# Improving power grid transient stability and transfer capability using HVDC emergency power controls


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*Abstract*— **In the future, with a high level of renewable energy sources penetration, the transmission corridors will have to be flexible to operate under faster transients, and variable power flows. Fast power ramping and overloading capabilities of HVDC system can be utilized to ensure transient stability of the interconnected power grid. In this paper, HVDC auxiliary controllers have been studied that can provide the power grid with additional synchronizing and damping torques through fast DC power changes in response to arising system conditions. The effectiveness of the auxiliary controllers in improving transient stability is demonstrated by performing dynamic simulations on the detailed model of the Western Interconnection system.**



***Index Terms*—AC-DC corridor, HVDC link, Power modulation control, Transient stability.**


## I. INTRODUCTION

MOST power systems around the world have been designed to accommodate variability and uncertainty of present in the system. However, in order to achieve the ambitious goals of high levels of renewable energy integration into the electric grid, the power system needs to be far more flexible. Specifically, with respect to the transmission infrastructure, the challenge is in maintaining the reliability of the corridors even under large amounts of variable power flow, and during faster and larger transients while ensuring the operating limits of these corridors are not reduced. Thus, the transmission corridors will have to be much more flexible and controllable.

HVDC transmission systems are designed to control the power flow through the link. The precise power control will help in managing the variable power flows better. The fast power control can also enhance the response time of the power grid against large or extreme disturbances. Post contingency stress can be mitigated by utilizing their overloading capability. Especially in the case of line-commutated converter (LCC) HVDC systems, rapid change of active power flow well beyond its rated capacity (say 30-50%) for a few seconds is possible. This transient overloading capability of LCC-HVDC systems can be used for improving the transient stability of the grid because the duration of the critical angular swing is typically less than 2-3 seconds.

During power swing conditions following a critical contingency, appropriate power modulation of the HVDC transmission system could mitigate acceleration of synchronous machines and thus avoid system instability [1]. In the 1960s, the ability of the parallel DC link to improve transient stability was shown experimentally [2]. Later, it was determined that factors like the amount of DC current duration of increased current, has an impact on the improvement of the transient stability margin [3].

Various HVDC auxiliary control algorithms like the feed forward control [4], PI controls [5], bang-bang control [6], and optimal control have all been evaluated. All these controllers have their own advantages and disadvantages [7-12]. Various control inputs have also been tested. But the most widely used controls are based on the frequencies or the phase angles measured at HVDC converter terminal stations. They are good indicators of the power transfer situation. In the context of HVDC auxiliary controllers [13,14], they are already being used for small signal stability in practice. There has been some effort to develop wide area based controls for improving transient stability of the system. In [15], the wide area controls are used to increase the boundary transfer in the Great Britain network.

In all of these cases, the simulation tests were conducted on simple systems. There is a need to study the effect of using the auxiliary controller on a detailed system to not only prove its effectiveness but also ensure it does not have any adverse effects on the power system. The focus of the work previously conducted [16], was on demonstration of improved transient stability of critical AC-DC corridor in the WECC system using frequency measurements as inputs. In this work phase angle measurements based transient stability control is proposed and compared with the frequency measurement based control. Furthermore, integrated emergency power control that includes post contingency corrective power flow control is also proposed.

The rest of the paper is organized as follows. The HVDC auxiliary controller is presented in Section II, and the study system is discussed in Section III. Simulation results are


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presented and discussed in Section IV. Some discussions regarding the overloading capability are provided in Section V, and the post-contingency corrective power flow control is discussed in Section VI. The paper is concluded in Section VII.

## II. Emergency Power Control of HVDC System

The auxiliary controller of HVDC system for emergency power control (EPC) under grid disturbances is shown in Fig. 1. The integrated emergency EPC controller includes the following functions:

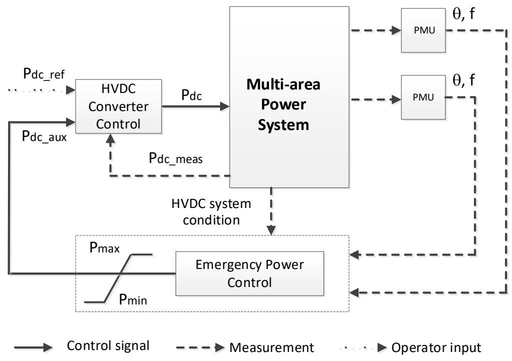


Fig 1. Schematic of integrated EPC scheme

i) Transient stability control function to provide timely synchronizing torque to the AC network and prevent the risk of instability caused by critical swing;

ii) Power oscillation damping control function to provide sufficient damping torque to the AC network and prevent the risk of instability caused by poor damping;

iii) Corrective power flow control to mitigate post-contingency stress of AC network.

Power oscillation damping strategies using HVDC on WECC have been investigated in detail [13,14]. The focus of this work is on the transient stability control and the post-contingency corrective power flow control strategies

### *A. Transient stability control*

In this paper, the two transient stability control schemes are as follows.

The first control scheme is based on frequency input. This control is a response based control by which the power flow through HVDC system is varied according to the frequency difference of the converter terminals. The power can be increased or decreased based on detected frequency difference:

$$\Delta Pdc = Kp * \Delta f \tag{1}$$

The second control scheme is based on phase angle input. This control is also a response based control by which the power flow through HVDC system is varied according to the phase angle difference of the converter terminals. The power can also be increased or decreased based on the detected frequency difference:

$$\Delta Pdc = K\text{p} * (\Delta\theta - \Delta\theta\text{ref}) \tag{2}$$

Unlike the frequency difference, which is zero in pre-disturbance and post-disturbance steady states, the phase angle difference during pre-disturbance and post-disturbance steady states may be quite different due to possible line trips. Hence, a reference angle difference needs to be considered such that the control acts only when the phase angle difference changes dramatically from the pre-disturbance reference value.

A proportionality constant (*Kp)* is to be chosen such that the HVDC system provides sufficient response. The control is triggered only after the frequency difference or phase angle difference is higher than a preset value. This preset value is to ensure that small disturbances do not trigger the auxiliary controller. The control diagram is shown in Fig. 2.

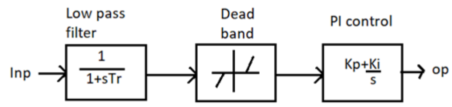


Fig 2. Proposed controller

The complete proposed controller for transient stability is shown in Fig. 3. The first step involves collecting local or wide area measurements. A large disturbance in the power system is detected using these measurements, and the transient stability controller is activated. Depending on the control algorithm, the controller provides an auxiliary signal to increase or decrease the HVDC current or power orders. The HVDC might not be able to provide the additional support if the HVDC system is not in normal operation condition, for example, if the fault is close to the converter station. Therefore, the power change is activated only after the DC system reaches the normal conditions. The controller continues to function until it detects that the system has become stable or critical power swing has been effectively mitigated. In most cases, the first swing is considered to be critical. Hence, the controller would be switched off after the system is seen to be stable.

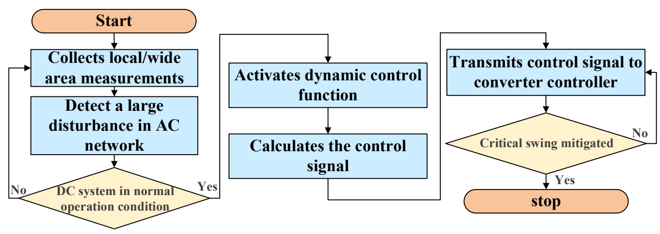


Fig 3. Illustration of the control algorithm.

### *B. Corrective power flow control*

The corrective power flow control function automatically redispatches the post-contingency power flow of the HVDC system by emulating the power flow response of an AC transmission line. The power flow on an AC transmission line can be expressed in terms of the power angle relationship as follows:

$$P = \frac{U_1 U_2}{X} \sin(\theta_1 - \theta_2) \tag{3}$$

In terms of the HVDC system, the power P can be modulated by the converter station, while $U_1$ and $U_2$, $\theta_1$ and $\theta_2$ can be measured at the converter terminal AC buses. Thus, the AC line impedance emulated by the HVDC system by modulating the power P is

$$X = \frac{P_{DC}}{U_1 U_2 \sin(\theta_1 - \theta_2)} \tag{4}$$

Following a network contingency, the HVDC system can modulate power flow according to this target impedance as

$$P_{DC} = \frac{U_1 U_2}{X_{ac-emulated}} \sin(\theta_1 - \theta_2) \tag{5}$$

## III. Study System Discussion

The study is performed using the detailed model of the Western Interconnection system, which consists of over 21000 buses. The power flow case is based on the high summer system operating scenario. Among the 66 transmission corridors in the Western Interconnection system, the California Oregon Intertie (COI) is one of the most congested transmission paths. The COI consists of three 500 kV AC lines; a set of double circuit lines from Malin to Round-Table substation and another from Olinda to Captain Jack. The thermal limit of these three 500kV AC lines is about 10,000 MW.

However, the power transfer capability of the COI is far below the thermal capacity limit due to transient stability concerns. During the summer peak, the COI is allowed to deliver up to 4800 MW from North to South. The parallel COI and the Pacific DC Intertie (PDCI) corridors are highly utilized and operate at above 90% of the transfer capability limits for more than 14% of the year. It can be expected that if the stability limit of the parallel COI and PDCI corridors is improved, additional less expensive power could be delivered from the North region to California load areas.

The model of the Western Interconnection system is in PSLF format, and the PDCI is modeled using the generic two-terminal HVDC model (EPCDC) available at the PSLF model library. In the current model, the PDCI operates at the rated power of 3100 MW at 500kV. The power flow direction is from North to South. Hence, the substation at Celilo acts as the rectifier, and the Sylmar station operates at the inverter mode. Recently, the PDCI has been upgraded to carry about 3220 MW at 520 kV. For dynamic simulation studies, the HVDC auxiliary controller is implemented as a user-defined model which provides an auxiliary signal to the EPCDC model to modulate the DC current or DC power in PDCI link.


Fig 4. PDCI with parallel AC lines [17]

## I. Improving Grid Stability by HVDC Control

### A. Case descriptions

The base case is the high summer peak case of 2016 with 3800 MW of power flow in COI from North to South. In order to develop a case with conditions reaching the transient stability limits, a stressed power flow case is developed with 4500 MW of power flow in COI from North to South [18-19]. Large disturbances are simulated by creating a fault at one of the COI lines, thus restricting the power flow from north to south. In this paper, we applied a three-phase ground fault at

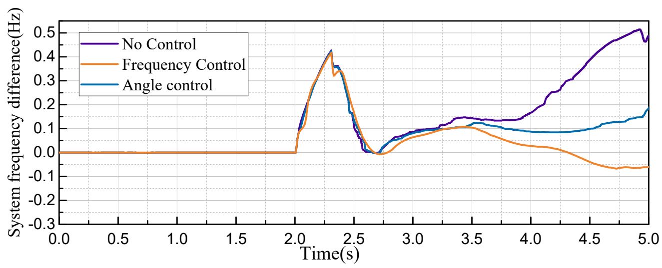


Fig. 4a. Frequency difference

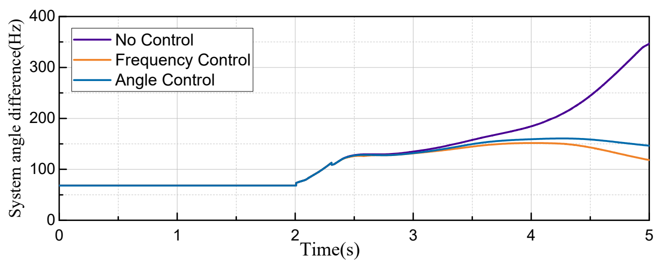


Fig. 4b. Phase angle difference.

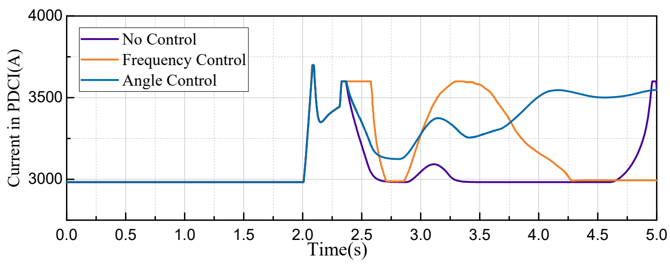


Fig. 4c. DC current in PDCI

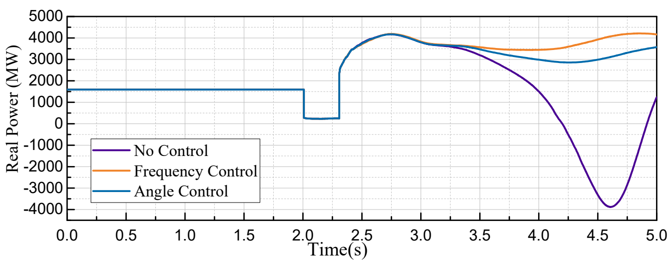


Fig. 4d. Power flow in Olinda-Cap-Jack line

the Malin substation. The fault is cleared after an extended duration of 300ms followed by tripping the double circuit lines between Malin substation and Round Mountain substation.

### *B. Control parameters*

The two auxiliary controllers described in the previous section are tested. The inputs (frequencies and phase angles) are obtained from the converter station AC buses. The transient overloading capability of the PDCI system is assumed to be 20% which is quite conservative for a period of a few seconds. A frequency difference of 0.1 Hz between the two regions is chosen as the triggering criterion for the frequency based controller. The angle based controller is triggered when the phase angle difference between the two regions changes by about 40 degrees from the pre-disturbance reference value. The controller is not activated till the voltage at the converter terminal reaches 0.9 p.u. to ensure that HVDC system is in normal operation condition. The controllers are tuned to ensure that the overloading capability of the HVDC system is optimally utilized under moderate disturbances. After the system is seen to be stable, the controller is switched off to avoid unnecessary control actions.

The simulation results of both frequency and phase angle measurements based controller are presented in Fig. 4a, 4b, 4c, and 4d. Both frequency based and phase angle based HVDC control schemes are effective for mitigating the potential risk of first swing transient instability. After the first swing, the phase angle based control maintains the increased DC power until post-disturbance steady state is established.

### *C. Features of phase angle based control scheme*

As demonstrated by the simulation results, the performance of phase angle based control is similar to that achieved by frequency based control. The phase angle based control is only triggered when a large change in phase angle difference is detected from the recorded pre-disturbance steady state value. This steady state value varies along with system power flow conditions.

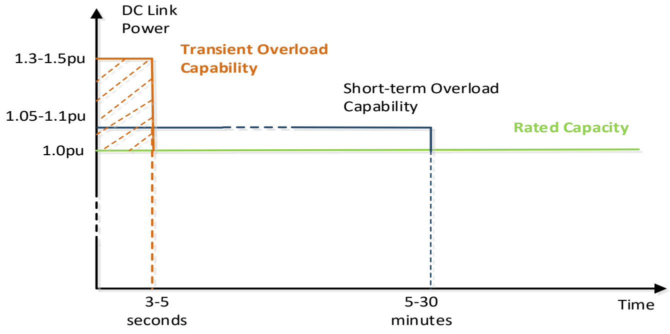


Fig. 5 Overloading capability of LCC HVDC system.

In the simulation cases, the post-disturbance phase angle difference is quite higher than the pre-disturbance value due to increased path impedance. Hence, the controller attempts to maintain increased DC power till post-disturbance steady state is established. The controller will then be deactivated by ramping down the DC power to the scheduled pre-disturbance power order. It is also feasible to ramp down the DC power to a value higher than the pre-disturbance scheduled power. This post-disturbance corrective power flow control will help reduce the stress of parallel AC lines during post-disturbance operating conditions.

## II. Effect of Overloading Capability

The overloading capability of the HVDC system depends on the design of the system. Most of the LCC system inherently have additional overloading capability depending on the duration, as shown in Fig. 5.

The overloading capability is needed only for a couple of seconds. Therefore, the assumption that the system could be overloaded to 20% is valid. However, in order to determine the actual amount of overloading capability required, a simulation study is performed. The simulation results are presented in Fig 6a, 6b, 6c and 6d. It can be seen that with both 5% and 10 % overloading capability the system becomes unstable. Thus 20% overloading capability seems to be the appropriate amount to improve the transient stability of the system.

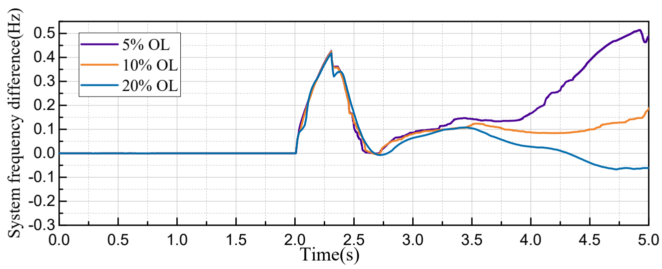


Fig. 6a.Frequency at Celilo

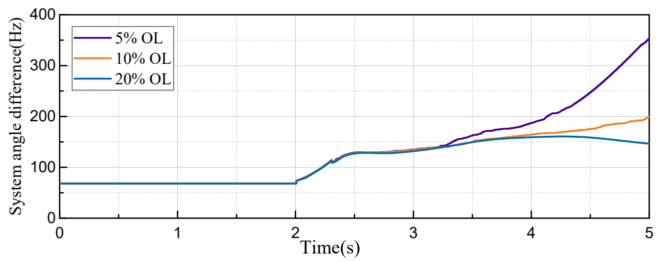


Fig. 6b. Phase angle difference

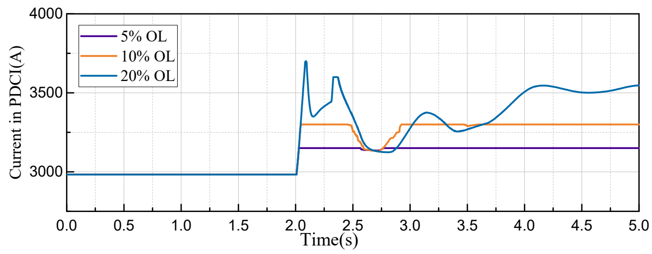


Fig. 6c. Power in PDCI

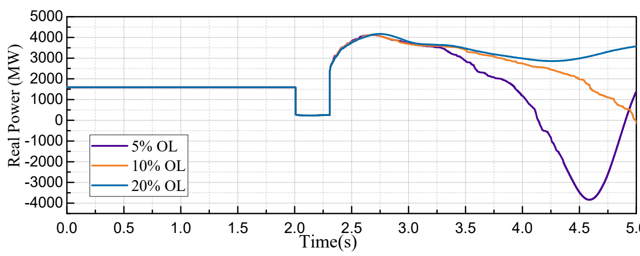


Fig. 6d. Power in Olinda-Cap-Jack line

For this study, the overloading

## III. Corrective Power Flow Control

In order to completely utilize the overloading capability of the HVDC system, it is efficient to use the transient overloading capability to ensure the first swing stability of the system. As this will be needed only for a couple of seconds, the HVDC could be overloaded to the maximum possible extent. After, the first swing stability is ensured, the power in the HVDC system is ramped down to the long-term overloading capability to either provide additional damping or to mitigate the post contingency stress of the system. The DC current flowing through the HVDC line is shown in Fig 7a.

The increased power flow in the HVDC system causes a reduction in the power flow of the parallel AC system, thus reducing the stress on the AC line. The current in the PDCI is ramped down to around 3250 A. Assuming the rating of the PDCI is at 3220 MW at 520kV, this corrective control is set at 5% overloading capability.

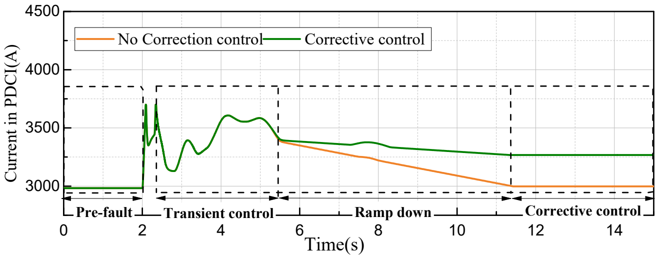


Fig 7a. Corrective power flow control

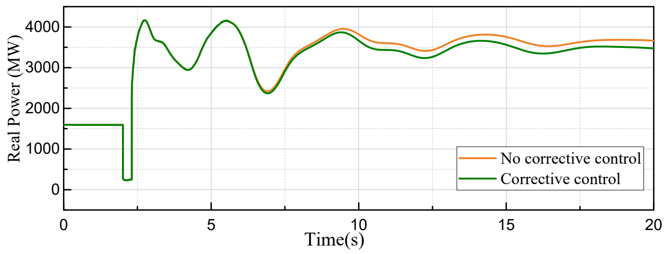


Fig 7b. Corrective power flow control

## IV. Conclusions

In this paper, an auxiliary HVDC controller to improve the transient stability of the power system has been proposed. The performance of the controllers is demonstrated by simulations of the full dynamic model of Western Interconnection system. From the perspective of improving first-swing transient stability, the performance of phase angle based control is similar to that achieved by frequency based control. For phase angle based control, it is feasible to automatically redispatch the post-disturbance DC power to a value higher than the pre-disturbance scheduled power within the allowed short-term overloading capability. This post-disturbance corrective power flow can help reduce the stress of parallel AC lines. Measurements from remote PMUs can be used as inputs of the HVDC auxiliary controller to ensure availability of the needed information. In some cases, inputs from remote measurements may be considered as better indicators for the concerned system operation risks.

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