DC Grid Control Through the Pilot Voltage Droop Concept – Methodology for Establishing Droop Constants

Bertil Berggren, Senior Member, IEEE, Kerstin Lindén, Member, IEEE, Ritwik Majumder, Member, IEEE

Abstract—Control of voltage-source-converter high-voltage dc (VSC-HVDC) transmission systems embedded in ac systems is a central issue requiring attention in the context of multi-terminal dc grids. A number of power drooped against dc voltage control concepts have been proposed in the literature for this purpose. However, there is at this time no clear methodology available on how to select the size of the droop constants for distributing a power mismatch, following, e.g., a converter trip, on several converters. This paper proposes a methodology for establishing droop constants for a variant of power drooped against dc voltage called pilot voltage droop control. The methodology is derived from the basic control laws in a straightforward fashion and the accuracy is exemplified by time domain simulations in Digsilent’s Powerfactory platform.

Index Terms—High-voltage dc, voltage source converters, dc grid, droop control.

I. INTRODUCTION

The potential future introduction of dc grids based on VSC-HVDC transmission systems has during recent years received substantial attention [1]. One issue requiring attention is the converter control in a dc grid context. The main aim of this paper is to elaborate on a power drooped against direct voltage concept for the control of dc grids, the concept being referred to as the pilot voltage droop concept.

A number of droop control concepts have been proposed in the context of multi-terminal dc grid control for the purpose of allowing several converters to share a power mismatch following a disturbance. Most of the proposed concepts rely on local measurements only. In, e.g., [2] the difference between power set-point and locally measured power is drooped against the difference between direct voltage set-point and measured local converter direct voltage. In [3] the difference between set-point in direct current and measured direct current output from the converter is drooped against the difference between global (common for all converters) dc voltage set-point and local converter direct voltage. Another variant is proposed in [4] which is similar to [2] but different droop constants are suggested depending on the deviation between direct voltage set-point and measured value, thus providing more degrees of freedom. All droop control concepts based on local voltage measurement suffer to some extent from the circumstance that the dc voltage magnitude varies across the dc grid due to resistance in the dc transmission.

Comparing with power drooped against frequency control in ac systems, the advantage of having a common signal (the frequency at steady state) across the system is evident. The pilot voltage droop concept, which is discussed in this paper, uses communication for the purpose of establishing a common dc voltage signal across the dc grid and thus improving the performance of droop control. The concept provides a number of advantages such as straightforward establishment of set-point tracking and precision in how power mismatches following disturbances are shared between converters through proper sizing of droop constants. These advantages come of course with the extra complexity of having to handle, e.g., latencies that may be introduced by the communication. It is expected that a control concept based on communication, such as this concept, should have a fallback control option based on locally available measurements in case excessive latencies are encountered.

The pilot voltage droop concept was initially proposed in [5], and it has also been discussed in, e.g., [6], where the concept was discussed in the context of adaptive droop.

This paper focuses on developing a methodology for establishing fixed droop constants as part of, e.g., day ahead operations planning. Having the ability to decide in a precise manner which converters that should take large or small portion of a power mismatch, following, e.g., a converter trip, is advantageous from a combined ac/dc system security perspective. In other words, it allows the operator to direct a change in power to converters which from both an ac and dc system perspective have the appropriate capacity, thus avoiding, e.g., overloads and ac stability issues.

Other aspects of the concept, such as how to establish set-point tracking and how to handle latencies will be the focus of forthcoming publications.

The structure of the paper is as follows. Section II and III briefly describes the assumed station main circuit and the control system structure in which the pilot voltage droop control is introduced. Section IV describes the pilot voltage droop concept and Section V describes how power and voltage deviations can be estimated, and how a methodology for establishing droop constants can be devised. Section VI provides with simulation results to support the proposed methodology.

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II. CONVERTER STATION MAIN CIRCUIT

The following notation will be used, cf. Fig. 1.

- \( P_{\text{PCC}}, Q_{\text{PCC}} \) : Active and reactive power at the point of common coupling (PCC).
- \( I_v \) : Valve current.
- \( V_v \) : Valve voltage.
- \( V_{dc} \) : Converter direct voltage.

![Fig. 1. Converter station main circuit.](image)

III. GENERAL CONVERTER CONTROL STRUCTURE

Fig. 2 illustrates the general converter control structure which will be assumed in this paper.

![Fig. 2. General converter control structure.](image)

The active power/direct voltage control block (AP/DV) takes as input, e.g., active power and direct voltage measurements together with set-points and generates a valve current order in d-axis direction as output. The reactive power/alternating voltage control block (RP/AV) takes as input, e.g., reactive power and alternating voltage measurements together with set-points and generates a valve current order in q-axis direction as output. The valve current orders are fed into the valve current control block for the purpose of establishing valve voltage references which in turn are fed into the valve control block to be effectuated.

The general control structure, and specific example control implementations of each control block, can be found in [7], although similar proposals can be found elsewhere, see, e.g., [8] – [11].

The pilot voltage droop control, which is the focus of this paper, will be implemented by only changing the AP/DV control block as compared to what was presented in [7].

IV. PILOT VOLTAGE DROOP CONTROL

An AP/DV control block for a basic pilot voltage droop control implementation is shown in Fig. 3. The feature that distinguishes the pilot voltage droop from other power drooped against dc voltage concepts is that all converters on this type of droop control receives the same dc voltage information. In other words, the pilot voltage error, \( V_{\text{error}, \text{dc, pilot}} \), is common for all converters on pilot voltage droop control (for a bipole system it is common for all converters connected to the same pole network).

![Fig. 3. AP/DV control block for pilot voltage droop.](image)

The pilot voltage measurement, \( V_{\text{dc, pilot}} \), as such may be obtained as the dc converter voltage as measured at a specific point in the dc grid or it may be obtained as, e.g., the average of several converter voltages.

It follows that the pilot voltage measurement, \( V_{\text{dc, pilot}} \), and the corresponding set-point, \( V_{\text{ref}, \text{dc, pilot}} \), need to be communicated to all stations on this type of control. The difference between measured active power at PCC, \( P_{\text{PCC}} \), and the corresponding set-point, \( P_{\text{ref}, \text{PCC}} \), is then multiplied with a droop constant \( D \) which size we would like to establish.

It is here assumed that some sort of “dc grid code” will stipulate a dc voltage range within which the converters should operate, as also proposed in, e.g., [3]. By adding a measurement of the local dc voltage, \( V_{dc} \), before a dc voltage limiter and then subtract it again after the limiter, the controls will not take the local dc voltage outside the allowed dc voltage range.

Assume that there are \( n_p \) converters on pilot voltage droop control and further denote this set of converters \( S^{\text{pilot}} \). For converter \( k \) belonging to this set we will, due to the PI control, at steady state have

\[
\left( P_{\text{PCC},k} - P_{\text{ref}, \text{PCC},k} \right) D_k + V_{\text{ref}, \text{dc, pilot}} - V_{\text{dc, pilot}} = 0, \quad k \in S^{\text{pilot}},
\]

assuming that the solution is within limits.

V. ESTIMATING POWER AND VOLTAGE DEVIATIONS

One reason for considering various types of droop control in the context of multi-terminal dc grids is the possibility to distribute a power mismatch on several converters, following some form of disturbance. The size of the individual droop constants will in general terms decide the distribution for all
droop concepts. One advantage with the pilot voltage droop concept is that the distribution of a power mismatch easily can be estimated for a given disturbance, and as a consequence a straightforward methodology to establish droop constants, as part of, e.g., day ahead planning, can be devised.

Let \( S^{\text{rest}} \) denote the set of converters in the dc grid that do not belong to \( S^{\text{pilot}} \). In general we may write
\[
\sum_{k \in S^{\text{rest}}} P_{\text{PCC},k} + \sum_{k \in S^{\text{pilot}}} P_{\text{PCC},k} + P_{\text{losses}} = 0,
\]
indicating that the sum of active power injected into the ac system at all converter PCCs plus losses in-between the PCCs should add to zero. If we sum (1) over all converters in the set \( S^{\text{pilot}} \) we obtain
\[
\sum_{k \in S^{\text{pilot}}} P_{\text{PCC},k} = \sum_{k \in S^{\text{pilot}}} P_{\text{ref},k}^{\text{a}} - \left( V_{\text{dc},\text{pilot}}^{\text{ref},a} - V_{\text{dc},\text{pilot}}^{b} \right) \sum_{k \in S^{\text{pilot}}} \frac{1}{D_k},
\]
and (3) inserted in (2) gives
\[
\sum_{k \in S^{\text{pilot}}} P_{\text{PCC},k} = \sum_{k \in S^{\text{pilot}}} P_{\text{PCC},k}^{\text{pilot}} + P_{\text{losses}} = \left( V_{\text{dc},\text{pilot}}^{\text{ref},a} - V_{\text{dc},\text{pilot}}^{b} \right) \sum_{k \in S^{\text{pilot}}} \frac{1}{D_k}.
\]
Consider an operating point, \( a \), where
\[
\sum_{k \in S^{\text{pilot}}} P_{\text{PCC},k}^{\text{ref},a} + \sum_{k \in S^{\text{pilot}}} P_{\text{PCC},k}^{\text{pilot}} + P_{\text{losses}} = \left( V_{\text{dc},\text{pilot}}^{\text{ref},a} - V_{\text{dc},\text{pilot}}^{b} \right) \sum_{k \in S^{\text{pilot}}} \frac{1}{D_k} = 0,
\]
i.e., where the voltage error is zero. Let us then initially consider a trip of a converter in the set \( S^{\text{pilot}} \).

A. Trip of converter on pilot voltage droop

At operating point \( b \) we assume that converter \( h \in S^{\text{pilot}} \) has tripped such that we have
\[
\sum_{k \in S^{\text{pilot}}} P_{\text{PCC},k}^{\text{ref},a} + \sum_{k \in S^{\text{pilot}}} P_{\text{PCC},k}^{\text{pilot}} + P_{\text{losses}} = \left( V_{\text{dc},\text{pilot}}^{\text{ref},a} - V_{\text{dc},\text{pilot}}^{b} \right) \sum_{k \in S^{\text{pilot}}} \frac{1}{D_k} \neq 0,
\]
where \( S^{\text{pilot}} \) is the set of pilot voltage droop controlled converters except \( h \). Forming the difference between the two operating points we obtain
\[
-P_{\text{PCC},h}^{\text{ref},a} + \sum_{k \in S^{\text{pilot}}} \left( P_{\text{PCC},k}^{\text{pilot}} - P_{\text{PCC},k}^{a} \right) + P_{\text{losses}} - P_{\text{losses}} =
\]
\[
\left( V_{\text{dc},\text{pilot}}^{\text{ref},a} - V_{\text{dc},\text{pilot}}^{b} \right) \sum_{k \in S^{\text{pilot}}} \frac{1}{D_k}.
\]
As a first step, we may simplify this expression by assuming that the losses remains essentially the same, i.e.,
\[
P_{\text{losses}} - P_{\text{losses}} \approx 0.
\]
As a second step, we may assume that the set \( S^{\text{rest}} \) only contains converters on constant active power control or frequency control (as would typically be the case for converters connected to wind farms). Assuming that the wind remains constant during the time it takes to reach the new steady state, these two types of control have in common that the power remains constant, i.e.,
\[
\sum_{k \in S^{\text{rest}}} \left( P_{\text{PCC},k}^{b} - P_{\text{PCC},k}^{a} \right) = 0.
\]
It follows that the pilot voltage deviation can be estimated as
\[
V_{\text{dc},\text{pilot}}^{\text{ref},a} - V_{\text{dc},\text{pilot}}^{b} \approx \frac{P_{\text{PCC},a}^{\text{pilot}}}{\sum_{k \in S^{\text{pilot}}} \frac{1}{D_k}},
\]
and, if this is inserted in (1), we can estimate the power deviation for the converters at pilot voltage droop control as
\[
P_{\text{PCC},k}^{b} - P_{\text{PCC},k}^{a} \approx \frac{P_{\text{PCC},k}^{\text{ref},a}}{\sum_{k \in S^{\text{pilot}}} \frac{1}{D_k}}, \quad k \in S^{\text{pilot}}.
\]

B. Changes in power in other converters

In the following we maintain the assumption that the set \( S^{\text{rest}} \) only contains converters on constant active power control or frequency control as in the previous section. However, in this section we assume that the power mismatch is due to changes in set \( S^{\text{rest}} \), e.g., due to trip of a converter or changes in wind power production. Let us define the total change in power in this set as
\[
\Delta P_{\text{rest}} = \sum_{k \in S^{\text{rest}}} \left( P_{\text{PCC},k}^{b} - P_{\text{PCC},k}^{a} \right).
\]
In a similar fashion as in the previous section it can be shown that the pilot voltage deviation can be estimated as
\[
V_{\text{dc},\text{pilot}}^{\text{ref},a} - V_{\text{dc},\text{pilot}}^{b} \approx -\frac{\Delta P_{\text{rest}}}{\sum_{k \in S^{\text{pilot}}} \frac{1}{D_k}},
\]
and the corresponding power deviation can be obtained as
\[
P_{\text{PCC},k}^{b} - P_{\text{PCC},k}^{a} \approx \frac{\Delta P_{\text{rest}}}{\sum_{k \in S^{\text{pilot}}} \frac{1}{D_k}}, \quad k \in S^{\text{pilot}},
\]
for the converters on pilot voltage droop control.

C. Methodology to establish droop constants

In the previous two section, estimates of pilot voltage deviation and power deviation for the converters on pilot voltage droop control have been presented given knowledge of the disturbance and the droop constants. These estimates can now be used to devise a methodology for determining the droop constants, e.g., as part of day ahead planning. In the following it is assumed that an “n-1” security criteria is applied, although it appears reasonable to assume (although it remains to prove) that it also can be modified to allow for more independent contingencies if so required.

In order to simplify the notation we introduce the quantity
\[
A_k = \frac{1}{D_k}, \quad k \in S^{\text{pilot}}.
\]
Next we introduce the load sharing constants, \( T_k \), defined as
\[
T_k = \frac{A_k}{\sum_{i \in S^{\text{pilot}}} A_i}, \quad k \in S^{\text{pilot}}.
\]
We may note that \( 0 < T_k < 1 \) and
\[
\sum_{k \in S^{\text{pilot}}} T_k = 1.
\]
It follows that we may only decide \( n_y - 1 \) load sharing constants \( T_y \), the last constant will be given by the circumstance that the sum should be one. We will in the following also use the relation

\[
\sum_{k \in S^{\text{pilot}}} \frac{1}{D_k} = \sum_{k \in S^{\text{pilot}}} A_k = \left(1 - T_y\right) \sum_{k \in S} A_k.
\]

Now, we may write the pilot voltage and power deviation for pilot voltage droop controlled converters as

\[
V_{\text{dc, pilot}}^{\text{ref}, a} - V_{\text{dc, pilot}}^b \approx -\frac{1}{\sum_{k \in S^{\text{pilot}}} A_k} \frac{P_{\text{PCC}, k}^{\text{ref}, a}}{1 - T_y},
\]

\[
(9)
\]

\[
P_{\text{PCC}, k}^{b} - P_{\text{PCC}, k}^{\text{ref}, a} \approx T_y \frac{P_{\text{PCC}, k}^{\text{ref}, a}}{1 - T_y}, \quad k \in S^{\text{pilot}},
\]

if a pilot voltage drooped converter is tripped, (5)-(6), and

\[
V_{\text{dc, pilot}}^{\text{ref}, a} - V_{\text{dc, pilot}}^b \approx -\frac{\Delta P_{\text{PCC}, k}^{b}}{\sum_{k \in S^{\text{pilot}}} A_k},
\]

\[
(10)
\]

\[
P_{\text{PCC}, k}^{b} - P_{\text{PCC}, k}^{\text{ref}, a} \approx T_y \Delta P_{\text{PCC}, k}^{b}, \quad k \in S^{\text{pilot}},
\]

if a constant power controlled converter is tripped, (7)-(8), (in which case \( \Delta P_{\text{PCC}, k}^{b} = P_{\text{PCC}, k}^{\text{ref}, a} \)), i.e., the power of the tripped converter at steady state prior to the trip).

Clearly, by deciding \( n_y - 1 \) load sharing constants \( T_y \), the portion of the power mismatch each converter on pilot voltage droop should pick up is decided. The remaining degree of freedom will be used to limit the maximum pilot voltage deviation for the set of credible contingencies (in this case in the n-1 sense). Let us denote this maximum as

\[
\Delta V_{\text{pilot}}^{\text{max}} \geq V_{\text{dc, pilot}}^{\text{ref}, a} - V_{\text{dc, pilot}}^b.
\]

(11)

Similarly, let us denote the maximum power imbalance that the pilot voltage droop controlled converters need to handle in the set of credible contingencies as

\[
P_{\text{PCC}, k}^{\text{max}} = \max_{k \in S^{\text{pilot}}} \left\{ \frac{P_{\text{PCC}, k}^{b}}{1 - T_y} \right\},
\]

(12)

where we may note that in this sense, tripping a pilot voltage droop controlled converter implies that the corresponding active power conversion loss is magnified due to the corresponding loss of a droop control contribution.

Based on the expressions for voltage deviation in (9) and (10), we can now write

\[
\sum_{k \in S^{\text{pilot}}} A_k = \frac{P_{\text{PCC}, k}^{\text{max}}}{\Delta V_{\text{pilot}}^{\text{max}}},
\]

and we can conclude that the last degree of freedom, in terms of selecting the size of the droop constants, can be used to limit the pilot voltage deviation following a credible contingency. The droop constants can now be obtained as

\[
D_k = \frac{1}{A_k} = \frac{1}{T_y} \sum_{k \in S^{\text{pilot}}} A_k \frac{\Delta V_{\text{pilot}}^{\text{max}}}{T_y P_{\text{PCC}, k}^{\text{max}}}, \quad k \in S^{\text{pilot}}.
\]

(13)

The methodology for selecting the droop constants can now be summarized as shown in Fig. 4.

Fig. 4. Methodology for establishing droop constants

As already stated, the methodology outlined above is based on an easily obtained, and accurate, estimation of the post-disturbance steady state, see also Section VI. The estimation assumes that limits, as implemented by various limiters in the control system, are not violated. If limits are violated, the accuracy of the estimates will certainly deteriorate.

The assumption that losses at pre- and post-disturbance steady state essentially are equal is typically a fairly good approximation. However, the assumption that the set \( S^{\text{pilot}} \) only can consist of converters on constant active power control or frequency control is of course a limiting factor. The extent to which the proposed methodology can be used also for other control concepts, e.g., other droop control concepts, remains to be established.

Finally, it should also be mentioned that the size of the droop constants also influences the dynamic performance of the control in terms of, e.g., settling time. Thus, a trade-off between, e.g., maximum pilot voltage deviation and settling time may be necessary in practice.

VI. SIMULATION RESULTS

As an example a small test system has been implemented together with the controls in a commercially available software platform, namely PowerFactory provided by the company Digsilent. Some hints on how to implement the controls on this platform can be found in [7]. First a brief description of the test system is provided.

A. Test system

A four station dc grid, Fig. 5, with bipole structure is used as the test system. The four stations are interconnected with four sets of cables. Each of the cable sets consists of positive pole, negative pole and metallic return cables. The neutral point system, to which the metallic return cables are connected, is
directly grounded at station 1. The ac system is represented with one ac voltage source connected to each station PCC. Each pole converter is rated 608 MVA and the nominal direct voltage is 320 kV (pole-to-ground). Station 1, 3 and 4 are configured to be on pilot voltage droop control, whereas station 2 is assumed to be connected to a wind farm which for the purpose of this test system is represented as a constant power controlled station. The converter voltages (positive and negative pole respectively) of station 4 are used as pilot voltage measurements.

The pre-disturbance operating point is shown in Table I, where \( P_{\text{PCC},p} \) and \( P_{\text{PCC},n} \) are the power in MW at PCC for positive and negative pole respectively (positive power corresponds to inverter operation). \( V_p, V_n \) and \( V_m \) are the positive pole to ground, negative pole to ground and mid-point to ground direct voltages in kV respectively.

**TABLE I**

<table>
<thead>
<tr>
<th>Station</th>
<th>( P_{\text{PCC},p} ) (MW)</th>
<th>( P_{\text{PCC},n} ) (MW)</th>
<th>( V_p ) (kV)</th>
<th>( V_n ) (kV)</th>
<th>( V_m ) (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+294.26</td>
<td>-303.99</td>
<td>-0.33</td>
<td>-303.99</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>-350.00</td>
<td>-350.00</td>
<td>-0.33</td>
<td>-307.29</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>-250.00</td>
<td>-250.00</td>
<td>-0.33</td>
<td>-306.35</td>
<td>0.00</td>
</tr>
<tr>
<td>4</td>
<td>+300.00</td>
<td>+300.00</td>
<td>-0.33</td>
<td>-303.94</td>
<td>0.00</td>
</tr>
</tbody>
</table>

It can be concluded that the pre-disturbance steady state corresponds to symmetric operation with 5.74 MW losses per pole. The power and pilot voltage deviations at pre-disturbance steady state are assumed to be zero, i.e., the power schedule is established. In other words, the power references are equal to actual power in column 2 and 3 in Table I and the pilot voltages are obtained as

\[
V_{\text{dc,pilot},p} = 303.94 - 0.0 = 303.94 \text{ [kV],}
\]

\[
V_{\text{dc,pilot},n} = 0.0 - (-303.94) = 303.94 \text{ [kV]},
\]

based on the voltages at station 4.

### B. Determining droop constants

In order to exemplify the methodology for establishing droop constants, we apply it to the test system. For clarity in terms of interpreting results, we assume that each of the three pilot voltage droop controlled converters have the load share constants \( T_p = 1/3 \). This gives the maximum power imbalance for respective pole as

\[
P_{p}^{\max} = P_{n}^{\max} = \max \begin{bmatrix} 294.26 & \cdot & -350 \cdot & -250 \cdot & 300 \\ 1 & 0.33 & 1 & 0.33 & 1 & 0.33 \end{bmatrix}
\]

\[
= 450.0 \text{ [MW].}
\]

Setting (more or less arbitrarily in this case) the maximum allowed pilot voltage deviation for the respective pole to \( \Delta V_{\text{pilot},p}^{\max} = \Delta V_{\text{pilot},n}^{\max} = 6 \text{ [kV]} \), we obtain the positive pole droop constants \( D_p = D_p = D_p = 0.04 \text{ [kV/MW]} \), and similar for the negative pole.

Next we will compare the estimated solution, which the droop scheduling methodology is based on, with time simulation results. First a pilot droop controlled converter is tripped.

### C. Trip of pilot droop controlled converter

Assuming that positive pole converter in station 1, which is on pilot voltage droop control, is tripped, the estimated control errors, i.e., power and pilot voltage deviations (9), would be according to Table II, where for respective pole

\[
\Delta P_p = P_{\text{PCC},p}^{\text{ref}} - P_{\text{PCC},p}^{\text{act}} \text{ [MW]},
\]

\[
\Delta V_{\text{pilot}} = V_{\text{dc,pilot}}^{\text{ref}} - V_{\text{dc,pilot}}^{\text{act}} \text{ [kV]},
\]

<table>
<thead>
<tr>
<th>Station</th>
<th>( \Delta P_{p,k} )</th>
<th>( \Delta P_{n,k} )</th>
<th>( \Delta V_{\text{pilot},p} )</th>
<th>( \Delta V_{\text{pilot},n} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>147.13</td>
<td>0</td>
<td>-5.89</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>147.13</td>
<td>0</td>
<td>-5.89</td>
<td>0</td>
</tr>
</tbody>
</table>

Thus, we expect that the negative pole converters would be undisturbed, as well as the positive pole converter on constant power control, whereas the two remaining positive pole converters on droop control would share the power mismatch equally (147 MW each) and that the magnitude of the pilot voltage deviation would be limited below 6 kV. For comparison, the same scenario is simulated in PowerFactory.

Fig. 6 shows active power in per unit at the respective PCCs for the 4 stations. At \( t=3 \text{ s} \), positive pole converter in station 1 is tripped. Station 2, which is on constant active power control returns to pre-disturbance power after a short transient. Positive pole converters in station 3 and 4 on pilot voltage droop control changes their positive pole power to accommodate for the power mismatch.
Table III gives the post-disturbance operating point as obtained from the time simulation. It can be concluded that the post-disturbance steady state corresponds to asymmetric operation with 9.37 MW losses for the positive pole and 7.03 MW losses for the negative pole. The control errors obtained at \( t=15 \) s (approximately post-disturbance steady state) are shown in Table IV.

### TABLE III
Post-Disturbance Operating Point

<table>
<thead>
<tr>
<th>Station</th>
<th>( P_{\text{PCC},p} )</th>
<th>( P_{\text{PCC},n} )</th>
<th>( V_p )</th>
<th>( V_n )</th>
<th>( V_m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00</td>
<td>+293.81</td>
<td>318.12</td>
<td>-299.76</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>-350.00</td>
<td>-350.00</td>
<td>319.24</td>
<td>-303.10</td>
<td>2.21</td>
</tr>
<tr>
<td>3</td>
<td>-104.65</td>
<td>-250.45</td>
<td>316.99</td>
<td>-302.15</td>
<td>3.50</td>
</tr>
<tr>
<td>4</td>
<td>+445.35</td>
<td>+299.55</td>
<td>313.92</td>
<td>-299.75</td>
<td>4.17</td>
</tr>
</tbody>
</table>

Comparing Table II and Table IV it can be concluded that estimated and simulated results agree quite well. The main reason for the small differences is the change in losses.

Next we consider a trip of a constant active power controlled converter.

#### D. Trip of constant active power controlled converter

Returning to the pre-disturbance operating point shown in Table I, we assume that positive pole converter in station 2 on constant active power control is tripped instead. Table V gives the estimated control errors (10) for this case.

### TABLE V
Estimated Post-Disturbance Control Errors

<table>
<thead>
<tr>
<th>Station</th>
<th>( \Delta P_p )</th>
<th>( \Delta P_n )</th>
<th>( \Delta V_{\text{pilot},p} )</th>
<th>( \Delta V_{\text{pilot},n} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-116.67</td>
<td>0</td>
<td>4.67</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>-116.67</td>
<td>0</td>
<td>4.67</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>-116.67</td>
<td>0</td>
<td>4.67</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>-116.67</td>
<td>0</td>
<td>4.67</td>
<td>0</td>
</tr>
</tbody>
</table>

Thus, the negative pole converters are assumed to be undisturbed, whereas the three positive pole converters on pilot voltage droop control share the power mismatch equally with the magnitude of the pilot voltage deviation being less than 6 kV. Again, for comparison, the same scenario is simulated in PowerFactory.

### TABLE V
Simulated Post-Disturbance Control Errors

<table>
<thead>
<tr>
<th>Station</th>
<th>( \Delta P_p )</th>
<th>( \Delta P_n )</th>
<th>( \Delta V_{\text{pilot},p} )</th>
<th>( \Delta V_{\text{pilot},n} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-116.62</td>
<td>-0.91</td>
<td>+4.66</td>
<td>+0.04</td>
</tr>
<tr>
<td>2</td>
<td>-116.62</td>
<td>+0.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>-116.62</td>
<td>-0.91</td>
<td>+4.66</td>
<td>+0.04</td>
</tr>
<tr>
<td>4</td>
<td>-116.62</td>
<td>-0.91</td>
<td>+4.66</td>
<td>+0.04</td>
</tr>
</tbody>
</table>

Comparing Table V and Table VI it can be concluded that estimated and simulated results agree very well.

Next, a situation where a limiter is activated is considered.

#### E. Trip followed by limiter action

In order to illustrate the behavior when a limiter is hit, we may consider the case in Section VI.C, but increase the voltage at the pre-disturbance operating point such that the maximum voltage limiter is activated following the disturbance. It is here assumed that the maximum converter voltage limit is 1 per unit, i.e., 320 kV. The pre-disturbance operating point is shown in Table VII, where it can be noted that the pole voltage magnitudes are higher (and losses slightly lower) as compared with Table I.

### TABLE VII
Pre-Disturbance Operating Point

<table>
<thead>
<tr>
<th>Station</th>
<th>( P_{\text{PCC},p} )</th>
<th>( P_{\text{PCC},n} )</th>
<th>( V_p )</th>
<th>( V_n )</th>
<th>( V_m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+294.43</td>
<td>+294.43</td>
<td>308.79</td>
<td>-308.79</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>-350.00</td>
<td>-350.00</td>
<td>312.04</td>
<td>-312.04</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>-250.00</td>
<td>-250.00</td>
<td>311.11</td>
<td>-311.11</td>
<td>0.00</td>
</tr>
<tr>
<td>4</td>
<td>+300.00</td>
<td>+300.00</td>
<td>308.74</td>
<td>-308.74</td>
<td>0.00</td>
</tr>
</tbody>
</table>

The estimated post-disturbance control errors will still be the same as in Table II.

Simulating the scenario, where positive pole converter in station 1 is tripped at \( t=3 \) s, the post-disturbance operating point as obtained at \( t=15 \) s is shown in Table VIII.
TABLE VIII
Post-Disturbance Operating Point

<table>
<thead>
<tr>
<th>Station</th>
<th>$P_{PCC,p}$</th>
<th>$P_{PCC,s}$</th>
<th>$V_p$</th>
<th>$V_s$</th>
<th>$V_m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.00</td>
<td>+293.91</td>
<td>321.62</td>
<td>-304.81</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>-307.50</td>
<td>-350.00</td>
<td>322.44</td>
<td>-308.09</td>
<td>2.44</td>
</tr>
<tr>
<td>3</td>
<td>-125.03</td>
<td>-250.52</td>
<td>320.79</td>
<td>-307.16</td>
<td>3.17</td>
</tr>
<tr>
<td>4</td>
<td>+424.97</td>
<td>+299.48</td>
<td>317.66</td>
<td>-304.79</td>
<td>3.92</td>
</tr>
</tbody>
</table>

It can be noted that positive pole converter in station 2 is at the maximum converter voltage limit (322.44-2.44=320.0 kV), and that the converter no longer maintains constant active power control. The control errors obtained at t=15 s are shown in Table IX.

TABLE IX
Simulated Post-Disturbance Control Errors

<table>
<thead>
<tr>
<th>Station</th>
<th>$\Delta P_{p,h}$</th>
<th>$\Delta P_{n,h}$</th>
<th>$\Delta V_{pilot,p}$</th>
<th>$\Delta V_{pilot,n}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>-0.52</td>
<td>-</td>
<td>+0.02</td>
</tr>
<tr>
<td>2</td>
<td>+42.50</td>
<td>+0.00</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>+124.97</td>
<td>-0.52</td>
<td>-5.00</td>
<td>+0.02</td>
</tr>
<tr>
<td>4</td>
<td>+124.97</td>
<td>-0.52</td>
<td>-5.00</td>
<td>+0.02</td>
</tr>
</tbody>
</table>

Again, the positive pole converter in station 2 is at its maximum converter voltage limit and cannot maintain constant active power control, and instead reduces the power (in absolute terms) such that a control error is obtained. The power deviations of positive pole station 3 and 4 are as a consequence reduced and so is also the magnitude of positive pole pilot voltage error, as compared to the estimate in Table II. However, we can conclude that the positive pole pilot voltage droop controlled converters continues to share the power mismatch according to their load share constants (in this case equally) although the total power mismatch the droop controlled converters need to handle is reduced due to the activation of the limiter in station 2.

In other words, the estimate is not very accurate any longer, but the basic feature of sharing the power mismatch according to the droop constants in a precise manner remains true for the pilot voltage droop controlled converters that are within limits.

VII. CONCLUSIONS

A methodology for establishing droop constants for a power drooped against pilot converter dc voltage is proposed in this paper. The methodology was derived based on the basic control law for pilot voltage droop control and the methodology was validated through numerical simulations. It can be concluded that the estimate of power and pilot voltage deviation are quite accurate, at least as long as no limits are violated. Furthermore, it is concluded that even if some limits are violated, and the estimates thus become less accurate, the converters on pilot voltage droop control that remain within limits will continue to share the power mismatch according to their droop constants.

VIII. REFERENCES


IX. BIOGRAPHIES

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