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Oscillation Damping Control Using Multiple High Voltage DC Transmission Lines: Controllability Exploration

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***Abstract*-- This paper explores the controllability of power system oscillation modes by multiple high voltage DC (HVDC) transmission lines. The controllability exploration is performed in a reduced model of the Western Electricity Coordination Council (WECC) system, with added HVDC lines according to previously proposed lines. The exploration shows that various oscillation modes, across several system areas, can be simultaneously controlled by coordinating three or more HVDC lines. The degree of damping in each oscillation mode can be selected by designing a multi-input multi-output control system on the HVDC lines.**

***Index Terms*-- HVDC transmission, power system dynamics, power system stability, power system control.**

I. Introduction

THE power flow on a high-voltage DC (HVDC) line is managed by a high-speed control system, and if the line is part of an underlying AC network, the power flow can be made to react in response to conditions on the AC side. The application of a DC line to provide power system stabilization was being considered almost as soon as HVDC became practical. The first commercial-scale DC power system was an underwater line to the Swedish island of Gotland, commissioned in 1954 [1] [2], at which time [3] and [4] were studying stability issues. Mittelstadt, at Oregon State University, had written on methods of aiding system stability [5]- [6]. In his discussion of that paper, Kimbark at the Bonneville Power Administration, mentioned the use of a large DC line on the west coast of the US. At the same time, the Edison Electric Institute built a large simulator to study AC/DC interactions, including the modulation of DC power flow to aid stability in the AC power systems [7]. The simulator was also used to test the idea of controlling generator exciters to aid stability [8] [9]. Model predictive control (MPC) has been proposed to damp inter-area oscillations of power systems via the HVDC link [10] [11]. The MPC scheme is able to cope with hard constraints on inputs, outputs, and states. The MPC can address actuator limitations and enables operation closer to the system constraints which results in faster system response. The use of HVDC with various flexible AC transmission system (FACTS) devices has also been studied to damp power system oscillations [12] [13]. The supplementary control of HVDC, SSSC, SVC and TCSC enhances the overall stability of large-scale interconnected system with introducing the suitable wide area control signals. A robust probabilistic methodology based power oscillation damping (POD) controller using HVDC lines is applied in large heavily meshed network exhibiting multiple inter-area modes [14]. Mitigation strategies were also proposed to deal with some extreme cases where the controllers fail to perform. Active damping, whether as a result of control signals applied to DC lines or to what became known as power system stabilizers (PSS), is now commonplace. The signals used in these methods are not generally the same; PSSs are more of a local control mechanism whereas DC lines affect power flows over large distances.

In this paper we consider that information suitable for the generation of the required damping signal may be available from Phasor Measurement Units. This approach is presently being experimentally investigated (a prototype controller has recently been put in operation) by two of us (Wilches-Bernal and Schoenwald) using the west-coast DC line now known as the Pacific DC Intertie (PDCI) [15] [16]. We study a frequency-based feedback modulation of the PDCI to provide damping control in the western North American power system (wNAPS) [15]. We conclude that modulation of no more than ±100 MW to ±200 MW is enough to provide significant damping. We propose a compensator designed with a shaped loop transmission function as a means to provide performance and noise response improvement with guaranteed stability in saturation [17].

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The increased use and interest of HVDC lines around the world, opens the possibility to not just use control on a line by line basis, but to study the possibility of controlling several lines at the same time. In addition to the PDCI line, there are existing and proposed HVDC lines in the WECC system, such as the existing Intermountain Power Project (IPP), and proposed TransWest Express transmission project (TWE). These HVDC lines could potentially be used for oscillation damping. We explore this possibility.

This paper reports on the damping of power system oscillation modes by modulating multiple HVDC lines. The results show that various oscillation modes across several areas of the system can be damped simultaneously, and the degree of damping in each pair of areas can be selected by designing a multi-input multi-output control system.

Remaining parts of this paper are organized as follows. Section II presents to the POD control method of point-to-point HVDC line. In Section III the controllability of multiple HVDC lines are discussed. Section IV presents simulation studies. Finally, conclusions are reported in Section V.

II. Control using HVDC point-to-point lines

A prototype using real-time PMU feedback to modulate the real power over PDCI is proposed in [15]. The control logic of the prototype is based on the frequency difference at the terminal of PDCI. The frequency difference is obtained from passing signals of electrical angle difference from PMUs through a derivative filter. In this work the damping is studied for the north-south oscillation mode, which is aligned with the PDCI.

Given multiple HVDC lines, for each one the simplest way is using similar method as [15] that uses the frequency difference between the HVDC terminals to modulate the power transmitted by the line, as shown in Fig.1. When the HVDC is operating at steady state and there is no oscillation, the frequency at the terminals are the same, thus the change to transmitted power is zero and the HVDC is working at the nominal states. When an interarea oscillation occurs, the frequency difference at the HVDC terminal is not zero and it is amplified with a proportional gain and used as a feedback signal to the modulation of HVDC transmitted power to damp the oscillation. The feedback signal is calculated as,

$$I_{mod} = K * (f_{rec} - f_{inv}) \tag{1}$$

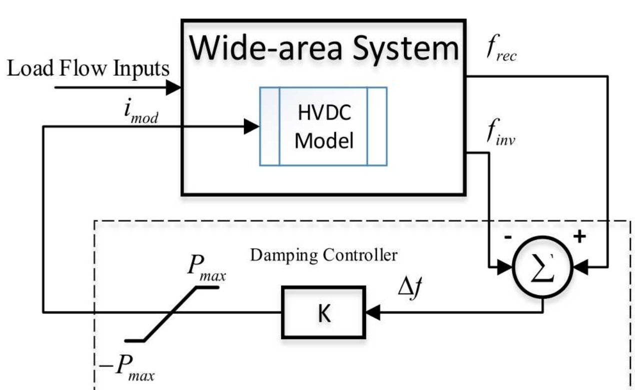

Fig. 1 HVDC damping controller based on frequency difference

III. Exploration of Controllability of Multiple HVDC Lines

To explore controllability of various HVDC lines, the concept of frequency difference control is expanded to a multiple-input, multiple-output (MIMO) control structure. In this section we formulate the controllers to apply to cases with two and three HVDC lines simultaneously controlled. This approach can be extended to additional lines.

A modified minniWECC system [18] with three HVDC lines is used to demonstrate the MIMO controller design, as shown in Fig. 2. This first HVDC line is the Pacific DC Intertie (PDCI), which transmits 2,850 MW at ±500 kV DC from northwest to the southwest. The second one is Intermountain Power Project (IPP), which transmits 1,900 MW at ±500 kV DC from mid-east to the southwest. The third one is TransWest Express Transmission Project (TWE), which transmits 2,500 MW at ±600 kV DC from east to the mid-southwest. It is also noted that the location of the inverter sides of PDCI and IPP are very close to each other. The minniWECC system has several interarea oscillation modes, of which the NSB and BC modes are lightly damped.

The PDCI and IPP lines already existed, and were modeled in the minniWECC system as simple positive and negative loads. These models were improved with more detailed dynamic models in this work. The TWE HVDC line was added with approximate location according to the real transmission plan. To model PDCI, IPP, and TWE, the HVDC model available in the Power System Toolbox (PST) program [19] was used. This model has rectifier and inverter models of line-commutated converters, where the rectifier controls the DC line current and the inverter controls the DC voltage.

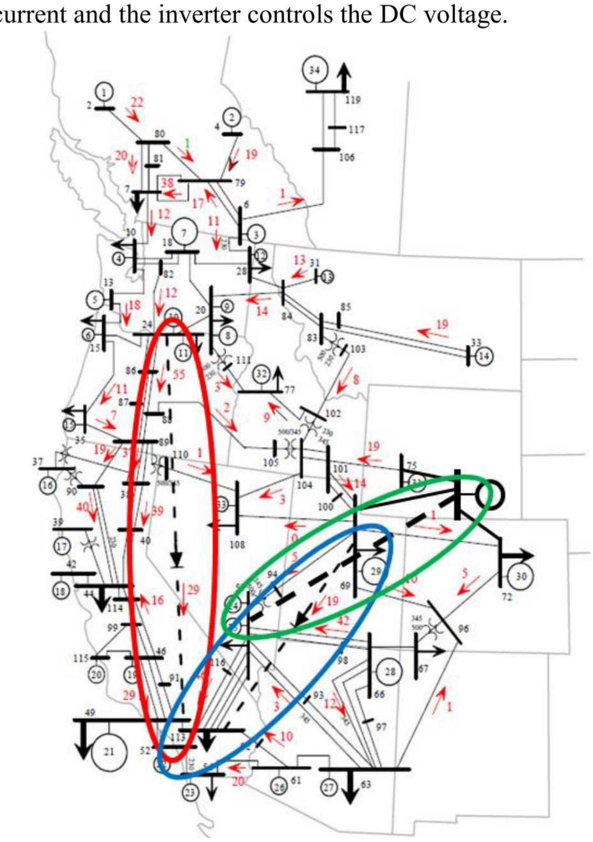

Fig. 2 Modified minniWECC system with three HVDC lines

The feedback signal for conventional modulation of a single HVDC line is calculated as equation (1). With three HVDC lines in the minniWECC, we have six input frequency signals (three from rectifiers and three from inverters). Multiple HVDC lines modulation based on the combinations of the six input frequency signals can be explored. With the consideration of different power transfer levels, as well as different location and direction of the lines, the coordinated modulation of the three HVDC lines could provide more benefits than individually modulation of each line. The proposed coordinated controller for three HVDC lines is as shown in (2).

$$\begin{bmatrix} I_{mod,1} \\ I_{mod,2} \\ I_{mod,3} \end{bmatrix} = K * \begin{bmatrix} f_{rec,1} \\ f_{inv,1} \\ f_{rec,2} \\ f_{inv,2} \\ f_{rec,3} \\ f_{inv,3} \end{bmatrix} \tag{2}$$

where $I_{mod,i}$ in [kA] is the modulation input signal for the HVDC line i (this value is added to the current command at the rectifier); $f_{rec,i}$ in [Hz] is the frequency measurement at the rectifier terminal of the HVDC line i; $f_{inv,i}$ in [Hz] is the frequency measurement at the inverter terminal of the HVDC line i; and $K \in \mathbb{R}^{6\times 6}$ [kA/Hz] is the control gain matrix for frequency measurements.

A. Design 1: frequency difference between two terminals of each line

This control strategy is to independently control of each of the three lines, depending on frequency measurements at each of their own rectifier and inverter ends, as follows:

$$\begin{bmatrix} I_{mod,1} \\ I_{mod,2} \\ I_{mod,3} \end{bmatrix} = \begin{bmatrix} K_1 & -K_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & K_2 & -K_2 & 0 & 0 \\ 0 & 0 & 0 & 0 & K_3 & -K_3 \end{bmatrix} * \begin{bmatrix} f_{rec,1} \\ f_{inv,1} \\ f_{rec,2} \\ f_{inv,2} \\ f_{rec,3} \\ f_{inv,3} \end{bmatrix} \tag{3}$$

Design 1 treats the three HVDC lines independently and does not consider the interaction between the three controllers. Each line will only focus on modulating the interarea oscillations at their own connected areas. It is three lines with similar controller as equation (1) at the same time.

B. Design 2: virtual lines combining two lines

Provided that PDCI and IPP lines (line 1 and 2) have their inverters ends near the same load center, this control strategy can be seen as a virtual HVDC line between rectifier end of PDCI line and rectifier end of IPP line.

$$\begin{bmatrix} I_{mod,1} \\ I_{mod,2} \\ I_{mod,3} \end{bmatrix} = \begin{bmatrix} K_4 & 0 & -K_4 & 0 & 0 & 0 \\ -K_4 & 0 & K_4 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} * \begin{bmatrix} f_{rec,1} \\ f_{inv,1} \\ f_{rec,2} \\ f_{inv,2} \\ f_{rec,3} \\ f_{inv,3} \end{bmatrix} \tag{4}$$

For Design 2, the sum of DC currents transmitted by PDCI and IPP to the inverter side is constant. Because the modulations of PDCI and IPP currents are based on the same frequency difference while have opposite sign of the gains, and the inverters control the DC voltages to keep them constants, the southwest ends of the lines should see no modulation. Instead, the modulation will be mostly observed between the two rectifier ends of PDCI and IPP (northwest and mid-east ends respectively). In terms of modulation, the result is as if there is a virtual line that connects the two rectifier buses of PDCI and IPP, and the power transmission direction is from rectifier of PDCI to rectifier of IPP (northwest to mid-east areas of the system).

C. Design 3: combination of designs 1, and 2

This control strategy is a combination of all of the above controllers.

$$\begin{bmatrix} I_{mod,1} \\ I_{mod,2} \\ I_{mod,3} \end{bmatrix} = \begin{bmatrix} K_1+K_4 & -K_1 & -K_4 & 0 & 0 & 0 \\ -K_4 & 0 & K_2+K_4 & -K_2 & 0 & 0 \\ 0 & 0 & 0 & 0 & K_3 & -K_3 \end{bmatrix} * \begin{bmatrix} f_{rec,1} \\ f_{inv,1} \\ f_{rec,2} \\ f_{inv,2} \\ f_{rec,3} \\ f_{inv,3} \end{bmatrix} \tag{5}$$

Design 1 and 2 can be considered as two different and independent control methods that target at different (maybe overlapped) interarea oscillation generator groups. Including the virtual DC line in design two, there are totally four DC lines in this design. The combination of Design 1 and Design 2 could complement each other on damping the oscillations.

IV. Simulation Studies

In this section, the numerical simulation studies are performed with different HVDC modulation designs in Section III. The modified minniWECC system with three lines is used as the test system. The modified MinniWECC contains 35 generators, 122 buses, and there are more than six interarea oscillation modes in the test system. It represent the overall interarea modal properties of the full-size system with enough complexity to accurately evaluate and test potential system-wide damping control technologies.

At time t=2.0 sec generator 33 is suddenly tripped, initiating a large disturbance with various interarea oscillation modes triggered. The proposed controller designs 1, 2, and 3 are tested for damping the oscillations by using the modulation of the three HVDC links, PDCI, IPP, and TWE. The modulation gains K_1 to K_4 in equation (3) ~ (5) are [3000, 1500, 1500, 3000] kA/Hz, respectively. The simulation results are presented in the following subsections.

A. Oscillations observed on AC lines in parallel with PDCI, IPP, TWE, and the virtual line of design 2

In this subsection, interarea oscillations observed on the AC transmission lines in parallel with PDCI, IPP, TWE, and the virtual line of design 2 under different controller designs are presented. Interarea oscillations can be observed in power flow of line 89-38, which is one of the AC tie-line in parallel with PDCI. Fig. 3 shows that all three proposed designs provide enhanced damping to the interarea oscillation observed in this line. In particular for power flow on line 89-38, the damping effect of design 2 and 3 is better than design 1.

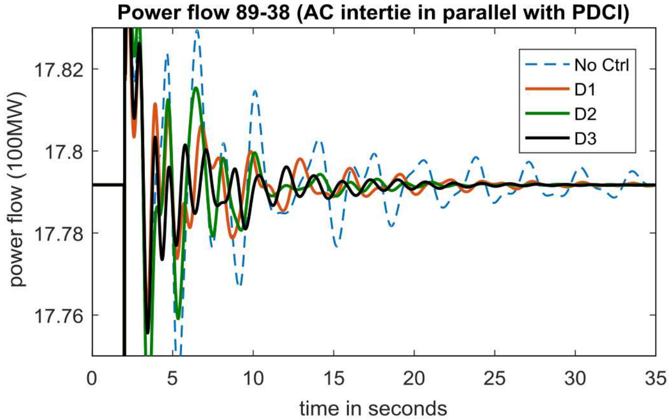

Fig.3 Power flow oscillation observed on AC line 98-38

Similarly, Fig. 4 shows the oscillations in power flow of line 57-113, which is an AC tie-line in parallel with IPP. It can be seen that all three proposed designs provide enhanced damping. In particular design 1 an design 2 provide similar damping to the oscillations, while the effect of Design 3 appears better than design 1 and 2.

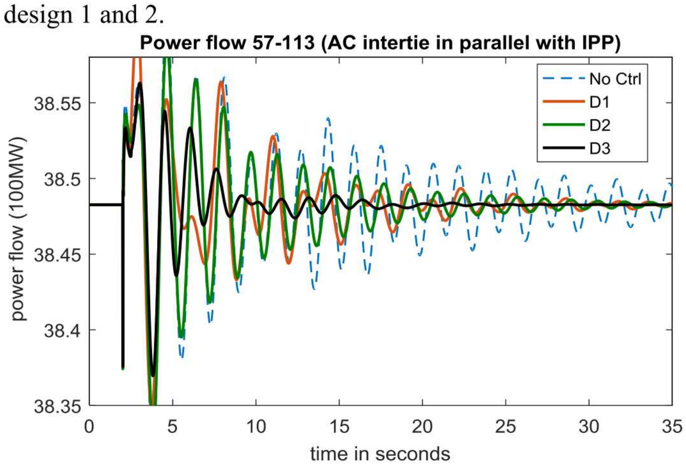

Fig.4 Power flow oscillation observed on AC line 57-113

Fig. 5 shows oscillations observed in power flow line 94-69, which is an AC tie-line in parallel with PDCI. It can be seen that all the three proposed designs provide enhanced damping. In particular, the effect of design 1 and 3 appear better than design 2.

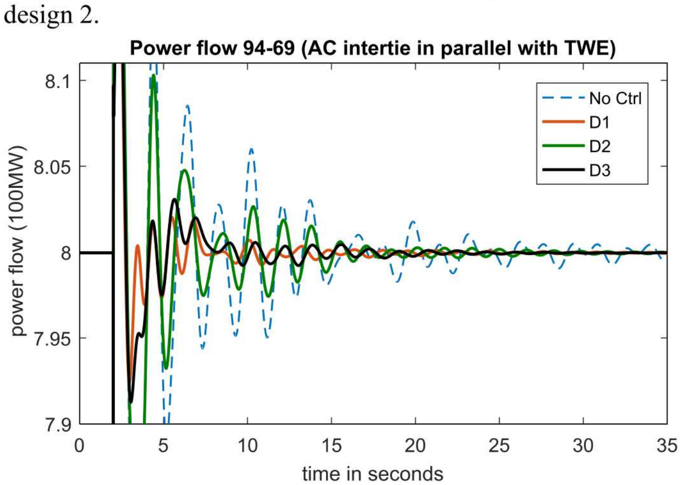

Fig.5 Power flow oscillation observed on AC line 94-69

The results of design 2 is as if there is a virtual line that connects the two rectifier buses of PDCI and IPP, and the power transmission direction is from rectifier of PDCI to rectifier of IPP (northwest to mid-east areas of the system). Fig. 6 shows the oscillations observed in power flow of line 102-77, which is an AC tie-line between the rectifier of PDCI and the rectifier of IPP. It can be seen that all three proposed designs provide enhanced damping. In particular, the damping effect of design 3 appears better than design 1 and 2.

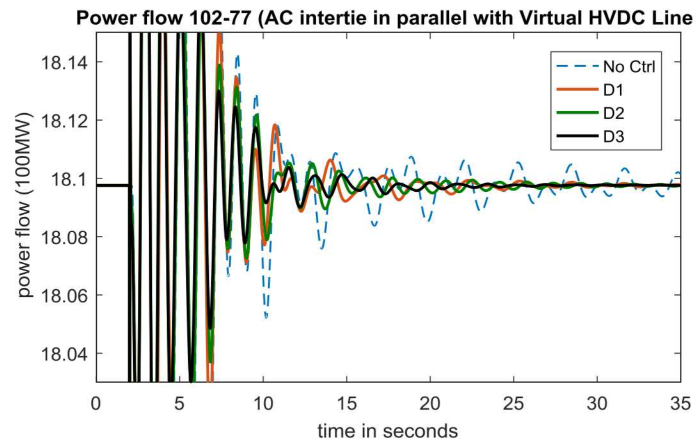

Fig.6 Power flow oscillation observed on AC line 102-77

B. Analysis of oscillation modes based on Prony's algorithm

A Prony's algorithm based analysis [20] is performed on the oscillation power flows for the above four power flow observations on AC lines. The analysis is able to determine the damping ratio of the dominant oscillation modes, and the results are summarized in Table I. The calculated damping ratios for the same mode may differ (in a small range) due to the location of the observed oscillations.

In Observation 1 of Table I, corresponding to oscillations observed in power flow of line 89-38 of Fig. 3, the BC mode and NSB mode are detected, while the East-West South mode is not observed due to the location and power flow direction of line 89-38 (it is not in the East-West South oscillation group). All the designs 1, 2, and 3 are able to increase the damping ratio of the oscillation modes. Design 2 and 3 provide higher increase of the damping ratios. This result is consistent with visual inspection of Fig. 3.

In Observation 2 of Table I, corresponding to oscillations observed in power flow of line 57-113 of Fig. 4, BC mode, NSB mode and East-West South mode are detected. All the designs 1, 2, and 3 are able to increase the damping ratio of the oscillation modes, except for the design 2 that cannot increase the damping ratio of East-West South mode. Design 3 provides higher increase of the damping ratios, as also visually observed in Fig. 4.

In Observation 3 of Table I, corresponding to oscillations observed in power flow of line 94-69 (see also Fig. 5), BC mode, NSB mode and East-West South mode are detected. All the designs 1, 2, and 3 are able to increase the damping ratio of the oscillation modes. Design 1 and 3 provide higher increase of the damping ratios, as Fig. 5 also verifies by visual inspection.

In Observation 4 of Table I, corresponding to oscillations observed in power flow of line 102-77 (see also Fig. 6), the BC mode, NSB mode and East-West South mode are detected. All the designs 1, 2, and 3 are able to increase the damping. Design 3 provides higher increase of the damping ratios, as also verified by visual inspection of Fig. 6.

Table I. Summary of damping ratio of interarea oscillations

Observation 1		**Damping Ratio (%)**			
Mode	**F (Hz)**	**No Ctrl**	**D1**	**D2**	**D3**
BC	0.630	2.455	2.714	5.058	4.711
NSB	0.299	3.696	7.134	15.875	19.022
Observation 2		**Damping Ratio (%)**			
Mode	**F (Hz)**	**No Ctrl**	**D1**	**D2**	**D3**
BC	0.634	1.849	2.849	3.647	5.466
NSB	0.299	2.968	7.088	14.867	18.443
E-W S	0.851	7.738	14.002	4.876	11.313
Observation 3		**Damping Ratio (%)**			
Mode	**F (Hz)**	**No Ctrl**	**D1**	**D2**	**D3**
BC	0.635	1.593	5.868	4.376	4.870
NSB	0.300	3.432	9.019	9.554	16.730
E-W S	0.848	4.471	4.495	5.307	6.258
Observation 4		**Damping Ratio (%)**			
Mode	**F (Hz)**	**No Ctrl**	**D1**	**D2**	**D3**
BC	0.629	1.309	3.646	2.746	4.475
NSB	0.293	6.217	8.629	17.541	22.648
E-W S	0.865	5.788	6.746	8.437	8.648

V. Conclusions

This paper explored damping provided by modulating DC currents according to frequency differences across various points of the AC system. The independent control of each line provides damping, which can be increased by coordinating the modulation of two of the lines. The best results are obtained when HVDC lines are controlled when combining the individual and coordinated control. Future work could include formalizing the control design, considering communication delays, and extension to other topologies of HVDC systems embedded in AC systems.

VI. Acknowledgment

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