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Droop-Based Frequency Support from Offshore HVDC Grids

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SUMMARY

Offshore HVDC grids are envisaged to render more reliable and economical solutions for transferring more offshore wind energy to onshore power systems. From the reliability point of view, the most promising operational/control strategy of HVDC grids is the dc voltage droop control. This control provides autonomous power-sharing among converters and promotes the frequency support to onshore power systems from other ends of HVDC grids without using fast communication links. The simultaneous use of frequency and dc voltage droops in an HVDC converter can transform frequency deviations into dc voltage changes. Other converters with dc voltage droop can react to the changes by regulating their power flow. Therefore, autonomous frequency support can be established through an HVDC grid. Although this method is reliable, fast, and economical, it gives rise to interactions between different droops, which can result in a reduction in the HVDC power that system operators can expect during frequency events. The present study investigates the effectiveness and challenges of the droop-based (*communication less*) control for providing frequency support in offshore HVDC grids. The frequency support is described mathematically, and a static transfer function between onshore frequency and HVDC power is derived as a function of the power system and control parameters. The function can be used to compensate for the adverse effect of frequency and dc voltage droop interactions; however, it is challenging in the case where an HVDC grid has more than one onshore ac systems since the transfer function of one ac system will depend on the parameters of other ac systems. A signal-flow model is developed for offshore HVDC grids to quantify the effects of onshore frequency deviations on different electrical parameters of the grid. Using this model the transfer function mentioned before can be obtained more easily. A point-to-point and a four-terminal HVDC connections are simulated and communication less control is numerically compared with communication-based control.

KEYWORDS

Offshore HVDC Grid, frequency support, droop control, offshore wind power

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1 INTRODUCTION

Adding a supplementary controller, the variable-speed wind turbines can provide frequency support by regulating their output active power in response to system frequency deviations [1]–[3]. For the shore wind turbines that are connected directly to ac power systems, implementing the frequency control is straightforward. The frequency deviation is sensed and fed to a droop controller which its output is added to the turbines reference power.
Such a simple controller is also applicable to the wind turbines of ac connected OWPPs. However, providing frequency support from OWPPs with HVDC connections is not easy since the offshore ac grid is isolated from onshore via dc links. In such plants, communication links between onshore and offshore are needed to communicate the onshore frequency deviation for adjusting the wind turbines output power.

Implementing the frequency support in dc connected OWPPs without using communication links has been investigated [4]. The onshore frequency deviation transforms into dc voltage change on the shore HVDC converter. On the offshore end, the dc voltage change is sensed and converted into offshore frequency change. Now the wind turbines can detect the frequency deviations and react by readjusting their output active power.

The multi-terminal offshore HVDC connections (HVDC grids) can be more economical and reliable power transmission systems for offshore wind power. The power flow through HVDC grids can be controlled in different ways [5]. Among others, the dc voltage droop control is found to be a reliable solution since more than one converter control the dc voltage, and thus, a more secure operation can be achieved.

Providing frequency support from an offshore HVDC grid can be relatively more flexible as the required power can be supplied from wind farms and/or from different ac systems connected to other ends of the dc link. To be able to use the offshore wind contribution in the (primary) frequency control, the wind power plant operation must be down regulated, i.e., there must be extra wind power for frequency support [6]–[12].

The communication less frequency support in offshore dc grids is feasible when the grid uses dc voltage droop control [6], [7]. However, the support cannot be as efficient as with communication links. Because in the communication less scheme the dc voltage and frequency droops interact against each other and result in a reduction of the power that should be supplied the ac system under frequency events [9]. The adverse effect of the droop interactions can be compensated if there is one onshore ac system equipped with frequency control. Otherwise, the compensation can be challenging.

In this paper, a transfer function between the frequency deviation of an ac system and the amount of active power that an offshore HVDC grid can provide is derived for the case of communication less frequency support. The transfer function shows how efficient the support can be, and also how challenging the compensation of droop interactions will be. To understand and quantify the effect of frequency deviations of an onshore system on different electrical parameters of an offshore HVDC grid a signal-flow model is introduced.

The paper is organized as follows. In Section 2 HVDC connections and their control systems are introduced. In Section 3 mathematical model for communication less frequency support is developed. Simulation results are presented in Section 4, and finally the study is concluded in Section 5.

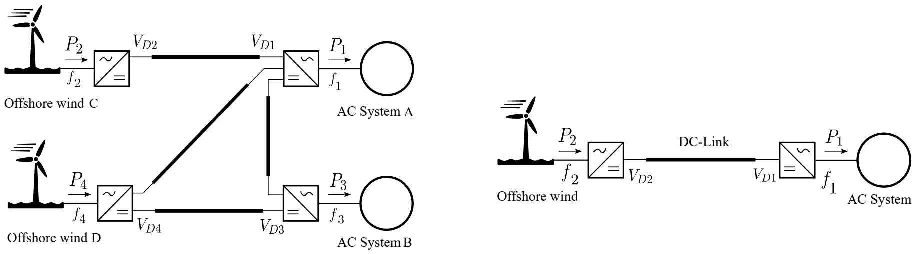

Figure 1: A point-to-point HVDC (right) and a four-terminal HVDC grid (left) used for frequency support studies.

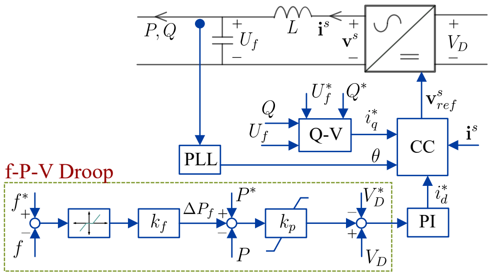

Figure 2: Onshore converter control with dc voltage and frequency droopson.

2 HVDC CONNECTIONS AND CONTROL MODELS

Two HVDC connections are used for investigations: a point-to-point (P2P) and an HVDC grid. This connections are shown in Figure 1. The P2P offshore HVDC is a mature technology which is in operation today. This connection is used in this paper as a base for evaluating the communication less frequency support.

In both HVDC connections (P2P and grid), each onshore ac systems is modeled as an aggregated synchronous machine with a turbine and governor. A passive load is also considered to create frequency deviations. The OWPPs are modeled as IEC type-4 (fully-rated) wind turbines using the aggregation method given in [13].

2.1 HVDC and Wind Turbines Control

It is supposed that the onshore converters operate with dc voltage droop control. These converters are also equipped with frequency droop control to support the ac system frequency. Figure 2 shows the control system of onshore converters. In this figure k_p and k_f are respectively the dc voltage droop and the frequency bias (inverse of frequency droop). CC stands for current control, PLL for phase locked loop, and Q-V represents the reactive power or ac voltage control. All control and electrical parameters have corresponding subscripts according to the ac system number. For example for ac system A, the subscript for all parameters will be 1, and for ac system B, it is 3.

The control systems of offshore HVDC converters as well as wind turbines are shown in Fig. 3. The offshore HVDC converters form ac grids for offshore ac networks, i.e., they establish the frequency of offshore ac networks. Adding dc-voltage-frequency droop in these converters' control, the dc voltage changes can be converted into offshore frequency changes by a droop gain k_v. As shown in Figure 3 the frequency changes can be detected by the wind turbines and their output power changes with respect to a droop k_f. In wind turbine control the frequency derivative is also shown which is used for inertia control. This control is not withing the scope of this paper. Only primary frequency control is studied.

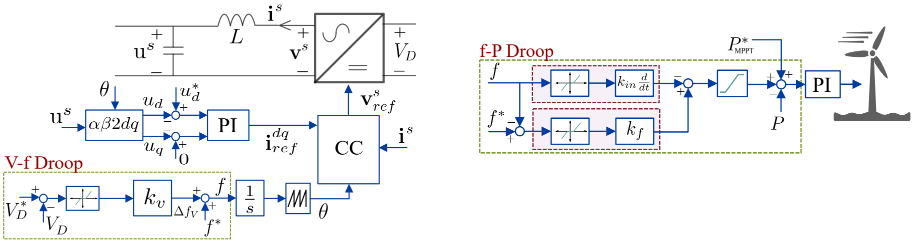

Figure 3: Control systems of offshore HVDC converters (left) and wind turbines (right).

3 MATHEMATICAL MODEL OF FREQUENCY SUPPORT

To understand how efficient the droop-based (communication less) frequency support is, and what the associated challenges are a transfer function between onshore frequency deviation and the HVDC power change is developed. Because of simplicity, a P2P connection can help to understand the mechanism of the frequency support from HVDC and related challenges. Therefore, the transfer function is first developed for a P2P connection, and then extended to HVDC grids.

3.1 Poin-to-Point HVDC Connections

Based on the control systems shown in Figure 2 and 3, the post-disturbance steady state (when there is a frequency drop Δf_1 on the onshore system) for the P2P connection shown in Figure 1 can be written as

$$\begin{aligned} \text{Onshore} &\rightarrow V_{D1} - V_{D1}^* + k_{p1}\left[P_1^* - P_1 + k_{f1}\left(f_1^* - f_1\right)\right] = 0 \\ \text{Offshore} &\rightarrow P_2^* - P_2 + k_{f2}\left(f_2^* - f_2\right) = 0, \quad f_2 = f_2^* + k_{v2}\left(V_{D2} - V_{D2}^*\right) \end{aligned} \tag{1}$$

After a load or generation perturbance, the onshore frequency deviates as Δf_1 and makes the other parameters (except reference values) to vary by Δ values. Considering only the variations of electrical parameters from their pre-disturbance values, (1) can be written as

$$\begin{aligned} \text{Onshore} &\rightarrow \Delta V_{D1} - k_{p1}\Delta P_1 - k_{p1}k_{f1}\Delta f_1 = 0 \\ \text{Offshore} &\rightarrow \Delta P_2 + k_{f2}k_{v2}\Delta V_{D2} = 0. \end{aligned} \tag{2}$$

Assuming loss-less dc transmission links the dc voltage and active power at both ends of the dc link will be the same, i.e., $V_{D1} = V_{D2}$, $P_1 = P_2$. With such assumption and also by defining $k_{p2} = 1/(k_{f2}k_{v2})$, the transfer function between onshore frequency deviation Δf_1 and HVDC power change ΔP_1 can be derived as

$$\Delta P_1 = -k_{f1} \underbrace{\frac{k_{p1}}{k_{p1} + k_{p2}}}_{\text{attenuation factor}} \Delta f_1. \tag{3}$$

ΔP_1 in (3) is less than the TSO's expected power which is $\Delta P_{exp} = -k_{f1}\Delta f_1$. This means that the droop-based frequency support is not able to meet the grid code requirement. The reason is that the frequency and dc voltage droops counteract each other and attenuate the transfer function derived in (3). This is not, however, a significant challenge in the case of P2P connections since the attenuation can be compensated by multiplying the k_{f1} by the inverse of the attenuation factor. Since the compensation is made on the onshore converter, it always need to know the value of offshore control parameter k_{p2}.

3.2 HVDC Grid

It is assumed that offshore C and onshore B can supply extra active power to onshore A in case of frequency support. Both onshore HVDC converters are equipped with frequency droop control. The offshore D operates with constant power (maximum available power), i.e., $P_4^* - P_4 = 0$. Assuming a load disturbance on onshore A, the post-disturbance steady state for entire HVDC grid can be stated as

$$\begin{aligned} \text{Onshore A} &\rightarrow V_{D1} - V_{D1}^* + k_{p1}\left(P_1^* - P_1 + k_{f1}\left(f_1^* - f_1\right)\right) = 0 \\ \text{Onshore B} &\rightarrow V_{D3} - V_{D3}^* + k_{p3}\left(P_3^* - P_3 + k_{f3}\left(f_3^* - f_3\right)\right) = 0 \\ \text{Offshore C} &\rightarrow P_2^* - P_2 + k_{f2}\left(f_2^* - f_2\right) = 0, \quad f_2 = f_2^* + k_{v2}\left(V_{D2} - V_{D2}^*\right) \end{aligned} \tag{4}$$

Assuming loss-less dc links, the dc voltage of all converters will be the same, and the power balance in the dc grid can be written as $P_1 + P_3 = P_2 + P_4$. Therefore, a small deviation from steady state will result in

$$\begin{aligned} \text{Onshore A} &\rightarrow \Delta V_D + k_{p1}\left(-\Delta P_1 - k_{f1}\Delta f_1\right) = 0 \\ \text{Onshore B} &\rightarrow \Delta V_D + k_{p3}\left(-\Delta P_3 - k_{f3}\Delta f_3\right) = 0 \\ \text{Offshore C} &\rightarrow \Delta P_2 + k_{f2}k_{v2}\Delta V_D = 0 \end{aligned} \tag{5}$$

where Δf_3 and ΔP_3 are the frequency and power deviations of onshore B caused by the disturbance on onshore A. The value of these parameters depends on the governor settings and damping factors of onshore B. This dependency can be written mathematically by considering the motion equation of system B as

$$\Delta f_3 = \frac{1}{sH_3 + D_3 + k_{g3}}\Delta P_3, \quad k_{g3} = 1/R_{g3} \tag{6}$$

where H_3, D_3 and R_{g3} are respectively the inertia constant, damping factor and governor droop of system B. The steady state form of (7) is $\Delta f_3 = \left(D_3 + k_{g3}\right)^{-1}\Delta P_3$ which can be substituted in (5) which results in

$$\Delta P_1 = -k_{f1}\underbrace{\frac{k_{p1}k_{p2} + k_{p1}k_{p3} + \frac{k_{p1}k_{p3}k_{f3}}{D_3 + k_{g3}}}{k_{p1}k_{p2} + k_{p1}k_{p3} + k_{p2}k_{p3} + \frac{\left(k_{p1} + k_{p2}\right)k_{p3}k_{f3}}{D_3 + k_{g3}}}}_{\text{attenuation factor}}\Delta f_1. \tag{7}$$

The transfer function derived for the dc grid in (7) is more complicated than that of P2P connection in (3), and as a result its compensation is not straightforward. Moreover, estimation of the values of D_3 and R_{g3} is not easy in practice. The transfer function can be even more complicated if offshore D is also participating in frequency control.

For a P2P connection, it is mentioned that the compensation can be fulfilled by multiplying the inverse of the attenuation factor by the frequency bias k_{f1}. In an HVDC grid, this type of compensation cannot be achieved simultaneously for all of the shore ac systems because the frequency bias of ac systems depend on each other. For example in (7) the derived transfer function depends on k_{f3}, and if we derive the same transfer function for onshore B, it would depend on k_{f1}. In other words, as long as the onshore converters operate with dc voltage droop control, their active power flow cannot be independent.

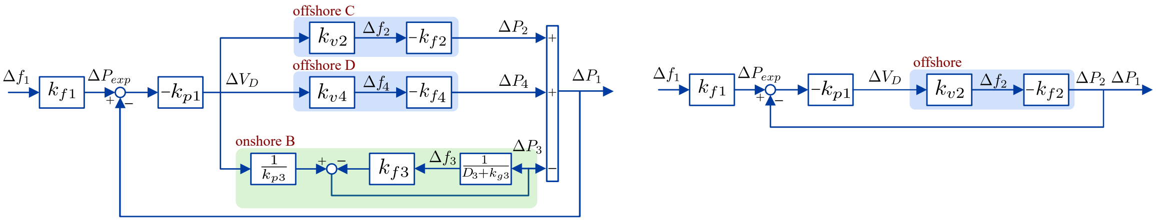

Figure 4: Signal-flow model of a P2P (right) and an HVDC grid (left).

3.3 Proposed Signal-Flow Model

Obtaining power-frequency transfer function for larger HVDC grids is not easy especially if more than one onshore ac system is connected to the grid. A signal-flow model is proposed to promote the calculations. Figure 4 shows models for a P2P and HVDC grid. The well known Mason's Rule [14] can be used to calculate the power-frequency transfer function from the proposed signal-flow model. It is also possible to calculate the effect of onshore frequency deviation on any other electrical parameters in the grid, for example, the effect of frequency deviation of system A on the frequency of system B. In the signal-flow model of the HVDC grid, it is assumed that both OWPPs and onshore B contribute in frequency support of system A. If any of these are not contributing, their corresponding blocks in the signal-flow model can be omitted.

4 SIMULATION RESULTS

Both P2P and HVDC grid connections shown in Figure 1 have been simulated using DIgSILENT tools. Synchronous machines, turbines, and governors of onshore systems are similar. The inertia constant of each system is 10 s, and the damping factor 0.1 pu. The governor frequency bias is 0.05 pu. A frequency drop has been created on onshore A by a sudden load increase of 400 MW.

In the case of the HVDC grid, it is assumed that the grid code requirement related to frequency support from OWPPs applies to onshore HVDC converter. Otherwise, communication links are needed to meet the requirements. In fact, another challenging factor of communication less frequency support is that the related grid code requirements cannot be directly fulfilled by OWPPs because the dc voltage is not directly proportional to only one ac system frequency, and the control system (frequency and dc voltage droops) of other ac system is also playing role.

The frequency support using communication links is simulated for both P2P and grid connections to use the results as references to evaluate the communication less support.

4.1 P2P Connection

Before applying power disturbance on onshore ac system the OWPP was producing 810 MW. The frequency bias used for HVDC is 0.015 pu. The bias is intentionally chosen too low to create more visibility on simulation results.

Four different scenarios have been simulated: without HVDC contribution in the frequency control, support with communication links, support without communication links and without compensation, and finally the communication less support with compensation. The simulation results for these case studies are shown in Figure 5 which includes onshore and offshore frequencies, HVDC active power and dc link voltage.

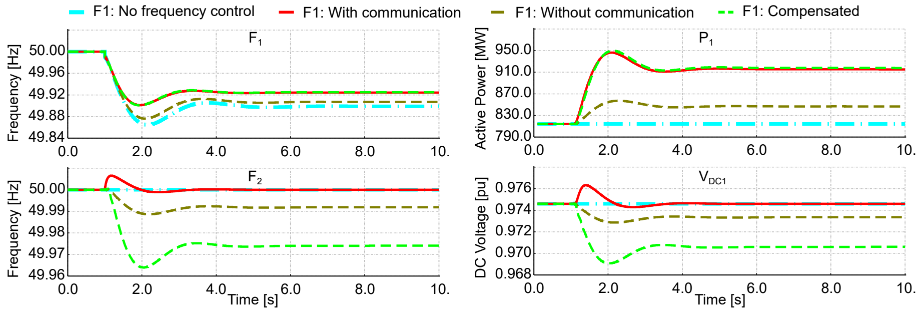

Figure 5: Simulation results of P2P offshore HVDC connection.

The simulation results show that the communication less scheme can provide frequency support. However, it is not as efficient as with communication links. When compensated, although it is adequately efficient, it results in significant frequency drop on offshore ac network. This adverse effect can be mitigated by increasing the active-power bias k_{p1} on the shore converter so that the dc voltage drops more. There should be a tradeoff between dc voltage, and the offshore frequency falls to avoid the risks of an abnormal operation where the parameters (dc voltage and/or offshore frequency) can exceed the limits.

4.2 HVDC Grid

In these simulations each of shore converters uses dc voltage and frequency droops simultaneously. Both OWPPs contribute in the frequency support requested from onshore A with and without using communication links. The one without communication links is used for comparing the results and analyzing the efficiency of the communication less method.

Four different case studies are simulated. Case A: OWPPs do not contribute in the frequency support. Because of the frequency and dc voltage droops on the shore converters, system B supports the frequency of system A automatically. Case B: both OWPPs and onshore B provide frequency support without using communication links. Case C: OWPPs contribute in the frequency support using communication links. Onshore B doesn't associate in the support. Case D: the communication less is compensated on converter A.

The dc voltage and frequency droop control parameters used for simulations are shown in Table 1. The simulation results are presented in figures 6, 7 and 8. It is obvious from the results that even though the compensated method satisfies the grid code requirement of system A, it results in highest fall on both dc voltage and offshore frequencies. This averse effect may not be acceptable in practice. Only in the case of using communication links, the frequency of onshore B has not been affected. This means that there must be a regulatory agreement between system A and B operators in providing frequency support to each other's network, otherwise, either communication-based frequency support should be used or onshore converters should not used dc voltage droop.

The dc voltage is not changing in the case of using communication links. This is because the droop controls on onshore A and OWPPs counteract each other in changing the dc voltage. Therefore, the supportive power is supplied from offshore plants without changing the voltage profile. This is a positive aspect of using communication links.

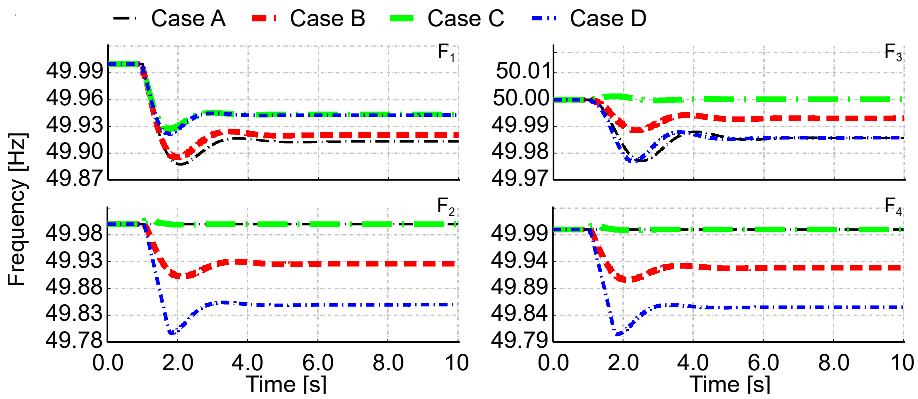

Figure 6: Frequencies of onshore ac systems (top) and OWPPs (down).

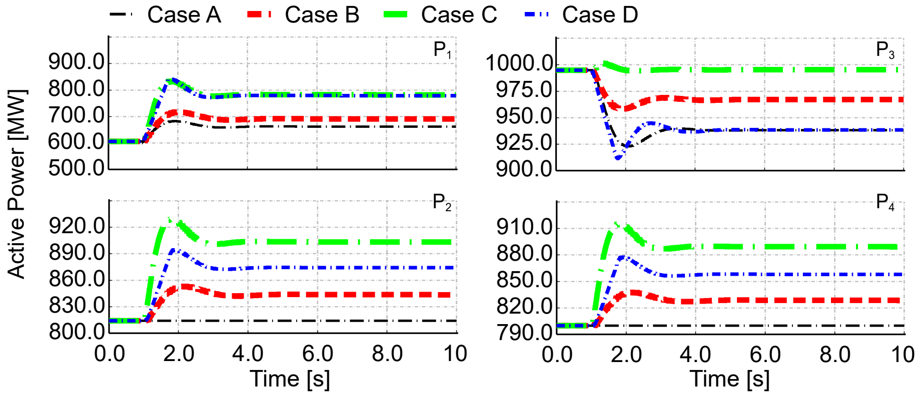

Figure 7: Active powers of onshore HVDC converters (top) and OWPPs (down).

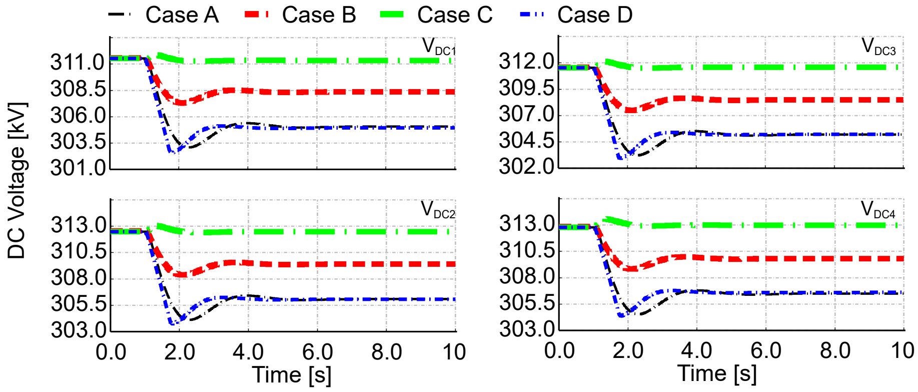

Figure 8: DC voltage on onshore (top) and offshore (down) terminals.

Table 1: DC voltage and frequency droop control parameters used for different case studies.

Case Studies	Control Parameters							
	k_{p1}	k_{p3}	k_{f1}	k_{f2}	k_{f3}	k_{f4}	k_{v2}	k_{v4}
Case A	0.25	0.25	78.74	20	78.74	20	0.15	0.15
Case B	0.25	0.25	157.48	78.74	-	78.74	0	0
Case C	0.25	0.25	78.74	0	78.74	0	0	0
Case D	0.25	0.25	222.22	20	78.74	20	0.15	0.15

5 CONCLUSIONS

Frequency support from offshore HVDC without using communication links between onshore and offshore was investigated. The support from a point-to-point and grid connections was studied, and challenges related to the latter were outlined. It was shown analytically (mathematically) that in the case of communication less frequency support, the dc voltage and frequency droop controls interact with each other and result in a reduction of the desired power. Therefore, compensation is needed. A signal-flow model was developed to derive transfer functions between onshore frequency and the HVDC active power. The transfer function is useful for compensating the droop interactions. In point-to-point connections, it is relatively straightforward to realize the compensation; however, in the case of HVDC grids with more than one onshore ac systems, it is not; because the compensation depends on ac system parameters which are not easily estimated in practice. It was also shown that the communication less frequency support could result in interactions between onshore ac systems. The dc voltage and offshore frequency fall can be another adverse effect of communication less support.

6 ACKNOWLEDGEMENT

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