T.K. Vrana, J. Beerten, R. Belmans and O.B. Fosso, “A classification of DC node voltage control methods for HVDC grids,” *Electric Power Systems Research*, vol. 103, pp. 137–144, Oct. 2013.

Digital Objective Identifier: [10.1016/j.epsr.2013.05.001](https://doi.org/10.1016/j.epsr.2013.05.001)

URL:

<http://www.sciencedirect.com/science/article/pii/S0378779613001193>

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A Classification of DC Node Voltage Control Methods for HVDC Grids

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Abstract:

In a DC grid, contingencies such as converter outages give rise to a current imbalance that is reflected in the DC node voltages in the grid. This imbalance has to be accounted for by changing the currents flowing in and out of the DC system. These DC node voltages can be directly influenced by controlling the DC current of the HVDC converter at that node. Different control strategies can be applied to balance the currents in a DC grid after a contingency.

In this paper, the different converter control strategies are introduced systematically, thereby aiming to provide a framework for classifying the different converter control strategies available in literature. It is discussed how all converter control strategies theoretically can be regarded as limiting cases of a voltage droop control. It is also explained how the different converter control concepts can be combined, leading to more advanced converter control schemes such as voltage margin control, dead-band droop control and undead-band droop control.

Based on the introduced converter control strategies, different grid control strategies are introduced and classified. The application of the advanced converter control strategies results in advanced grid control strategies and the advantages of those are discussed.

Keywords: HVDC; Power Converter; AC-DC Converter, Voltage Control; Droop Control; Meshed DC Grids; Dead-Band.

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1. Introduction

The academic community as well as transmission grid operators and manufacturers have gained a strong interest in meshed HVDC grids [1]. No system of this kind has ever been built, and the entire subject is a future vision and still subject to basic research. The drivers for this development are both technology push and demand pull. Improved semiconductors, increasing power ratings for AC/DC converters and the first prototypes of DC breakers put HVDC grids within reach. The widespread renewable energy development demands new solutions for electric power transmission, especially when it comes to remote offshore wind farms.

The first place where meshed HVDC grids could emerge is the North Sea [2]. In this region massive wind farm construction has started and is planned for the coming decades, and many of these farms will be far away from shore. These remote offshore wind farms require HVDC connections, since long distance subsea transmission is not suitable for AC. The large number of planned wind farms and HVDC links within the North Sea indicates that an integrated grid-based system solution will offer significant benefits (compared to a one cable per farm solution) [3][4][5][6]. The countries around the North Sea have agreed to build the North Sea Super Grid (NSSG) under the North Seas Countries Offshore Grid Initiative [7].

A second future application could be the European Super Grid. Although still more a vision than a project, the super grid concept has gained remarkable attention during the last years, since it could be of high relevance for the desired pan-European electricity market. A super grid, interconnecting various regions with their own generation mixes and load patterns, would be beneficial for a large-scale renewable energy development. A HVDC based electricity grid spanning over entire Europe is envisioned [8], with possible extensions to northern Africa [9].

Although many similarities exist, the working principles and operational characteristics of such a DC grid are

different from the ones in AC systems. The main differences result from the fact that no reactive current, reactive power and phase angle exist. Therefore the DC node voltages are the most important measure, which define the system state and the power flow. Since DC voltages are directly linked with DC currents, it makes sense to refer to a current balance in the DC system rather than a power balance as in an AC system.

This article aims at classifying the different node voltage control methods, which have been proposed in literature in the recent years. The control objectives and requirements and the steady state working conditions of DC node voltage control are discussed, while the actual control implementation is not covered. Slower control actions, like power rescheduling are not treated in this article. Mathematically, this means that no set-point changes are considered for DC voltage control. The focus is purely on DC voltage control as a means of active power balancing, similar to primary frequency control in AC systems.

2. HVDC Converter Control Requirements for Large DC Grids

The requirements for HVDC converters connected to large DC grids are substantially different from the state of the art control requirements for two-terminal HVDC schemes. Additional challenges arise when small AC islands like offshore wind farms are connected. The main requirements of large DC grids are explained in this section.

2.1. High Reliability

For all existing point-to-point HVDC systems, single component faults can degrade system performance and even lead to system shut down. A meshed HVDC grid, possibly integrating many gigawatts of generation units, has to be much more reliable, since its performance is essential for the connected AC grids.

2.2. Integration of Electrical Islands

Requirements of the HVDC converter control depend on what type of AC system they are connected to. It is expected that onshore power systems are more suited to contribute to balancing control, when compared to offshore wind farms. The wind farms can be considered to be electrical island with a large volatile power source. Hence, the offshore wind farm converters have much less flexibility with respect to controlling the power injection to the DC grid, as they need to deliver the wind power to the DC grid, in real time. Therefore, fewer possibilities exist for the wind farms to participate in the aforementioned balancing control, which has to be performed mainly by the onshore stations, which are connected to larger AC systems.

2.3. Plug and Play

The principle of “plug and play” is important, meaning the controls have to be defined in a general way. This takes into account the specifics of the DC grid dynamics, whilst assuring the interoperability of different types of converters. Meanwhile, these general control principles should include control specifics that can be different for each converter in a multi-vendor set-up, while not compromising the interoperability and overall functionality of the grid. This means that the general control principles of the first converters installed should be controlled in such a way, that its control outline would not be subject to change in the case where many more converters are added to the same DC system in the future.

2.4. Autonomous Converter Control

A loss of communication is always a possible threat. Therefore all converters must be able to survive with local measurements only. This is similar to onshore AC power systems, where primary frequency control ensures reliable system operation without the need for communication.

2.5. AC Grid Integration

When the DC grid interconnects different non-synchronized zones, it is possible to share the primary frequency reserves of these different zones by implementing an AC frequency control. If a significant part of the power that is supplied to the AC systems is coming from the DC grid, it is beneficial if the HVDC converters take part in the AC frequency control. In [10], a control scheme was presented to combine the aforementioned DC voltage control with an AC frequency control.

3. Basic Control Principles

All methods described in this article utilise local DC voltage measurements in order not to fully rely on external data for the control to work. However, the overall performance might be improved by using a common voltage signal for feedback, as proposed in [11].

In this article, positive current and power is defined as flowing out of the DC grid, which is coherent with the physical definitions of voltage, current and power. In power systems, a reverse convention is often in use, which might be more intuitive as production being positive and loads being negative. Given the definition on the DC side and the convention on the AC side, an HVDC converter in inverter mode has positive current and power and in rectifier mode negative. The direction reference is therefore consistently defined for both the AC and the DC

side. This leads to regular AC frequency droop curves having a negative slope, and DC voltage droop curves (e.g. Figure 2, Section 4) having a positive slope.

The control of the DC voltage shows a lot of similarities with frequency control in an AC power system. Whenever a deficit occurs in the current that flows in/out the DC grid, the voltage at the different nodes will immediately react to this change as a result of the capacitors and cable capacitance discharging or charging. This current deficit can occur, for example when a converter faces an outage. If the converter was exporting to the AC system, the outage will cause a current surplus leading to a voltage increase. On the contrary, if the converter was importing into the DC grid, the converter outage causes a current shortage leading to a voltage decrease. DC voltage can therefore be taken as a balance indicator, similar to AC frequency in AC power systems.

In AC systems however, the frequency is the same throughout the entire system. The active power flow on a line is observed through the phase angle. In DC systems, DC voltage is both influenced by the global balance as well as by the currents on the lines. Therefore DC voltage is not a true global measure and it is therefore more challenging to use the DC voltage as a reference for balancing control. Despite these difficulties in terms of control, the DC voltage still appears to be the best indicator for stable DC grid operation.

Based on the described behaviour, it is clear that the current balance has to be restored as soon as possible in order to keep the voltage from falling or rising. All control structures discussed further on in this article rely on the fact that the deviation with the controlled DC voltage (local measurement at each DC bus) is determined and corrected for by the control action, which come down to restoring the current balance.

Assuming a lossless system, all node voltages would be identical and the current balance can be directly rewritten as a power balance. In a real system, DC line losses will add to the power balance equation and cause a mismatch between imported and exported power. Still, the general phenomena are the same: A change in the power balance will cause the DC voltage to deviate.

There are two basic principles how DC voltage can be controlled: Current based control and power based control [12][13]. It is important to mention, that both current based control and power based control behave identically at the operating point. The larger the DC voltage deviates from the reference value, the larger the differences between power and current based control become.

3.1. Current Based Control

In a current-based control scheme, the relationship to be used to control the DC voltage is an I-V characteristic [14][15]. The main advantage of a voltage-current control characteristic is that it reflects linear

control behaviour in the sense that a voltage deviation will result in an equivalent current deviation. As the voltage is linked with charging or discharging the capacitive DC system, the control is linear and is the same for all voltage deviations from the reference value. The voltage power relation is consequently non-linear (parabolic).

Current based control can be directly linked with the DC network dynamics: The charging of the capacitances in the DC network relies on a linear current voltage relation, which has the physical unit Ω . This makes current based control somehow intuitive from a physical perspective as it has the same physical units as the DC line impedance.

3.2. Power Based Control

As an alternative to the current based control, the DC voltage control can be expressed in terms of active power, as discussed in [16][17][18]. The power voltage relation is here linear. Contrary to current based control, power based control shows non-linear (hyperbolic) control behaviour. One should take into account the fact that DC voltage control therefore is non-linear.

Power based control has the advantage that it is more intuitive from a power system perspective, where the focus often is on transmitted power. It is also somehow similar to power frequency control in AC systems. The power voltage relation would have a physical unit of $1/A$ or Ω/V , which does not have a direct intuitive physical meaning.

Power based control can easily be integrated with the existing vector control schemes, which is well suited to be used with the standard dq-current controllers used in VSC HVDC systems. As discussed in [19], it is also possible to use the current based control to create an AC current reference.

3.3. Converter and system limits

There are several limits for HVDC converter control. The 3 most important are briefly described here and shown in Figure 1. The values for the limits in the figure are chosen for good graphic illustrations and do not represent realistic HVDC converter limitations.

[Figure 1 about here.]

- *DC voltage limits:* The DC voltage has an upper and a lower limit. The upper limit is determined by the insulation of the switching components. The lower limit is more complex as it is based on a limitation of the modulation index, and it also depends on the converter topology and the converter control implementation. These details are out of scope of this article.
- *Power limits:* The active power has an upper limit. This power limit is caused by the semiconductor current limit, which limits the AC current and consequently the power (assuming a constant AC voltage). The power limit appears as a hyperbolic curve in the IV-curves, and as a straight vertical line in the PV-curves.
- *DC current limits:* The DC current has an upper limit, based on the current rating on the connected DC components. This appears as a straight vertical line in the IV-curves and as a straight line towards the axes intersection in the PV-curves. As the limits depend on the connected DC equipment, there is no general answer whether these limits can be reached: The lower voltage limit might be reached before the current limit is hit.

4. Basic Converter Control Strategies

In the previous section, emphasis has been put on how a converter can control the DC voltage control and the distinction that can be made based on the P-V or I-V relationship. In this section, it will be discussed how different control schemes can be approached as a generalised case of a voltage droop control. The discussion holds both for an I-V or a P-V based droop.

The control is complicated by the fact that the voltage in the DC grid varies as a result of the DC grid power flow. In order to obtain a certain power flow, the voltage set points have to be different for all converters and should reflect the steady-state power flow solution of the DC network.

The explanation provided in this section reflects the mathematical representation of the control objective in terms of droop characteristics. The actual implementation, however, does not necessarily rely on the proportional droop controller, as discussed below. The term “basic strategies” refers to consistent control strategies, which do not depend on the operating point. The control strategies have only a single parameter, which is the droop value

or control gain. The control is therefore linear. The advanced control schemes in Section 5 can be seen as a combination of the three control types discussed in this section.

4.1. Voltage droop control (positive droop constant)

Voltage droop control creates a proportional relationship between the voltage and the control base (current or power) and is shown in Figure 2.

[Figure 2 about here.]

The droop constant is called k . The control base is indicated by the subscript “I” or “P”. The subscript “ref” indicating the voltage, current and power set-points, with the natural relationship: $P_{ref} = V_{ref} \cdot I_{ref}$. The voltage, current and power deviations are defined as: $\Delta V = V - V_{ref}$ and $\Delta I = I - I_{ref}$ and $\Delta P = P - P_{ref}$.

The I-V droop relation can be written as:

$$\Delta I_I = \frac{1}{k_I} \Delta V \quad (1)$$

Rewriting (1) in terms of active power yields the corresponding power equation which is parabolic:

$$\Delta P_I = \left(\frac{V_{ref}}{k_I} + \frac{P_{ref}}{V_{ref}} \right) \Delta V + \frac{1}{k_I} \Delta V^2 \quad (2)$$

The expression for the P-V droop relation is similar to (1), namely:

$$\Delta P_P = \frac{1}{k_P} \Delta V \quad (3)$$

Rewriting (3) in terms of current yields the corresponding current equation which is hyperbolic:

$$\Delta I_P = \left(\frac{1}{k_P} - I_{ref} \right) \frac{\Delta V}{\Delta V + V_{ref}} \quad (4)$$

The slope of the I-V or P-V characteristic is determined by the droop value, which is the inverse of the proportional controller gain. The droop value k in these equations stems with the slope of the characteristics in Figure 1, and is the inverse of the proportional controller gain used in the actual implementation. The stability of the droop controller depends on the droop value and the actual implementation. If well designed, the voltage droop control leads to a stable operation. When a contingency occurs, the droop control is characterised by a steady-state deviation from the voltage reference as a result of the proportional control action.

4.2. Constant flow control (infinite droop constant)

Constant flow control means constant current control and constant power control (depending on the control base) and can respectively be represented as a vertical line segment in the I-V and P-V plane. Mathematically, the constant flow control can be expressed as a limiting case of the aforementioned voltage droop, with a droop constant equal to infinity, thereby not changing the current/power flow whenever the DC voltage changes. The converter will, at all cost try to maintain the current/power injection constant, irrespective of the value of the DC voltage at its DC bus.

Figure 3 shows the characteristic curves for both constant flow control types in the P-V and I-V plane. Constant current control leads to a linear behaviour in the P-V plane. Constant power control leads to hyperbolic behaviour in the I-V plane.

[Figure 3 about here.]

In reality, however, constant flow control is implemented using a PI-controller to keep the current/power equal to its reference value. This is due to dynamic reasons, but theoretically, this comes down to the limiting case of an infinity droop value.

4.3. Constant voltage control (zero droop constant)

Constant voltage control can be represented as a horizontal curve in the I-V or P-V plane (Figure 4). The DC voltage control can be regarded as the limiting case for which the droop constant goes to zero. From Equation (1) and (3), it is clear that the converter in this case controls the voltage limit to its reference value. In Figure 4 no distinction between current and power based control is shown, since the curves are identical. A converter with this type of control is often referred to as a DC slack bus.

[Figure 4 about here.]

This control modus relates to a proportional control gain of infinity. This of course is unrealistic and will lead to instability. Constant voltage control is therefore in reality not realised with an infinite gain, but with a PI controller. In theoretic steady state the outcome is the same, but due to dynamic reasons, the infinite control gain is not viable.

5. Advanced Converter Control Strategies

In this section control methods are covered, that cannot be described by a single control parameter. They are therefore nonlinear, or to be more precise piecewise-linear. The actual control behaviour depends on the operating point, thereby making a distinction between normal and disturbed operation. The advanced converter control strategies behaviour changes when large disturbances occur.

5.1. Voltage Margin Control

Voltage margin control has first been proposed for DC networks in [20] and later been applied and developed further in [21][22]. It is a combination of constant current/power control and constant voltage control. A converter with voltage margin control normally operates in constant current/power control modus (as long as the voltage is within the normal operation voltage margin). If the voltage deviation reaches the limit of the voltage margin, the converter controller switches to constant voltage control, clamping the voltage at the margin limit to prevent further voltage deviation. This is shown in Figure 5.

[Figure 5 about here.]

5.2. Dead-Band Droop Control

Another advanced control strategy is droop control with an additional dead-band [23]. Just like with voltage margin control, the converter operates at constant current/power control modus as long as the voltage is within the normal operation band or margin. If the voltage deviates to the limit of the dead-band, the controller switches to droop control. Voltage margin control can be seen as the limiting case of dead-band droop control with a zero

droop constant. This is shown in Figure 6.

[Figure 6 about here.]

5.3. *Undead-Band Droop Control*

Another approach to DC voltage control, the so-called undead-band droop control, has been proposed in [24] and developed further in [25]. The control is fully based on voltage droop, but distinguishes between normal and disturbed operation by defining different droop constants for these two operation regimes. It offers the possibility to optimise the droop constants and the overall control separately for normal and disturbed operation. This is shown in Figure 7. A similar concept has been proposed in [26].

[Figure 7 about here.]

The definition of undead-band droop control is most general, and all the other mentioned control methods can in fact be considered as specific examples of parameter sets of undead-band droop control. For example, dead-band droop control can be seen as the limiting case of undead-band droop control with an infinite droop constant (constant current/power) under normal operation. Similarly, voltage margin control can be seen as the limiting case of undead-band droop control with an infinite droop constant under normal operation (constant current/power) and a zero droop constant under disturbed operation (constant voltage). Regular droop control can be seen as the limiting case of undead-band droop control with the same droop constant in both operation modes.

Also other strategies, not mentioned in this article, can be perceived accordingly. As a compliment to dead-band droop control, a zero droop constant under normal operation (constant voltage) can be combined with droop control under disturbed operation. Unlike a dead-band, where the converter does not react on voltage changes, this scheme keeps the voltage constant under normal operation [27]. Another possible variation is a controller with droop control under normal operation and with zero droop (constant voltage) under disturbed operation [28].

6. Basic Grid Control Strategies

In general, the DC voltage can be controlled to its reference value at one centralised voltage-controlling converter or by using a distributed control approach. The basic grid control strategies discussed in this section are based on the basic converter control strategies from section 4.

6.1. Centralised Voltage Control

One converter has a droop value of zero, controlling a constant DC voltage at its bus (Section 4.3), thereby acting as a DC slack bus. The other converters have a droop value of infinity (Section 4.2) and control their current/power to the setpoint. The control concept is similar to the normal operation of a point-to-point VSC HVDC system.

Centralised voltage control gives rise to a well-defined operating point, since all but one converters operate at their current/power set-points. This strategy can hold for quite large networks under normal operating conditions. Since only one converter has to account for all disturbances within a grid, this method would only be applicable for relatively small fluctuations around the operation point in a larger system. With increasing network size, current/power fluctuations increase as well, thereby finally limiting the applicability of centralised voltage control. This type of operation would also have a significant influence on the AC system connected to that converter.

The most critical problem, however, is how to handle severe disturbances such as an imbalance, which exceeds the capabilities of the slack bus or the outage of the DC slack bus, for which no back-up control is provided.

6.2. Distributed Voltage Control

Distributed balancing control is applied to all large AC power systems and it is therefore a natural thought to consider this control method for DC power systems as well [29]. Distributed voltage control is implemented by applying droop control to all converters (Section 4.1).

It is not necessary that all converters take part in the control of the DC voltage. Droop controlled converters and current/power controlled converters can easily be integrated into the same DC grid. This is similar in AC grids, where some power stations take part in primary frequency control while others do not.

The integration of voltage controlled converters could cause problems: Similar to a frequency droop in AC systems, the power sharing amongst different droop controlled converters is determined by the relative droop

values of the different converters. The smaller the droop value, the higher the share of a particular converter in the power sharing. A voltage controlling converter can be considered as the limiting case for the droop constant going to zero, thereby significantly reducing the power sharing of the other converters. In this way, adding a voltage controlling converter would partly undermine the distributed control principle of droop control. In this case only the changes in the voltage drops on the lines determine the changes in the operation points of the droop controlled converters, leading to small control contributions.

7. Advanced Grid Control Strategies

The advanced grid control strategies are based on the advanced converter control strategies from section 5. Compared to the basic strategies the main difference is the inclusion of back-up mechanisms to handle large disturbances. For distributed voltage control, this back-up is an improvement, while for centralised voltage control, it is a necessity as illustrated in section 6.

7.1. Centralised Voltage Control with Centralised Back-Up

The back-up system for the centralised control method can be implemented with the centralised approach as well. That means that a converter that normally controls current/power switches to voltage control to take over the task from the regular voltage controlling converter. The modification from centralised voltage control is to replace the converter controllers with constant current/power control with voltage margin control.

If the voltage deviates significantly (i.e. the voltage controlling converter fails to do his task), a converter with voltage margin control hits the limit of the voltage margin and turns into a new DC slack bus and starts to control the DC voltage at the limit of the voltage margin. In this way, the task of the slack can be passed back and forth between converters many times.

For smaller DC systems, this control can be a good choice, as long as the converter ratings and the system rating are in the same range. One slack bus converter can be selected, but for extraordinary conditions other converters help out. This is similar to the real implementation used in point-to-point connections.

For large DC systems this method might pose problems. With increasing system size, operation modulus changes will appear more often. This creates highly nonlinear system behaviour, where local voltage measurements lose its information on the general system state. Furthermore, when more converters participate in the voltage margin control, the number of voltage steps increases, which might give rise to voltage deviations that are too large. These two factors make it complicated to oversee and therefore control the network.

7.2. Centralised Voltage Control with Distributed Back-Up

A better way to provide a back-up mechanism for centralised voltage control for large DC grids is to use dead-band droop control instead of voltage margin control. If the voltage controlling converter fails, the voltage control task is not transferred to another converter (as with voltage margin control), but to all other converters with a distributed approach. At larger disturbances, the consequences are split among all converters leading to a new stable operating point.

Compared to voltage margin control, this method can provide an improvement when it comes to handling large disturbances. However, it still faces similar problems under normal operation for very large power systems, where the converter ratings are very small compared to the system rating. The regular power fluctuations increase with system size, eventually exceeding the capability of one single converter, and therefore operation outside the dead-band is likely to become more frequent.

7.3. Distributed Voltage Control with Distributed Back-Up

Generally, the distributed voltage control can safely operate a DC grid without a back-up mechanism. But still, also with a distributed voltage control approach, it might be desirable make a distinction between normal and disturbed operation, e.g. stay close to the operation point under normal conditions, as discussed in [26], whilst having a back-up control with different settings. In this way, converters with droop control that contribute to voltage control can increase their contribution (lower droop value) in case of a severe disturbance. This can be implemented with undead-band droop control.

Similarly, current/power controlled converters that do not contribute to voltage control could in some cases be implemented as dead-band droop controlled converters, thereby also contributing to the voltage control back-up system.

8. Conclusion

The currents in and out of a DC grid can be balanced by controlling the node voltages within defined limits. The DC node voltage can be influenced by controlling the current/power of the HVDC converter at that node. To ensure secure operation of the DC grid, the control should be robust and reliable and to some degree distributed and autonomous. It should also be flexible and easily expandable.

In this paper three overall converter control strategies are systematically introduced: constant voltage control, constant power/current control and voltage droop control. It has been discussed to which extent these control

strategies comply with or compromise the control requirements. It has been discussed that the constant current/power control and constant voltage control characteristics theoretically can be regarded as limiting cases of the droop control. The control concepts can be combined, leading to more advanced converter control strategies such as voltage margin control, dead-band droop control or undead-band droop control. These advanced converter control strategies distinguish between normal and disturbed operation.

Based on the introduced basic converter control strategies, two basic grid control strategies are introduced and classified: Centralised and distributed voltage control. The application of the advanced converter control strategies results in advanced grid control strategies, which have a back-up system to handle large disturbances.

Acknowledgement

Jef Beerten is funded by a research grant from the Research Foundation – Flanders (FWO).

The authors would like to thank Luke Livermore (Cardiff University) and Pierre Rault (L2EP, Ecole Centrale of Lille) for their input and support.

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List of Figures

1. Converter and system limits
2. I-V curve and P-V curve for droop control
3. I-V curve and P-V curve for constant flow control
4. I-V curve and P-V curve for constant voltage control
5. I-V curve and P-V curve for voltage margin control
6. I-V curve and P-V curve for dead-band droop control
7. I-V curve and P-V curve for undead-band droop control

Figure 1:

Figure 2:

Figure 3:

Figure 4:

Figure 5:

Figure 6:

Figure 7: