Dynamic behaviour of multi-terminal VSC-based HVDC after a converter outage: DC control strategy

This item was submitted to Loughborough University's Institutional Repository by the/an author.


Additional Information:

- Originally presented at: International Conference on Renewable Energies and Power Quality (ICREPQ 16), Madrid, Spain, 4-6 May, 2016.

Metadata Record: https://dspace.lboro.ac.uk/2134/21537

Version: Published

Publisher: © EA4EPQ

Rights: This work is made available according to the conditions of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International (CC BY-NC-ND 4.0) licence. Full details of this licence are available at: https://creativecommons.org/licenses/by-nc-nd/4.0/

Please cite the published version.
Dynamic Behaviour of Multi-Terminal VSC-Based HVDC after a Converter Outage: DC Control Strategy

F. Gonzalez-Longatt 1, S. Arnaltes 2, J.L. Rodríguez-Amenedo 2

1 The Wolfson School: Electronic, Electrical and Systems Engineering, Loughborough University, Loughborough, LE113TU (United Kingdom)
Phone/Fax number: +44(0)150 9227061, e-mail: fglonatt@fglongatt.org

2 Escuela Politécnica Superior, Universidad Carlos III de Madrid, C/ Butarque 15, 28911 Leganés (Spain)
Phone: +34 - 91 624 9911, fax: +34 - 91 624 9430, e-mail: santiago.arnaltes@uc3m.es, amenedo@ing.uc3m.es

Abstract.
The aim of this paper is to evaluate the effect of DC-voltage control strategy on the dynamic behaviour of multi-terminal Voltage-Source Converter (VSC)-Based HVDC after a converter outage. In this paper, two dc voltage control strategies are considered: (i) standard voltage margin method (SVM) and (ii) standard voltage-droop method (SVD). The impact is evaluated in this paper using time-domain simulations on a simple test system using DlgSILENT® PowerFactoryTM considering a sudden disconnection of a converter-station. Simulation results demonstrate how important is the dc-voltage control strategy and the location/number of dc-buses involved in the dc-voltage on the dynamic response of the MTDC systems. The voltage margin control is capable of surviving a converter outage just if this converter is operating in constant power mode.

Key words
Dynamic response, multi-terminal HVDC, MTDC, Voltage Source Converters.

1. Introduction
European Union (EU) has imposed a dramatic reduction of CO₂ emissions, for such purpose, it is required a massive reduction of emission in electricity generation sector, as a consequence, it is really important to maximize the power contribution coming from offshore wind power plants distant from the shore. Dc networks look quite attractive for the network integration of this clean energy [1, 2]. Voltage Source Converter (VSC) High Voltage DC (HVDC) transmission systems empower the usage of more elaborate configurations such as the Multi-terminal VSC-HVDC (MVSCDC) networks. It offers higher reliability, redundant and flexible technology to enable the massive integration of offshore wind power in future power systems [3].

Outstanding efforts on the research on MTDC have been developed in several areas in recent times. A quite a number of publications are devoted to several subject of MTDC involving since the classical steady state performance [4-8], classical and security constrained optimal power flow [7, 9-11], modelling [12-14], control and protection [15-20], and simulation of dynamic behaviour [4, 21-24]. An aspect that requires evaluation, the traditional reliability and availability related to outages as to transient reliability related to performance during and recovery after temporary faults and disturbances. Cable and converter station outages create a serious risk of instability in hybrid ac/dc network because to a large amount of power transmitted by MTDC system. Dc voltage control is the vital aspect that indicates the power balance and the stability of an MTDC system.

The objective of this paper is to evaluate the impact of the dc voltage control strategies on the dynamic behaviour of multi-terminal VSC-based HVDC following a converter outage, two strategies are analysed in this paper: Standard Voltage Margin Method (SVM) and Standard Voltage Droop Method (SVD). Section 2 presents a general introduction to the main control systems in MTDC systems and presents the theoretical background of dc voltage strategies. Section 3 shows the simulations results and discussion about the impact of the dc voltage control strategies on the dynamic behaviour of multi-terminal VSC-based HVDC following a converter outage. Finally, Section 4 concludes. The contribution of this paper includes: (i) demonstrates bipolar configuration can provide minimal voltage deviation from the initial nominal voltage than mono-polar network (ii) bipolar configuration (small dc voltage droops) allow the operation within the rated voltage limits.

2. Control of MTDC Systems
The control schemes have a large impact on system dynamics. It is an important task to determine the modelling requirements of the control schemes. The control system for a MTDC is composed of two different layers of controllers [25]: (i) terminal controllers and (ii) a master controller as illustrated in Fig. 1.
The master controller is provided with a minimum set of functions necessary for the coordinated operation of the terminals and the terminal controllers (outer controllers) are mainly responsible for active power control, reactive power control, dc voltage regulation, and ac voltage regulation. The current controller loop is the inner and faster part of the cascaded control strategy. This control produces the firing signals from the current reference values (i^d_A, i^q_A) received from the outer controllers and dq transformed currents from transducer devices (i_a, i_q).

Dc voltage control is certainly one of the most important tasks given to the VSC-HVDC stations inside a MTDC system. A well-controlled dc voltage on a MTDC system is a guarantee of the power balance between all the interconnected nodes. Considering the operational requirements for dc voltage on MTDC, the literature provides two main control strategies which possibly can be applied in future transnational networks [26]: (i) Standard Voltage Margin Method (SVM) and (ii) Standard Voltage Droop Method (SVDM). These methods enable sharing of load among two or more dc voltage regulating terminals operating in parallel and provide controls in MTDC.

Dc voltage control is certainly one of the most important tasks given to the VSC-HVDC stations inside a MTDC system. A well-controlled dc voltage on a MTDC system is a guarantee of the power balance between all the interconnected nodes. Considering the operational requirements for dc voltage on MTDC, the literature provides two main control strategies which possibly can be applied in future transnational networks [26]: (i) Standard Voltage Margin Method (SVM) and (ii) Standard Voltage Droop Method (SVDM). These methods enable sharing of load among two or more dc voltage regulating terminals operating in parallel and provide controls in MTDC.

Dc voltage control is certainly one of the most important tasks given to the VSC-HVDC stations inside a MTDC system. A well-controlled dc voltage on a MTDC system is a guarantee of the power balance between all the interconnected nodes. Considering the operational requirements for dc voltage on MTDC, the literature provides two main control strategies which possibly can be applied in future transnational networks [26]: (i) Standard Voltage Margin Method (SVM) and (ii) Standard Voltage Droop Method (SVDM). These methods enable sharing of load among two or more dc voltage regulating terminals operating in parallel and provide controls in MTDC.
directly controlling their reactive power injections (constant P-mode). The converter station VSC37 is also used to control the voltage at bus 3 (\(U_3 = 0.98\) pu). Case II: This case considers the use of multiple dc slack buses, in this case, all converter stations are using controller based on SDVDM considering \(K = -1.00\). Case III: It is similar to Case II but it consider \(K = -3.00\). Case IV: \(K = -4.00\), Case V: \(K = -6.00\), Case VI: \(K = -0.50\) and Case VII: \(K = -0.20\). A single contingency is considered where outage converter station is VSC37.

A. Mono-polar Network Configuration

The plot of \(U_{dc}\) versus \(P_{dc}\) of the Cases I-VII following a sudden disconnection of VSC37 are shown in Fig. 3. Results show that there is some level of control coupling between the converter terminals using SVMM and SDVDM.

![Graph](image1)

Fig. 3. Simulation results: \(U_{dc}-P_{dc}\) plot of several Cases. Mono-polar Network Configuration.

On dc bus 6, Case II (\(K = -0.2\)) attains the highest maximum instantaneous voltage value of 2.0761 pu at 0.30 sec taking a longer period of time to peak. Case VII where \(K = -6.00\) takes shorter time of 0.15 sec to reach the maximum instantaneous voltage on the dc buses having its lowest values 1.0759 pu on bus 6. Case I shows the lowest variation of steady state voltage at 1.0376 pu and Case II have the highest variation of 1.6885 pu.

It can be concluded that the slope \(K\) in droop control influences the voltage response in the system such that, the smaller the slope value, the lower the peak value attained and the faster it takes to peak having low variation from steady state voltage. There is power imbalance resulting from the converter outage, however, the power produced is shared between the terminals having the same droop characteristics provided the terminals have enough capacity to compensate the power unbalance. Case I using VMM shows the highest variation of steady state power flow because only one converter is capable of controlling the dc voltage in the system at a time (\(U_{dc}-Q\) mode) with the other converters controlling active power (\(P-Q\)).

Table I shows the percentage of change resulting from the converter outage on other buses. The lowest voltage change is in Case I and for droop controller as the \(K\) values get smaller, the voltage change decreases (where \(K = -0.40\) and \(-0.60\) showed low changes in value).

Table I. Percentage of dc voltage change (%), after sudden disconnection of VSC37 for Mono-polar Network

<table>
<thead>
<tr>
<th>Bus</th>
<th>Case</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>3.21</td>
<td>68.85</td>
<td>31.47</td>
<td>17.68</td>
<td>8.198</td>
<td>5.78</td>
<td>5.78</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.21</td>
<td>67.73</td>
<td>30.03</td>
<td>16.07</td>
<td>6.46</td>
<td>4.03</td>
<td>4.03</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.21</td>
<td>67.73</td>
<td>28.68</td>
<td>14.56</td>
<td>4.81</td>
<td>2.34</td>
<td>2.34</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>1.68</td>
<td>67.58</td>
<td>29.86</td>
<td>15.89</td>
<td>6.31</td>
<td>3.92</td>
<td>3.92</td>
<td></td>
</tr>
</tbody>
</table>

From Table I, Case II (\(K = -0.2\)) has very high percentage change in dc voltage and as the slope value decreases, the percentage change also decreases. It can be deduced that a system is prone to imbalance when operating large slope constants in droop control implying that a small slope \(K\) value results in greater sensitivity to dc bus voltage at the expense of larger deviations of power flow from the nominal power, however, this will allow for a stronger dc network. Case I maintained the lowest voltage change, voltages on buses 7 and 8 decreased to 149.6 kV, 0.21% less than controlled nominal voltage. The dc cable power flows response of the Cases I-VII following a sudden disconnection of VSC37 are shown in Fig. 4.

Table II. Maximum instantaneous dc power flow transfer (\(P_i\)) in dc power cables in MW

<table>
<thead>
<tr>
<th>Cable</th>
<th>Case</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-7</td>
<td>11.33</td>
<td>18.32</td>
<td>18.21</td>
<td>18.13</td>
<td>18.01</td>
<td>18.35</td>
<td>18.36</td>
<td></td>
</tr>
<tr>
<td>6-8</td>
<td>11.32</td>
<td>25.49</td>
<td>25.31</td>
<td>25.27</td>
<td>25.22</td>
<td>25.48</td>
<td>25.49</td>
<td></td>
</tr>
<tr>
<td>7-8</td>
<td>22.52</td>
<td>17.39</td>
<td>17.37</td>
<td>17.30</td>
<td>17.21</td>
<td>17.66</td>
<td>17.72</td>
<td></td>
</tr>
<tr>
<td>7-9</td>
<td>1.64</td>
<td>1.28</td>
<td>1.10</td>
<td>1.03</td>
<td>0.88</td>
<td>1.36</td>
<td>1.93</td>
<td></td>
</tr>
<tr>
<td>8-9</td>
<td>18.13</td>
<td>10.35</td>
<td>10.60</td>
<td>10.67</td>
<td>10.87</td>
<td>10.24</td>
<td>9.65</td>
<td></td>
</tr>
</tbody>
</table>

B. Bi-polar Network Configuration

Six instances, Case II-VII, are evaluated for the bipolar network in this paper. This considers the use of multiple dc slack buses, where all converter stations are using controller based on SVDM. The following slope coefficient \(K\) for the droop control is considered Case II-VII: \(K = -0.20\), \(-0.50\), \(-1.00\), \(-3.00\), \(-4.00\), and \(-6.00\).
Table II. Percentage of dc voltage change after sudden disconnection of VSC37: Bi-polar Network Configuration

<table>
<thead>
<tr>
<th>Case</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VIII</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>3.302</td>
<td>15.817</td>
<td>23.731</td>
<td>29.455</td>
<td>30.195</td>
<td>30.941</td>
</tr>
<tr>
<td>7</td>
<td>2.674</td>
<td>16.229</td>
<td>24.186</td>
<td>29.946</td>
<td>30.691</td>
<td>31.441</td>
</tr>
<tr>
<td>9</td>
<td>2.914</td>
<td>16.293</td>
<td>24.256</td>
<td>30.028</td>
<td>30.765</td>
<td>31.514</td>
</tr>
</tbody>
</table>

Fig. 4. Simulation results: power flows on dc submarine transmission cables for several simulation cases. Mono-polar Network Configuration.

From the Table II, Case II on dc bus 6 has the highest nominal voltage change of 3.30% from the rated nominal voltage. As the slope constant decreased, the voltages were seen to be within the voltage limit. This is better be understood looking at it from the maximum instantaneous voltage attained where $K = -0.20$ reaches 1.720 pu which is 63.85 away from the rated nominal voltage. $K = -6.00$ reached a max of 1.055 pu which is just 0.5% deviation from the rated voltage and is able to come back to steady state voltage of 1.035 pu quickly (recall the operation limit is max 1.050 pu). Simulation results show a level of power imbalance resulting from the converter outage, however; the excess power produced was successfully shared between the terminals having the same droop characteristics provided the terminals have enough capacity to compensate for the power unbalance.

4. Conclusion

This paper evaluates the impact of the dc voltage control strategy on the dynamic behaviour of multi-terminal VSC-based HVDC following a Converter Outage, two strategies are analysed in this paper: SVMM and SVDM. Simulation results have shown that in the event of an outage of a converter station, there is a power imbalance in the MTDC network which is successfully distributed among the various converter terminals. The rate and efficacy of power balancing are however based on the control strategy and network configuration implemented. This was verified by the ability of converters using a smaller droop constant $K$ in SVDM to deliver a quicker response than those having a larger droop or using SVMM scheme. A comparison of monopolar and bipolar network showed that bipolar network delivered a better power stability with minimal voltage deviation from the initial nominal voltage than monopolar network. Bipolar using smaller droops were seen to operate within the rated voltage limit and had 3.3% overvoltage for a larger droop constant. Also, results showed that power oscillations in the ac side are transferable to the dc side if a converter exceeds the rated current limit.

Acknowledgement

This work has been partially supported in part by British Council under the UKIERI, under grant DST/INT/UK/P-61/2014.

Table A. Numerical parameters of controller used at VSC stations in MTDC network.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>VSC26</td>
<td>$Q$</td>
<td>$K_p = 3.00$</td>
<td>$T_q = 0.2$</td>
<td>-1.03</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>$P$</td>
<td>$K_p = 1.00$</td>
<td>$T_q = 0.1$</td>
<td>-1.03</td>
<td>1.03</td>
</tr>
<tr>
<td>VSC37</td>
<td>$Q$</td>
<td>$K_p = 3.00$</td>
<td>$T_q = 0.2$</td>
<td>-1.03</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>$P$</td>
<td>$K_p = 1.00$</td>
<td>$T_q = 0.1$</td>
<td>-1.03</td>
<td>1.03</td>
</tr>
<tr>
<td>VSC49</td>
<td>$Q$</td>
<td>$K_p = 1.00$</td>
<td>$T_q = 0.1$</td>
<td>-1.03</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>$P$</td>
<td>$K_p = 1.00$</td>
<td>$T_q = 0.1$</td>
<td>-1.03</td>
<td>1.03</td>
</tr>
<tr>
<td>VSC58</td>
<td>$Q$</td>
<td>$K_p = 3.00$</td>
<td>$T_q = 0.2$</td>
<td>-1.03</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>$P$</td>
<td>$K_p = 1.00$</td>
<td>$T_q = 0.1$</td>
<td>-1.03</td>
<td>1.03</td>
</tr>
</tbody>
</table>

Table B. Converter Set points.

<table>
<thead>
<tr>
<th>Converter Station</th>
<th>Control Mode</th>
<th>Active Power Set point [MW]</th>
<th>Reactive Power Set point [MVAR]</th>
<th>Operation Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>VSC37</td>
<td>$U_{ref}$-Q</td>
<td>4.100</td>
<td>0.000</td>
<td>DC slack bus</td>
</tr>
<tr>
<td>VSC26</td>
<td>P-Q</td>
<td>-60.00</td>
<td>40.00</td>
<td>Rectifier</td>
</tr>
<tr>
<td>VSC58</td>
<td>P-Q</td>
<td>35.00</td>
<td>5.00</td>
<td>Inverter</td>
</tr>
<tr>
<td>VSC49</td>
<td>P-Q</td>
<td>-25.00</td>
<td>0.000</td>
<td>Rectifier</td>
</tr>
</tbody>
</table>
References


