Active Power Control with Undead-Band Voltage & Frequency Droop for HVDC Converters in Large Meshed DC Grids

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Active Power Control with Undead-Band Voltage & Frequency Droop for HVDC Converters in Large Meshed DC Grids

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Abstract:

A new control method for large meshed HVDC grids has been developed, which helps to keep the active power balance at the AC and the DC side. The method definition is kept wide, leaving the possibility for control parameter optimisation. Other known control methods can be seen as specific examples of the proposed method. It can serve as a framework for the control of large DC grids, defining a common standard for the control scheme, but still leaving a lot of freedom for individual adjustments.

The proposed method is based on a so called “undead”-band, meaning that control activity is reduced within the band, but not set to zero as with a regular dead-band. It operates with a minimum of required communication. New converters can be added to the system without changing the control of the other individual converters. It is well suited to achieve high reliability standards due to the distributed control approach.

Keywords:

HVDC, Power Converter, Control, Droop, Meshed DC Grids, Dead-Band

1. Introduction

The scientific community as well as transmission grid operators and manufacturers have gained strong interest in meshed HVDC grids. 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 first prototypes of DC breakers seem to make HVDC grids feasible. 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 [1]. In this region massive wind farm construction has started and will take place in the next 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 a grid solution will offer significant benefits (compared to a one cable per farm solution) [2][3][4][5]. The countries around the North Sea have agreed to build the North Sea Super Grid (NSSG) under the North Seas Countries Offshore Grid Initiative [6].

Even though subsea long distance transmission has to be DC, wind farm collection grids are realised with AC nowadays. The NSSG will therefore not be purely DC, but a hybrid AC/DC grid, containing AC islands [1].

This article is on active power control of HVDC converters in a large meshed DC grid. A grid is meant to be large when any single power converter is very small compared to the total rating of all converters. The requirements for HVDC converters connected to large DC grids are substantially different from the state of the art of point to point connections. Additional challenges arise when small AC islands like offshore wind farms are connected, due to the interaction of two or more HVDC converters with comparable power ratings.

The main requirements are:

- High reliability
- Integration of uncontrolled electrical islands
- Distributed balancing control
- Plug and play
- Robustness against communication faults
- Consideration of DC voltage drop
- AC frequency support
- Robustness against manipulation
- Satisfying dynamic performance and stability

Several methods for DC voltage control have been proposed:

- Direct voltage control (Master/Slave control)
- Voltage margin control [7]
- Droop control [8]
- Dead-band droop control

For very small DC grids, the principles used for point to point HVDC connections (direct voltage control) can be adopted to serve their purpose, but will likely create problems with larger systems. Voltage margin control is based on direct voltage control, but extends the possibilities to somehow larger systems. Droop control is suitable for really large networks, but it does not separate between normal and disturbed operation. This issue can be partly solved by adding a dead-band, but this can create problems for very large systems.

To overcome the mentioned disadvantages of the existing DC voltage control methods regarding large DC grids, a new method has been developed and is proposed in this article. It combines the advantages of the other methods and also integrates AC frequency support [9]. The developed control strategy is designed to work for smaller systems that might be built in the near future, but it also can work for any size of HVDC grid, to avoid problems with future system expansions. It is tested on a small network with DIgSILENT Power Factory. Short term phenomena like switching transients and short circuits are not treated in this article. Long term power flow optimisation is neither part of the proposed method. The proposed control strategy's purpose is to keep the active power balance in the seconds-time-scale, similar to primary frequency control in AC systems.

2. Undead-Band Droop Control

The developed control strategy is mostly based on local measurements. The only external inputs are the setpoints for DC voltage and active power which have to be determined centrally. A DC grid system controller is used to determine the desired system flow. It determines the setpoints for active power and DC voltage and transmits them to all converters. This procedure is similar when other control methods are applied.

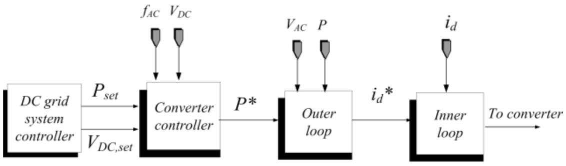

Figure 1. Overall block diagram for undead-band control.

Fig. 1 illustrates the control structure. The converter controller, which is described in this article, builds the active power reference, based on the received setpoints and local measurements of DC voltage and AC frequency. The proposed DC voltage control is treated in Section 2.1, AC frequency control in Section 2.2 and the combined control in Section 2.3. The outer loop is subject to future research and will take system dynamics into account. This is important to handle high steady state gains outside the undead-band. The inner loop is a standard current controller.

2.1. Undead-Band Voltage Droop Control

The main principle is similar to dead-band droop control, where control is significantly different in normal system operation and under extraordinary conditions.

The droop constant, giving droop control its name, is generally defined as the inverse of the proportional control gain parameter. This inverse definition is not intuitive from a control perspective and is therefore not used in this article. Converter control is described with proportional control gain parameters or K-values.

For undead-band droop control, all controllers have two separate K-values, for the two types of operating conditions ($\mathrm{K}_{\mathrm{v},1}$ for normal and $\mathrm{K}_{\mathrm{v},2}$ for disturbed operation).

During normal operation the system is controlled, using the $\mathrm{K}_{\mathrm{v},1}$ parameter. This is similar to normal droop control, but the K-value can be chosen more freely, since it is only being applied under normal operation. For regular droop control, K-values have to be selected in a way, that they can also handle large disturbances. The “optimal” K-value might not be the same for normal operation and disturbed operation, and while regular droop control needs to find a compromise, the $\mathrm{K}_{\mathrm{v},1}$ value can fully be optimised for normal operation. This is especially important if small and weak AC islands (like offshore wind farms) are to be relieved from the burden of system active power balancing under normal operating conditions.

At large disturbances, droop, dead-band droop and undead-band droop control behave similarly. All converters take their share in compensating the disturbance via their K-value ($\mathrm{K}_{\mathrm{v},2}$ for undead-band droop control). These shares, as well as the bands out of which $\mathrm{K}_{\mathrm{v},2}$ is active, do not necessarily need to be equal, but can depend on the converter rating and the strength of the connected AC bus. The $K_{v,2}$ parameter can be optimised for disturbed operation, as it is with dead-band droop control.

An interesting feature is that the developed control method includes all earlier mentioned control methods as possible examples of undead-band droop control parameter settings. This is shown in Table 1. The parameters A and B in the table are defined as $(0 < B < \infty)$ and $(0 \leq A \leq B)$. Zero relates to constant power operation and infinity relates to constant voltage operation.

For example, one converter having infinite $K_{v,1}$ while all others having zero $K_{v,1}$ would be exactly the same as normal dead-band droop control. For large power systems, several converters should have a non-zero $K_{v,1}$, to avoid the problems mentioned in Section 1. A few strong converters could carry the main load by having higher $K_{v,1}$ values, while the other converters could have smaller values (but not necessarily zero). The converters can be tuned individually, giving more freedom for system optimisation. Therefore the dead-band is called undead-band, since the control activity of the converters within the band is not fully dead, but only reduced.

Conv. 1		**Conv. 2**		**Conv. 3**		**Control Method**
$K_{v,1}$	$K_{v,2}$	$K_{v,1}$	$K_{v,2}$	$K_{v,1}$	$K_{v,2}$	
∞	∞	0	0	0	0	Direct Voltage
∞	0	0	∞	0	0	Voltage Margin
B	B	B	B	B	B	Droop
∞	B	0	B	0	B	Dead-Band Droop
B	B	A	B	A	B	Undead-Band Droop

Table 1. Comparison of control methods

Direct voltage control and droop control have the disadvantage, that normal and disturbed operation are treated identically and differentiated optimisation is not possible. Direct voltage control, voltage margin control and dead-band droop control have the disadvantage, that some of the parameters are set to zero and infinity, which again gives no freedom for optimisation.

For undead-band droop control, all parameters can be optimised freely. As already mentioned, any of the other control methods could be the result of the optimisation process. Still, the wanted differentiation between normal and disturbed operation, general concerns about control parameters being zero or infinity as well as the mentioned “one converter controls a large system”-problems should in many instances lead to a different outcome. An example of how the control parameters could look like is given in the following.

Power and Voltage limitations are given in Table 2. The power setpoint is in the range from -1 to 1 per unit, while a 10% converter overload capability is assumed. If the converter cannot be overloaded, the power setpoint has to be limited to a value smaller than 1 per unit, to achieve an operational margin.

The operation voltage of a DC grid is assumed to be limited from 0.8p.u. to 1.1p.u. [10]. The voltage setpoint is therefore limited from 0.9p.u. to 1.0p.u., to achieve the same 10% margin. Around the selected voltage setpoint a 2% tolerance is granted for voltage fluctuations in normal operation. A voltage deviation of more than 2% from the voltage setpoint is treated as disturbed operation.

	Min.	Max.
Power limitation	-1,1	1,1
Power setpoint	-1,0	1,0
Voltage limitation	0,8	1,1
Voltage setpoint	0,9	1,0
Voltage tolerance	-2%	+2%

Table 2. Power and voltage limitations

An example of how the power - DC voltage relation could look like is shown in Fig. 2 and the relating setpoints and K-values are given in Table 3. The values for voltage and power setpoint are arbitrarily chosen as an example. The $K_{v,1}$ and $K_{v,2}$ values are a proposal, but have not been optimised yet.

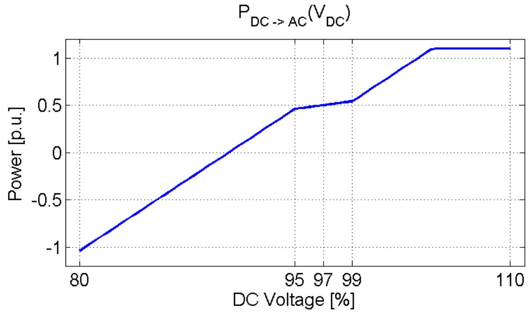

Figure 2. Power – DC voltage relation

V_{set}	0,97
V_{norm}	$0{,}97 \pm 0{,}02$
P_{set}	0,50
$K_{v,1}$	3
$K_{v,2}$	15

Table 3. Voltage setpoints and K-values

2.2. Undead-Band Frequency Droop Control

The same principles as introduced in Section 2.1 can be also used for AC frequency support. The power which is transferred by the HVDC converter therefore becomes a function of the AC frequency. Important is also the case sensitivity, if AC frequency is within the normal operation band, or if an extraordinary disturbance has occurred. The applied power limitations are the same as in Section 2.1

Since AC frequency is a global measure, the frequency setpoint for all converters is equal to 1p.u. (50Hz). The normal operation band of the AC frequency is given with a 0.4% (200mHz) tolerance in [11]. The disturbed frequency band is set with a margin of 2% (1Hz), to avoid load shedding and/or the disconnection of power plants. Power and frequency limitations are given in Table 4.

	Min.	Max.
Power limitation	-1,1	1,1
Power setpoint	-1,0	1,0
Frequency limitation	0,98	1,02
Frequency setpoint	1,0	
Frequency tolerance	-0,4%	+0,4%

Table 4. Power and frequency limitations

An example of how the power - frequency relation could look like is shown in Fig. 3 and the corresponding setpoints and K-values are given in Table 5. The value for the power setpoint is arbitrarily chosen as an example; the frequency setpoint is fixed. The $K_{f,1}$ and $K_{f,2}$ values are a proposal, but have not been optimised yet.

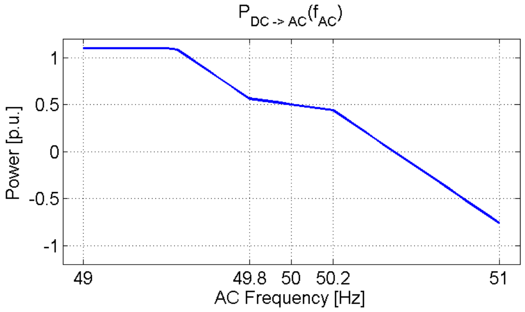

Figure 3. Power - frequency relation

f_{set}	1,00
f_{norm}	1,00 ± 0,004
P_{set}	0,50
$K_{f,1}$	−15
$K_{f,2}$	−75

Table 5. Frequency setpoints and K-values

2.3. Combined Voltage & Frequency Droop

To achieve a good control, both voltage and frequency droop should be used at the same time. The resulting control characteristic is shown in Fig. 4. The central square-shaped area with small slope is the normal operation area. The steeper band-shaped areas indicate disturbed operation with a higher K-value. The remaining very steep areas apply when both voltage and frequency are outside the tolerance. The totally flat areas at the top and bottom indicate the converters power limitation.

An active power reference change will have significant influence on the DC voltage, counteracting the initial change. Therefore the operating point is likely to move mostly left-right within the plane (the yellow area). The ratio between the frequency K-value and the DC voltage K-value defines how DC voltage and frequency are coupled.

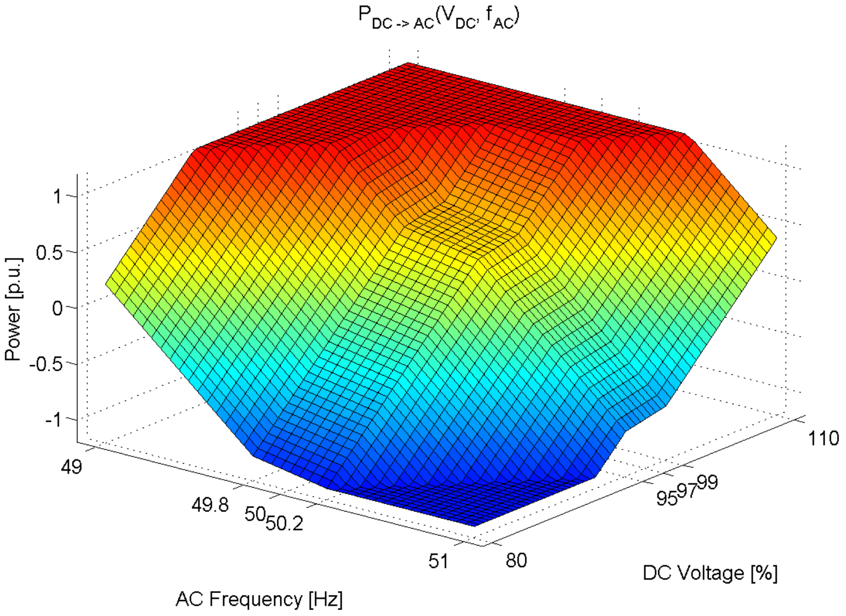

Figure 4. Complete control characteristic

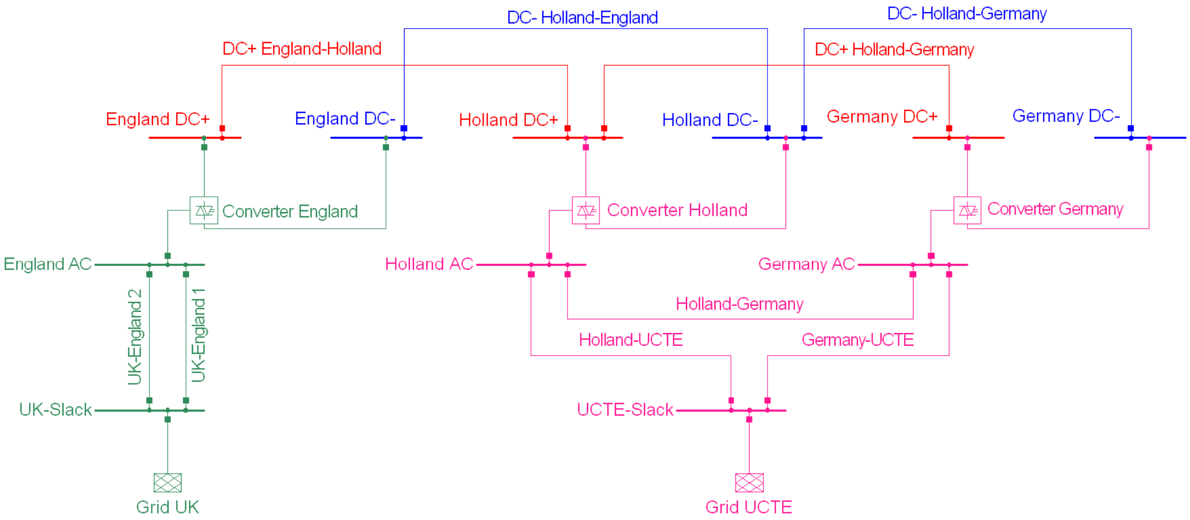

Figure 5. Test System

3. Simulation Results

The proposed control method has been implemented and tested in a simple model in the power system simulation tool DIgSILENT Power Factory, in order to achieve a first validation of the control principles and functionality of the undead-band controller.

The undead-band control has been inserted into the simple three-terminal model developed during a workshop at DTU Wind Energy in December 2011, within the OffshoreDC Nordic project. The basic model is freely usable and distributable under the GNU General Public License and is available at [12].

The grid layout that has been used in this work is the same as in the original model, while its control has been modified in order to perform the described undead-band action. A sketch of the test network is presented in Fig. 5.

In order to achieve a realistic scenario, a possible connection between continental Europe and England was represented, utilising two AC grids and three HVDC converters. Continental Europe is pink-coloured, England is green-coloured, while red and blue are used for positive and negative DC poles respectively.

The AC voltage level is 380 kV and the DC voltage is +/- 500 kV. Standard values for AC transmission lines parameters have been used and the resistance of the DC cables has been set to 0,012Ω/km.

The HVDC converters are thought to be located in England, Holland and Germany and are controlled differently as follows:

- England's converter is performing a usual droop-type control action on both frequency and DC voltage
- Holland's converter is operating as a fixed power injector, i.e. import/exporting a given fixed amount of active power
- Germany's converter is provided with the newly developed undead-band droop control

The base settings for initiating the test were so as to have a power import to England, mainly coming from Germany and partially supported by Holland. The dynamic steps applied during the simulation are regarding the power set-point for Holland's converter, following this sequence:

1. Reduction of power export at time t = 0s
2. Stop of power export at time t = 1s
3. Start of power import at time t = 2s

As a consequence, both England's and Germany's converter act based on their control strategy in order to accommodate the power unbalance. The variation of the DC voltage level at English and German terminals of the DC grid is shown in Fig. 6, while Fig. 7 depicts the variation in the power output of the two converters, illustrating the validity of the undead-band approach.

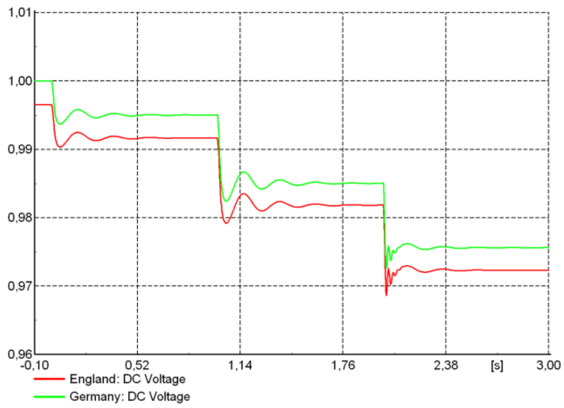

Figure 6. DC Voltage at Converter England (red) and Converter Germany (green)

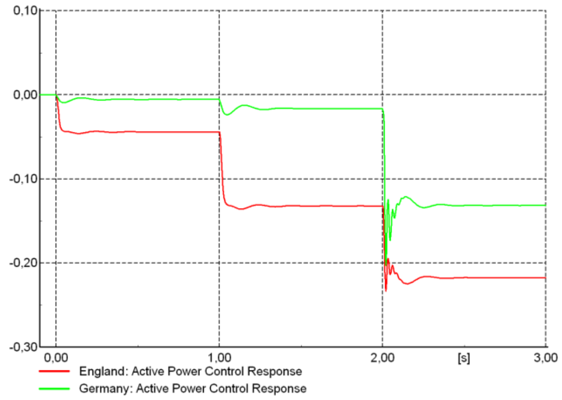

Figure 7. Controller responses

It can be seen that the principal regulating action, as long as the DC voltage remains within the undead-band, is coming from the reduction of power import of England's converter. On the other hand, when the voltage deviation becomes large enough, i.e. after step 3, Germany's converter intervenes more consistently by applying the larger K-value for disturbed operation and providing the desired control action to relieve the simply droop controlled converter from a part of the burden. Voltage deviations are limited to some extent.

The steady-state behaviour of the system is therefore as expected, demonstrating the validity of the approach. However, the dynamics can undoubtedly be improved by implementing a more advanced outer control loop, to effectively damp unwanted oscillations. This is however not the scope of the present study and is left for future work, where an optimisation of the parameters based on system's characteristics and taking into account both frequency and DC voltage control should take place.

4. Conclusion and Outlook

A new control method for large meshed HVDC grids has been developed, which helps to keep the active power balance at the AC and the DC side; even severe power imbalances can be handled. It is especially designed for large DC grids, where control is challenging compared to conventional HVDC systems with a small number of power converters. The method definition is kept wide leaving the possibility for control parameter optimisation. Other known control methods like droop control (with or without dead-band) can be seen as specific examples of the proposed method. The developed method can serve as a framework for the control of large DC grids, defining a common standard for the control scheme, but still leaving a lot of freedom for individual adjustments, based on manufacturers' preferences, converter topology, grid strength, etc.

The problem that no global balance indicator like AC frequency exists for DC grids is taken care of by the central DC grid controller by calculating the desired power flow and transmitting the resulting DC voltage setpoints to all converters. This way the issue is treated centrally, relieving the individual converters from having to deal with it. These converters control the active power based on the received power reference and local AC frequency and DC voltage deviations.

In a non-disturbed situation the converters follow the reference and the desired power flow is achieved. When active power balance is disturbed, AC frequency and/or DC voltage deviate, and the converters will change their active power, relieving the disturbance.

The proposed method operates with a minimum of required communication. A temporary loss of communication can be handled, since only the desired setpoints are transmitted, while the real references are determined locally. Even if wrong setpoints are received, stability is not necessarily lost; the central controller cannot directly force the converters to behave in a malicious way.

If new converters are to be added to the system, only the central system control has to be adapted, but the other individual converters can operate without changes.

The control method is well suited to achieve high reliability standards due to the distributed control approach. The integration of fluctuating power sources like wind farms is made possible in a stable way, since all converters take part in balancing, depending on their capabilities and limitations.

The control method takes also AC frequency into account; something that will gain increased importance with a growing share of HVDC connected generation units. If several asynchronous AC power systems are connected to the same DC grid (3 AC areas around the North Sea), the proposed control strategy automatically exchanges primary reserves between the AC systems. If the DC system contains energy storage, it is also automatically activated.

The next step of this research is to continue control method validation with computer simulations, to improve dynamic response and perform a parameter optimisation taking into account the system's characteristics and the coupling that can take place between DC voltage and AC frequency control. The inclusion of fluctuating production units like wind farms and their interfacing to the undead-band control will also be a topic for further research.

Acknowledgement

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