDCI	Pacific DC Intertie
PMU	Phasor Measurement Unit
PSS	Power System Stabilizer
WI	Western Interconnection (the western North American Power System)

I. INTRODUCTION

Forced oscillations in power systems are sustained oscillations driven by inputs external to the system that can occur at different frequencies [1]. Often, these oscillations are caused by cyclic loads, PSS misconfiguration or malfunction, and generator turbines. While forced oscillations above 1 Hz tend to have a localized effect in the system, forced oscillations below 1 Hz can interact with the modes of the system and can therefore affect the whole power system. If resonance occurs with a system inter-area mode, the stability of the system can be compromised [1]. Recently, with the advent of PMU technology the study, detection, and understanding of forced oscillations has taken a renewed interest [2].

Because of its dispersed nature of load and generation centers, the WI has multiple inter-area modes below 1 Hz. Damping these oscillations can be achieved by modulation of the active power flow of the PDCI [3]. The PDCI is an 846-mile long HVDC line joining the Washington-Oregon border with the Los Angeles area in Southern California and has a transmission power capacity of roughly 3.2 GW in either direction. Such type of damping control using the PDCI has been implemented in the actual system [4], [5].

Because interactions of inter-area oscillations with forced oscillations in the WI are of interest to the system operators as well as the whole power system community, this paper presents the effect that the PDCI damping controller in [4], [5] has on forced oscillations. Initially this analysis is performed on a reduced-order model of the WI and is based on a linearization of the system. The analysis considered forced oscillations located at different generators in the system. The magnitude of the resulting transfer functions indicate that the PDCI damping controller effectively mitigates forced oscillations near the wide area modes of the WI. Additionally, this paper presents time-domain simulation results on a detailed model of the WI as well as actual system test results. The system tests involved injecting forced oscillations and evaluating the performance of the PDCI controller. The results of these simulations and tests again show that the proposed active power modulation to the PDCI effectively damps forced oscillations in the frequency range of the inter-area modes of the WI.

II. BACKGROUND AND CONTROL STRATEGY

A. Inter-area Oscillations in the WI

Due to its sparse configuration of load and generation centers, the WI exhibits different inter-area oscillations. These oscillations have been studied in great detail for over 30

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years with actual system testing and model studies. The most dominant inter-area modes in the WI are:

- NSA mode nominally near 0.2 to 0.25 Hz;
- NSB mode nominally near 0.35 to 0.4 Hz;
- EWA mode nominally near 0.4 to 0.5 Hz;
- BC mode nominally near 0.6 Hz; and,
- Montana mode nominally near 0.8 Hz.

Of the five modes listed above, NSB is the one with more potential to do harm to the system. This mode appeared after the province of Alberta was connected to the WI. In this mode, the Pacific Northwest (including BC) oscillates against Alberta while at the same time oscillating against the southern part of the WI. Because of the points of interconnection with the AC system, modulation of the PDCI is able to control this mode [3], [4].

A reduced-order model of the WI was developed partly to facilitate small signal stability analysis within this power grid. This model is proposed and described in [6] and its one-line diagram is presented in Fig. 1.

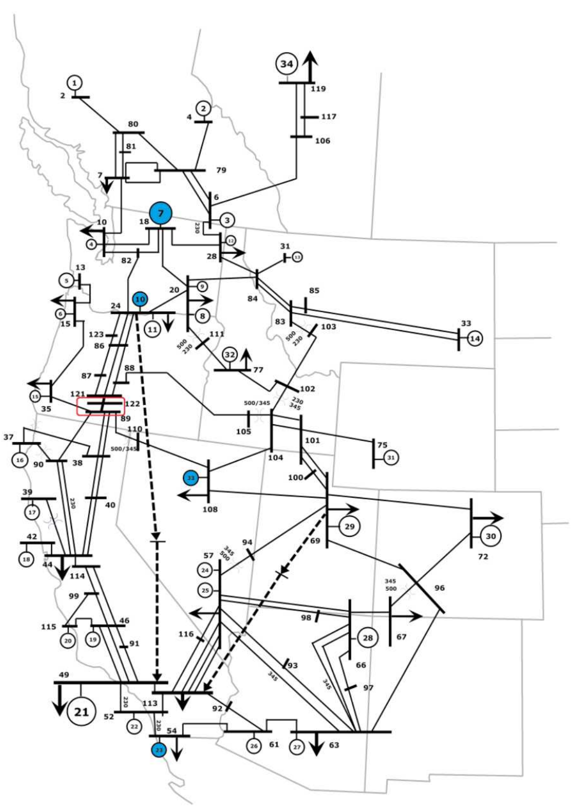


Fig. 1: The MinniWECC, a reduced order model of the WI. In blue are the generators for which transfer functions were analyzed.

B. Control Strategy

Damping the North to South modes in the WI can be effectively done by modulating the active power transfer of the PDCI [3]–[5]. The control strategy is a proportional gain to the relative frequency between the North and the South; this strategy can be described as

$$\Delta P_{\text{in}}(t) = k_d(f_{\text{local}}(t) - f_{\text{remote}}(t)) \tag{1}$$

This type of control has been implemented in the actual WI [4], [5]. Fig. 2 shows the schematic of the actual implementation of this type of controller. In this implementation phasor voltages from two locations within the WI are used as the input for the control action. V_{loc} denotes the voltage at a location on the northern end of the PDCI while V_{rem} denotes a location further south, near the COI. Voltage angles from V_{loc} and V_{rem} are passed through a derivative filter $H(z)$ to compute the frequency at each location. The difference between these two frequencies, the relative frequency Δf is then calculated. A gain k_d is applied to the relative frequency to determine the control signal to the PDCI. Note that because the voltage signals come with a delay the data from the two locations is time-aligned prior to the computation of the relative frequency [7],

$$\Delta f(t-\tau) = f_{\text{local}}(t-\tau) - f_{\text{remote}}(t-\tau)) \tag{2}$$

and,

$$\Delta P_{\text{in}}(t) = k_d(\Delta f)\Delta f(t-\tau) \tag{3}$$

where in practice, k_d, is mostly a constant gain with a dead-band and smooth transitions towards its upper and lower bounds.

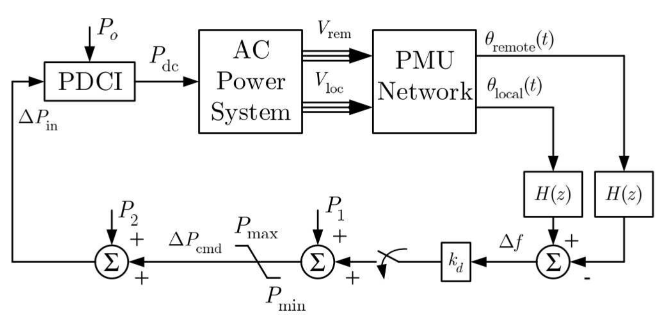


Fig. 2: Damping controller block diagram.

C. Linear Analysis

A small signal stability analysis of the WI can be performed by linearizing the system in Fig. 1. This analysis is performed in the MATLAB-based Power System Toolbox (PST) [8]. The linear representation of the system is

$$\dot{x} = Ax + Bu \tag{4a}$$

$$y = Cx \tag{4b}$$

where A is the system matrix. In this representation the derivative filters used to compute frequencies from voltage angles are already included as states of x. B and C are, respectively, the input and output matrices that can vary by the desired or available output measurements and input signals to the system (the actuators). When the actuator is the PDCI, $B = B_{\text{PDCI}}$, and when the output signals are the local and remote frequencies $C = C_f$. Using this formulation the damping controller in (1) is

$$u = k_d \begin{bmatrix} 1 & -1 \end{bmatrix} \begin{bmatrix} f_{\text{local}} \\ f_{\text{remote}} \end{bmatrix} = k_d \tilde{C}_f x \tag{5}$$

where $\tilde{C}_f = [1 \ \ -1]C_f$. For the system in Fig. 2 the local and remote frequencies are, respectively, those at Buses 24 and 49, i.e. $f_{\text{local}} = f_{24}$ and $f_{\text{remote}} = f_{49}$. By closing the loop with the damping controller the linear system becomes

$$\dot{x} = (A + B_{\text{PDCI}} k_d \tilde{C}_f)x + Bu = A_{\text{CL}} x + Bu \tag{6a}$$

$$y = Cx \tag{6b}$$

where $A_{\text{CL}} = A + B_{\text{PDCI}} k_d \tilde{C}_f$ is the closed loop system matrix, B is the input matrix to the system from other actuators such as generators and C is the output matrix of the signals of interest in the system.

III. Forced Oscillations with PDCI Damping Control

To analyze the effect of the damping controller on forced oscillations at different locations of the WI, the linear version of the system in Fig. 1 is used. The sources of forced oscillations considered were generators at four different locations within the WI. These generators are: Gen. 7 at the northern part of the system; Gen. 10 close to the northern terminal of the PDCI; Gen. 33 in Nevada; and Gen. 23 at the southern end of the system in Southern California. The oscillations were assumed to come independently from the active and the reactive power controls of the generators. In addition, forced oscillations coming from the PDCI active power flow were also analyzed.

The transfer functions for active power forced oscillations are

$$G_{\text{P,Pg}i}(s) = C_{\text{P,COI}}(sI - A^*)^{-1} B_{\text{Pm,g}i} \tag{7}$$

where $C_{\text{P,COI}}$ is a matrix that determines active power flow in the COI as an output (flow between Buses 89 and 122 in Fig. 1) and $B_{\text{Pm,g}i}$ is the input to the mechanical power of generator i. The transfer functions for reactive power forced oscillations are

$$G_{\text{Q,Vg}i}(s) = C_{\text{Q,COI}}(sI - A^*)^{-1} B_{\text{Vr,g}i} \tag{8}$$

where $C_{\text{Q,COI}}$ is a matrix that determines reactive power flow in the COI as an output and $B_{\text{Vr,g}i}$ is the input to the automatic voltage regulator of generator i.

Analysis in the frequency domain were performed for the open and closed loop systems. Whenever the system is in open loop, the system matrix in equations (7) and (8) $A^* = A$, and whenever the system is in closed loop $A^* = A_{\text{CL}}$. This analysis is done for all 4 generators, i.e., $\forall\, i = \{7, 10, 33, 23\}$. The frequency range of interest in this analysis is from 0.1 Hz to 1 Hz because this is the frequency range the PDCI damping controller is designed to be responsive.

Figs. 3a-3d show the magnitude of the transfer functions for active power oscillations coming from generators at buses, 7, 10, 33, 23, respectively. These figures show that the damping controller attenuates the magnitude of the components below 0.8 Hz and in particular the peak that appears in all transfer functions near 0.37 Hz.

Figs. 4a-4d show the results for forced oscillations in the reactive power of Gen. units at buses: 7, 10, 33, 23, respectively. Fig. 4 shows that the damping controller reduces the magnitude of the peak that appears in all transfer functions near 0.37 Hz and is also effective at attenuating frequency components below 0.8 Hz. These results are comparable to those in Fig. 3 and combined show that the PDCI damping controller can effectively damp forced oscillations appearing at different locations within the WI.

The analysis of forced oscillations coming from the PDCI is performed using the transfer function

$$G_{\text{P,PDCI}}(s) = C_{\text{P,COI}}(sI - A^*)^{-1} B_{\text{PDCI}} \tag{9}$$

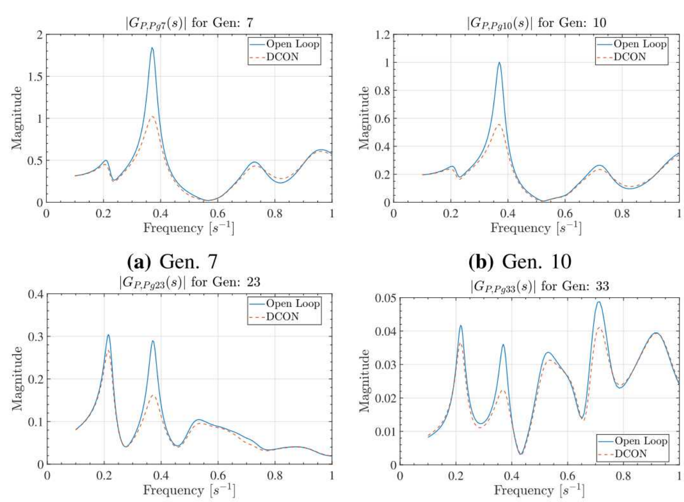
where B_{PDCI} is the input matrix that describe how the states of the system are affected with fluctuations in the PDCI active power. Fig. 5 shows the magnitude of the transfer function in (9) for the frequency range of interest. This figure shows that the PDCI damping controller is effective at damping forced oscillations that come from the PDCI itself.

IV. Simulations and Actual System Test Results

A. Time-Domain Simulations

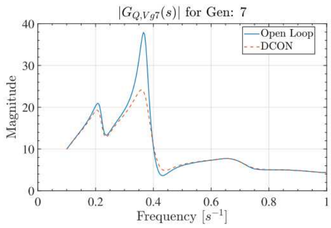
This section presents time-domain simulation results on the effect of the PDCI damping control on forced oscillations. These results are an extension of those presented in [9]. Initial simulations were performed in the system in Fig. 1 using PST [8]. The simulations presented in this section use a detailed WECC validated model of the WI. The model used has 31,409 buses, 4,063 generators and 10,748 loads. The software platform selected to perform these simulations was GE's Positive Sequence Load Flow (PSLF).

In the time-domain simulation, forced oscillations were inserted into the system by modulating the active power of the PDCI with a probing sinusoidal signal at predetermined frequencies. The tests were performed for the system with and without the PDCI damping controller. Fig. 6 shows the

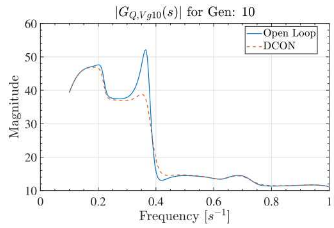


(a) Gen. 7 **(b)** Gen. 10 **(c)** Gen. 23 **(d)** Gen. 33

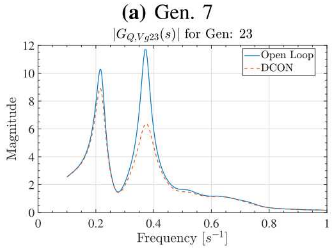
Fig. 3: Magnitude of transfer functions of the active power flow in the COI with respect to forced oscillations in the active power control at different generators within the system.



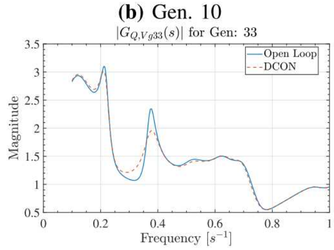
(a) Gen. 7



(b) Gen. 10



(c) Gen. 23



(d) Gen. 33

Fig. 4: Magnitude of transfer functions of the reactive power flow in the COI with respect to forced oscillations in the reactive power control at different generators within the system.

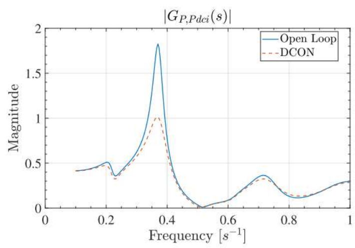


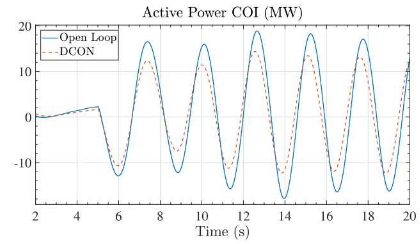
Fig. 5: Magnitude of transfer functions of active power flow in the COI with respect to forced oscillations in the PDCI active power flow.

simulation results when the probing signal is a sine-wave of 0.4 Hz. Fig. 6a shows the active power flow in the COI and Fig. 6b shows the power flow of the PDCI. The results in these figures demonstrate that the PDCI damping controller is effective at mitigating the forced oscillation from the probing signal. This means the two command signals the PDCI receives when in closed loop, the probing signal and the PDCI damping control signal, are out of phase with each other. Figs. 7a and 7b show, respectively, the active power at the COI and at the PDCI when the probing signal is a sine-wave of 1 Hz. These results show that there is only a small reduction on the 1 Hz wave signal when the PDCI damping controller is connected.

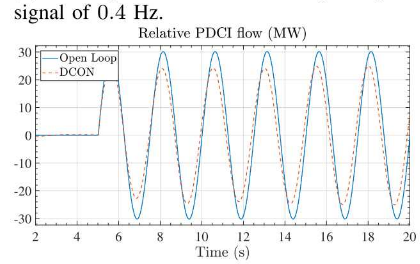
Overall, results in Figs. 6 and 7 are in line with those in Fig. 5, demonstrating that the PDCI damping control is very effective at mitigating forced oscillations of frequencies around 0.4 Hz.

B. Actual Test System Results

A series of tests on the WI were performed to evaluate the effect of the actual implementation of the PDCI damping controller in the system. These tests were carried out in May 2017 and May 2018 and consisted of injection of forced oscillation via active power modulation of the PDCI (similar to the simulations in Section IV-A). In this work we present the results for forced oscillations of 0.4 and 1 Hz. The full tests consisted of probing signals at other frequencies as well as disturbances to the system; some of these results are presented in [4], [10].

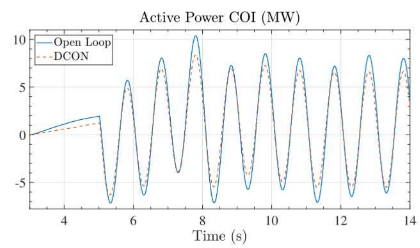


(a) Active power in the COI for a probing signal of 0.4 Hz.

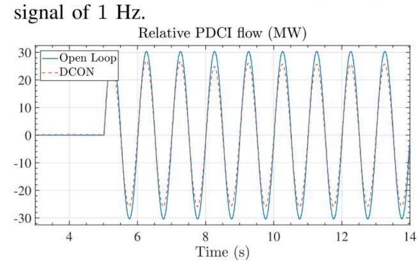


(b) PDCI power flow for a probing signal of 0.4 Hz.

Fig. 6: Simulation results PDCI and COI power flows for a probing signal of 0.4 Hz.



(a) Active power in the COI for a probing signal of 1 Hz.

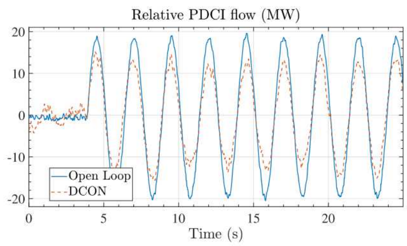


(b) PDCI power flow for a probing signal of 1 Hz.

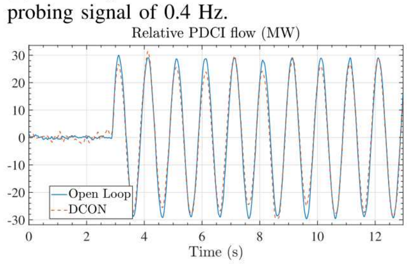
Fig. 7: Simulation results PDCI and COI power flows for a probing signal of 1 Hz.

Figs. 8 and 9 show the results of actual tests in the WI in May 2017 and May 2018, respectively. Fig. 8a shows the 2017 test results from a 0.4 Hz forced oscillation. The 0.4 Hz forced oscillation is effectively attenuated by the PDCI damping control. Fig. 8b illustrates the control system performance for a 1 Hz forced oscillation. At this frequency, the reduced gain of the control system results in less pronounced attenuation.

Figs. 9a and 9b show the results from the May 2018 tests at 0.4 Hz and 1 Hz. Results in these figures show the same outcome as those for the May 2017 tests. Overall, these results in the actual system were anticipated and are consistent with those presented previously in Sections III and IV-A. The results show that the PDCI damping controller can effectively damp forced oscillations in the system.

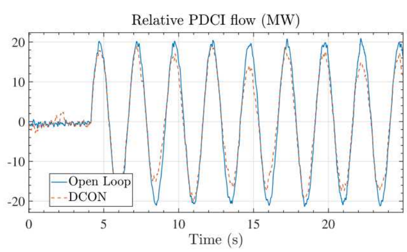


(a) Active power flow in the PDCI for a probing signal of 0.4 Hz.

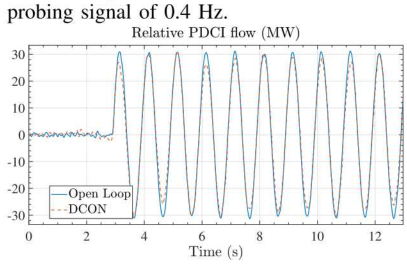


(b) Active power flow in the PDCI for a probing signal of 1 Hz.

Fig. 8: Actual-system test results for the May 2017 tests.



(a) Active power flow in the PDCI for a probing signal of 0.4 Hz.



(b) Active power flow in the PDCI for a probing signal of 1 Hz.

Fig. 9: Actual-system test results for the May 2018 tests.

V. Conclusions

This paper briefly presents a damping controller for inter-area oscillations by modulating the active power transfer on the PDCI. The paper then analyzes the effect of this controller on forced oscillations within the WI. The analysis is first performed on a reduced-order model of the WI using linear analysis to different transfer functions within the system. The analysis is performed for active and reactive power forced oscillations appearing at different locations of the WI. Because the damping controller is meant to be responsive only to inter-area oscillations the analysis is done only for frequencies between 0.1 and 1 Hz. In addition, the paper presents time-domain simulation results and actual-system test results for forced oscillations appearing the WI via PDCI modulation. The results of the small signal stability analysis in the reduced-order system as well as those of simulations and actual-system tests point all to the same result: the proposed PDCI damping controller for inter-area oscillations is effective at damping forced oscillations in the system in the frequency range of 0.1 to 1 Hz.

Acknowledgment

The authors would like to acknowledge the support of: the BPA Technology Innovation Program, project number TIP 289, Dr. Dmitry Kosterev, technical POC, and Mr. Gordon Matthews, PM, with matching funds provided by the U.S. Department of Energy Office of Electricity (DOE/OE) Transmission Reliability Program managed by Mr. Phil Overholt, and the DOE/OE Energy Storage Program managed by Dr. Imre Gyuk.

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