Transient stability versus damping of electromechanical oscillations in power systems with embedded multi-terminal VSC-HVDC systems

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Abstract

Multi-terminal high-voltage direct current technology based on voltage-source converter stations (VSC-MTDC) is expected to be one of the most important contributors to the future of electric power systems. In fact, among other features, it has already been shown how this technology can contribute to improve transient stability in power systems by the use of supplementary controllers. Along this line, this paper will investigate in detail how these supplementary controllers affect electromechanical oscillations, by means of small-signal stability analysis. The paper analyses two control strategies based on the modulation of active-power injections (P-WAF) and reactive-power injections (Q-WAF) in the VSC stations which were presented in previous work. Both control strategies use global signals of the frequencies of the VSC-MTDC system and they presented significant improvements on transient stability. The paper will provide guidelines for the design of these type of controllers to improve both, large- and small-disturbance angle stability. Small-signal stability analysis (in MatLab) has been compared with non-linear time domain simulation (in PSS/E) to confirm the results using CIGRE Nordic32A benchmark test system with a VSC-MTDC system. The paper analyses the impact of the controller gains and communication latency on electromechanical-oscillation damping. The main conclusion of the paper is that transient-stability-tailored supplementary controllers in VSC-MTDC systems can be tuned to damp inter-area oscillations too, maintaining their effectiveness.

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Abstract: Multi-terminal high-voltage direct current technology based on voltage-source converter stations (VSC-MTDC) is expected to be one of the most important contributors to the future of electric power systems. In fact, among other features, it has already been shown how this technology can contribute to improve transient stability in power systems by the use of supplementary controllers. Along this line, this paper will investigate in detail how these supplementary controllers affect electromechanical oscillations, by means of small-signal stability analysis. The paper analyses two control strategies based on the modulation of active-power injections (P-WAF) and reactive-power injections (Q-WAF) in the VSC stations which were presented in previous work. Both control strategies use global signals of the frequencies of the VSC-MTDC system and they presented significant improvements on transient stability. The paper will provide guidelines for the design of these type of controllers to improve both, large- and small-disturbance angle stability. Small-signal stability analysis (in Matlab) has been compared with non-linear time domain simulation (in PSS/E) to confirm the results using CIGRE Nordic32A benchmark test system with a VSC-MTDC system. The paper analyses the impact of the controller gains and communication latency on electromechanical-oscillation damping. The main conclusion of the paper is that transient-stability-tailored supplementary controllers in VSC-MTDC systems can be tuned to damp inter-area oscillations too, maintaining their effectiveness.


1 Introduction

Multi-terminal high voltage direct current systems based on voltage-source converters (VSC-HVDC) is a key technology for bulk power transmission and for the integration of renewable resources into power systems [1–3]. This enabler technology has received attention worldwide [4] and several conceptual large VSC-HVDC grids have already been proposed in the literature. For example, in Europe, an HVDC-based supergrid has been proposed for bulk power transmission through different countries and integration of offshore wind energy [1, 2]. In North America, a Macrogird consisting of several interregional HVDC interconnections has been proposed for massive integration of renewable energy sources [5, 6]. Similarly, an HVDC-based hypergrid has been proposed in Italy [7]. Meanwhile, actual examples of multi-terminal VSC-HVDC systems in operation in China are Zhoushan 5-terminal HVDC system [8], Nan’ao 3-terminal HVDC system [9–11] and Zhangbei 4-terminal system [12].

Although it is clear that the main application of VSC-HVDC systems is power transmission, they can also help to improve the operation of power systems by means of supplementary controllers [13, 14]. Previous publications have proposed supplementary controllers in multi-terminal VSC-HVDC systems (VSC-MTDC) to improve rotor-angle stability against small disturbances (electromechanical oscillations, i.e., power-oscillation damping, POD) and against large disturbances (transient stability).

The work in [15] proposed controllers in VSC-HVDC links to damp electromechanical oscillations (also known as power-oscillation-damping (POD) controllers), by modulating active-power (P) through a VSC-HVDC link and reactive-power (Q) injections at both converter stations. The controllers were designed using on robust control techniques. The work in [16, 17] proposed POD controllers in VSC-MTDC systems, where the VSCs modulate their P injections using the information from a Wide Area Measurement System (WAMS). The work in [18] proposed POD controllers in DC-voltage-droop-controlled VSC-MTDC systems. In this control strategy, one converter of the VSC-MTDC changes its DC-voltage set point proportionally to the locally measured frequency deviation, using the concept of DC-voltage loop shaping. The work in [19] proposed POD controllers in VSC-MTDC systems to modulate P and reactive-power (Q) injections of the VSCs and using global measurements of the frequencies at the connection points of the VSC stations of the MTDC system. Reference [20] proposed POD controllers in VSC-HVDC link embedded in an AC grid based on Linear Matrix Inequality (LMI) optimisation and modulating P/Q injections at the converter stations. POD controllers in VSC-MTDC systems of the references discussed above presented promising results.

The improvement of transient stability of a power system using a VSC-MTDC system has already been addressed in the literature. The work in [21] proposed a control strategy in VSC-MTDC systems for transient-stability improvement, where VSC stations control their P injections based on a bang-bang controller and using the speed deviations of the generators with respect to the speed of the centre of inertia (COI) as input signals. Reference [22] proposed controlling P injections of the VSC stations of a MTDC system based on a sliding-mode strategy and also using global measurements. The work in [23] proposed a control strategy where VSC stations controlled their P injections, using global measurements of the frequencies of the
MTDC system. This control strategy is a generalisation of the one proposed in [24] for point-to-point VSC-HVDC links, which modulates the active power transmitted through the link proportionally to the frequency deviation between the two AC terminals of the link. The work in [25] used the same input signal as in [23], but to control the Q injections of the VSC stations. The work in [26] proposed an active-power control strategy in VSC-MTDC systems using global measurements of the angles and frequencies at the connection point of the VSC stations.

In general, small- and large-signal rotor-angle stability are related and improving the latter often improves the former too, and vice versa. However, this is not always the case. For example, the study presented in [27] shows that an increase in the gain of the PSS of a synchronous generator improves the damping ratios of electromechanical modes, while transient stability deteriorates, in the system analysed. Hence, the following questions remain open:

- What is the impact of transient-stability-tailored controllers in VSC-MTDC systems on electromechanical-oscillation damping?
- Could transient-stability-tailored controllers in VSC-MTDC systems help to damp electromechanical oscillations too and play the role of POD controllers?

This paper addresses these two questions and studies the impact of transient-stability-tailored supplementary controllers in VSC-MTDC systems on electromechanical-oscillation damping by means of small-signal stability analysis. The paper analyses two control strategies based on the modulation of active-power injections (P-WAF) and reactive-power injections (Q-WAF) in the VSC stations of the MTDC system. Both control strategies use global signals of the frequencies of the VSC-MTDC system and they presented significant improvements on transient stability. Results suggest guidelines for the design of these type of controllers to improve both, large- and small-disturbance angle stability. Small-signal stability analysis techniques (in Matlab) will be used to assess electromechanical-oscillation damping, while non-linear time domain simulation (in PSS/E) will be used to confirm the results. Contributions will be illustrated in the Nordic32A test system with an embedded VSC-MTDC system. The paper analyses the impact of the controller gains and communication latency on electromechanical-oscillation damping.

Preliminary results were presented by the authors in [28], where a small-signal stability analysis of strategy P-WAF was carried out in a small test system. This paper extends the results an analyses not only the modulation of P injections (P-WAF), but also the modulation of Q injections (Q-WAF) and simultaneous modulation of P and Q injections (PO-WAF). Furthermore, this paper presents the results in a larger test system (Nordic32A benchmark system) and it analyses the impact of communication latencies on the performance of the control strategies, which was not analysed in [28].

The rest of the paper is organised as follows. Section 2 describes how VSC-MTDC systems are modelled. Section 3 describes the transient-stability-tailored control strategies in VSC-MTDC systems, which will be analysed in the paper. Section 4 presents the results obtained in the paper. Section 5 presents the conclusions obtained in this work. Finally, Appendix 5 contains the data used.

### 2 Modelling of multi-terminal VSC-HVDC systems

In VSC-MTDC system the of more than two VSC stations are connected to the same HVDC grid. Fig. 1 depicts the dynamic model of a VSC connected to an HVAC grid and to an HVDC grid, following the guidelines of [29–32] for electromechanical-type models of these types of systems (type-6 models, according to the classification of reference [33]). Outer control loops of VSCs are modelled in detail, while inner current control loops are approximated by a first-order transfer function between the current references and their actual values.

All the details of the dynamic model for VSC-MTDC systems used in this work can be found in [34] and, therefore, they are not included in this paper. The details of the linearised model used for small-signal stability analysis can be found in [28]. The initial operating point of the VSC-MTDC system is obtained with the AC/DC power flow method proposed in [35].

![Fig. 1: VSC and the HVDC grid based on the principles of [29].](image)

### 3 Control strategies

The control strategies to be investigated were proposed and described in detail in [23, 25] and this paper will analyse their impact on electromechanical-oscillation damping. Only the key aspects of the controllers are described in this section, in order to make the paper self contained.

When a disturbance occurs in a power system, bus frequencies change and, during the transient, frequencies at different buses of the [23] and reactive-power injections (Q-WAF) [25] in the VSC stations of the MTDC system. Both control strategies use global signals of the frequencies of the VSC-MTDC system and they presented significant improvements on transient stability.

The work in [25] used the same input signal as in [23], but to control the Q injections of the VSC stations. The work in [26] proposed an active-power control strategy in VSC-MTDC systems using global measurements (such as generator speeds or the speed of the COI) to be effective in different contexts [21, 38].

In the control strategies to be analysed in this work, global-but-practical measurements are used: they use global information of the dynamic behaviour of the system, but restricting the communication system between the converter stations of the VSC-MTDC system. Every converter of the VSC-MTDC system compares its own frequency measured at the AC bus with a frequency set point, which is calculated as the weighted average of the frequencies measured at the AC side of the VSC stations (weighted-averaged frequency, WAF):

$$
\omega^* = \bar{\omega} = \frac{1}{n} \sum_{k=1}^{n} \alpha_k \omega_k \text{ (pu)}, \quad \alpha_k \in [0, 1], \quad \sum_{k=1}^{n} \alpha_k = 1.
$$

where $\omega_k$ is the frequency measured at the AC bus of VSC$_k$ in pu.

The frequency error signal is used by every VSC to modulate its P Injection (strategy P-WAF) and/or its Q Injection (strategy Q-WAF).

#### 3.1 Strategy P-WAF

Fig. 2 shows the block diagram of control strategy P-WAF [23], where the frequency set point of the controller is calculated as in (1), which requires a communication system among the converter stations of the VSC-MTDC system, which is a strong but realistic restriction.

In order to share the control effort among all converters and avoid DC-voltage fluctuations, reference [23] proposed the following relationship between the gains and the weighting coefficients of the WAF:

$$
k_{P,k} = \alpha_k, \quad \text{with} \quad k_{P,T} = \sum_{j=1}^{n} k_{P,j}.
$$

while making $\alpha_k$ proportional to the nominal apparent power of each VSC$_k$ of the MTDC system.

#### 3.2 Strategy Q-WAF

Fig. 3 shows the block diagram of control strategy Q-WAF [25], where the frequency set point of the controller is also calculated
as in (1). The controller is activated only if the AC voltage at the connection point is above a certain threshold $V_{TH} (\gamma = 1$ if $u_s \geq V_{TH})$, to guarantee the control actions only after the fault is cleared (preventing the controller acting during a short circuit). This precaution improves the performance of the controller.

The work in [25] used the following design:

$$ \frac{k_{Q,k}}{k_{Q,T}} = \alpha_k, \quad k_{Q,T} = \sum_{j=1}^{n} k_{Q,j}. $$

(3)

4 Results

The case study considered consists of the CIGRE Nordic32A benchmark test system [39] with a 3-terminal VSC-HVDC system, as shown in Fig. 4. Each VSC has a nominal apparent power of 1000 MVA. A critical scenario with poorly damped inter-area oscillations is considered. The modifications made to stress the system and the data of the VSC-MTDC system are provided in the Appendix.

Each VSC of the MTDC system is controlled with DC-voltage droop control and constant reactive power injection. Table 1 depicts the initial steady-state operating point of the VSC-MTDC system, calculated with an AC/DC power flow [34, 35].

<table>
<thead>
<tr>
<th>Converter</th>
<th>$P_{dc,i}^0$ (MW)</th>
<th>$Q_{dc,i}^0$ (MVAR)</th>
<th>$u_{ac,i}^0$ (pu)</th>
<th>$u_{dc,i}^0$ (pu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VSC1</td>
<td>-350.00</td>
<td>0.00</td>
<td>1.0100</td>
<td>1.0006</td>
</tr>
<tr>
<td>VSC2</td>
<td>500.00</td>
<td>150.00</td>
<td>0.9982</td>
<td>0.9978</td>
</tr>
<tr>
<td>VSC3</td>
<td>-190.08</td>
<td>0.00</td>
<td>1.0149</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

Table 1: Initial operating point of the VSC-MTDC system.

The information about the electromechanical oscillations between different synchronous machines in the system can be extracted from the right eigenvectors of the linearised system (4), which are known as mode shapes [44]. The right eigenvector $v_k \in \mathbb{C}^n \times 1$ associated to eigenvalue $\lambda_k$ satisfies:

$$ \lambda_k v_k = A v_k. $$

(5)

The dynamic model of the system in Fig. 4 has been linearised around the steady-state operation point and the linearised model has been implemented in Matlab-based Small Signal Stability Tool (SSST) [40], as described in [28]. The linearised system reads:

$$ \Delta \dot{x} = A \Delta x. $$

(4)

where $A \in \mathbb{R}^{n \times n}$ is the state matrix, $\Delta x \in \mathbb{R}^{n \times 1}$ is the vector of increments of the state variables and $n_x$ is the number of state variables of the system.

Electromechanical oscillations have been identified using eigenvalue techniques and participation-factors [41–43]. The system has two inter-area modes with low damping ratios, as depicted in Table 2.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Eigenvalue (rad/s)</th>
<th>$\zeta$</th>
<th>Freq. (Hz)</th>
<th>Dominant machines</th>
<th>Oscillation</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$-0.1044 \pm j3.2333$</td>
<td>0.32</td>
<td>0.51</td>
<td>G4072, G4063</td>
<td>North against South &amp; Centre</td>
</tr>
<tr>
<td>B</td>
<td>$-0.3186 \pm j5.2160$</td>
<td>0.61</td>
<td>0.83</td>
<td>G4063, G4072, G1042</td>
<td>North against South &amp; Centre</td>
</tr>
</tbody>
</table>

Table 2: Inter-area modes.

Figs. 5 and 6 show the shapes of inter-area modes A and B (right eigenvectors associated to the speeds of the synchronous machines), respectively. In inter-area mode A, synchronous machines in the...
North oscillate against synchronous machines in the South and in the Centre: mode shapes of the speeds of the generators in the North have opposite phases to mode shapes of the speeds of the generators in the South. In inter-area mode B, synchronous machines in the North and South oscillate against machines in the Centre: mode shapes of the speeds of the generators in the North and South are in phase, while they have opposite phases to mode shapes of the speeds of the generators in the South.

4.1 Small-signal stability analysis

The impact of the controller gains of strategies P-WAF (P injections) and Q-WAF (Q injections) on inter-area modes is analysed. Gains at all VSC stations were changed (satisfying (2) and (3)) and eigenvalues and their damping ratios were obtained. Since gains in the range \( k_{P,i}, k_{Q,i} = [100, 300] \text{ pu} \) (pu's are referred to the converter rating) proved to be effective to improve transient stability [23, 25], now gains \( k_{P,i}, k_{Q,i} = [0, 500] \text{ pu} \) will be explored. The rest of parameters of the control strategies are provided in the Appendix.

Fig. 7 shows the evolution of the inter-area modes of the system and their damping ratios as the gains of control strategy P-WAF (P injections) increase. Inter-area mode A moves towards the left-hand side of the complex plane as \( k_{P,i} \) increases and its damping ratio increases, significantly. Inter-area mode B also moves towards the left-hand side of the complex plane as \( k_{Q,i} \) increases and its damping ratio also increases. However, the damping ratio of mode B is lower than the one of mode A and saturates. Therefore, controller gains \( k_{Q,i} \) have small impact on the damping ratio of other modes.

Results prove that with reasonable values of the controller gains for transient-stability improvement in strategies P-WAF and Q-WAF (e.g. \( k_{P,i} = k_{Q,i} = 200 \text{ pu} \)), inter-area modes are also damped successfully without affecting other modes significantly. Furthermore, small-signal stability techniques can be used to design the controller gains in order to obtain the required damping ratios of the electromechanical modes.

Fig. 5: Shapes of inter-area mode A.

Fig. 6: Shapes of inter-area mode B.

Fig. 7: Strategy P-WAF. Impact of gains \( k_{P,i} \) on (a) evolution of electromechanical modes and (b) damping ratio.
4.2 Non-linear time-domain simulation

The performance of the control strategies has been tested by means of non-linear time domain simulation in PSS/E tool (electromechanical simulation), using the model proposed in [34]. Four cases are compared:

- Base case: no supplementary control strategy.
- P-WAF: Strategy P-WAF (P injections) (Fig. 2), with $k_{P,i} = 200$ pu.
- Q-WAF: Strategy Q-WAF (Q injections) (Fig. 3), with $k_{Q,i} = 200$ pu.
- PQ-WAF: Simultaneous modulation of P and Q injections with strategies P-WAF and Q-WAF, with $k_{P,i} = k_{Q,i} = 200$ pu.

The rest of parameters of the control strategies are provided in the Appendix.

Line 4012-4022 (see Fig. 4) is tripped at $t = 1$ s. Fig. 9 shows the difference between the bus-voltage angles of generators 4072 (North) and 4063 (South). The three control strategies (P-WAF, Q-WAF and PQ-WAF) succeed in damping the inter-area oscillations present in the base case.

Figs. 10 and 11 show the active- and reactive-power injections of the VSC stations, respectively. In strategy P-WAF, only P injections are modulated. After the event, the P injection of VSC 1 decreases (P absorption of VSC 1 increases) because its frequency is above the WAF, while the P injections of VSCs 2 and 3 increase because their frequencies are below the WAF (see Fig. 12, as an example). Analogously, in strategy Q-WAF, only Q injections are modulated. The behaviour of Q injections in Q-WAF is similar to the behaviour of P injections in P-WAF, but with opposite direction, due to the negative sign of Fig. 3. In strategy PQ-WAF, both, P and Q injections are modulated. Both, modulation of P and/or Q injections of the VSC stations contribute positively to damp inter-area oscillations.
the maximum time duration that a fault can stay before clearance without eventually provoking loss of synchronism. An extremely severe fault is selected: a three-phase-to-ground short circuit applied to line 4031–4041a (close to bus 4041) (see Fig. 4), which is cleared by disconnecting the two circuits of the corridor (Fault I, for short). At the initial operating point, each circuit of the corridor carries 644.50 MW.

The impact of communication latency on the performance of the control strategies is also analysed by introducing a delay in the frequency set point calculated by each VSC (τ) when calculating the WAF in (1):

$$\omega^* = \bar{\omega} e^{-\tau s}$$

A second-order Padé’s approximation has been used to represent the transfer function of the delay in (6), as proposed in [45]. Realistic values for the delays (τ = 50 ms and τ = 100 ms) were tested [46].

Table 3 shows damping ratios and frequencies of the inter-area modes A and B, and the CCT of Fault I, obtained in the base case and for control strategies P-WAF, Q-WAF and PQ-WAF. In all cases, controller gains are set to \( k_{P,i} = k_{Q,i} = 200 \) pu and the rest of the parameters as described in the Appendix. The control strategies significantly increase the damping ratios of inter-area modes A and B, in comparison with the base case. The damping ratios deteriorate slightly in the presence of communication latency; however, the improvements are still significant. The control strategies increase the CCT of Fault I significantly. Communication latencies do not reduce the CCT in strategy P-WAF. This is consistent with the results presented in [47]: the DC-voltage droop attenuates the effect of communication latency when modulating P injections. However, the impact of communication latency is stronger when modulating Q injections with strategy Q-WAF. Nevertheless, results obtained in the presence of communication latency are better than those obtained in the base case.

Hence, results prove that control strategies P-WAF, Q-WAF and PQ-WAF improve significantly both transient stability and electromechanical-oscillation damping.

### 5 Conclusions

This paper analysed the impact of transient-stability-tailored supplementary controllers in VSC-MTDC systems on electromechanical-oscillation damping, by means of small-signal stability analysis. In the control strategies analysed, each VSC of the MTDC system compares its own frequency with the weighted-average frequency (WAF) of the VSC stations and it modulates its P injection, Q injection or both simultaneously (P-WAF, Q-WAF and PQ-WAF, respectively).

The conclusions obtained in this paper can be summarised as follows:

- Control strategies P-WAF, Q-WAF and PQ-WAF can be tuned to (a) improve transient stability and (b) damp inter-area electromechanical oscillations too.

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**Table 3** Comparison. EO: Electromechanical oscillations (small disturbance), TS: Transient stability (large disturbance).

<table>
<thead>
<tr>
<th>Case</th>
<th>EO</th>
<th>TS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MO A</td>
<td>MO B</td>
</tr>
<tr>
<td>Base case</td>
<td>3.23 %, 0.51 Hz</td>
<td>6.10 %, 0.83 Hz</td>
</tr>
<tr>
<td>Fault I, τ = 0 ms</td>
<td>19.27 %, 0.62 Hz, 17.38 %, 0.89 Hz</td>
<td></td>
</tr>
<tr>
<td>P-WAF, τ = 50 ms</td>
<td>22.24 %, 0.53 Hz, 13.18 %, 0.86 Hz</td>
<td></td>
</tr>
<tr>
<td>Q-WAF, τ = 100 ms</td>
<td>19.37 %, 0.54 Hz, 13.06 %, 0.86 Hz</td>
<td></td>
</tr>
<tr>
<td>PQ-WAF, τ = 100 ms</td>
<td>20.74 %, 0.71 Hz, 21.23 %, 0.91 Hz</td>
<td></td>
</tr>
</tbody>
</table>

---

**Fig. 11**: Reactive-power injection of each VSC \( (Q_{s,i}) \).

**Fig. 12**: Frequency deviations with respect to the weighted-average frequency (case P-WAF).
● The control strategies produce good results in the presence of communication delays, under small disturbances and under large disturbances.

● Although bulk power transmission and the recollection of non-dispatchable energy sources are the main purposes of a multi-terminal VSC-HVDC system embedded in a conventional HVAC system, the flexibility of VSC stations makes it possible the contribution of these systems to the overall improvement of the power system stability. This contribution adds a remarkable value to this technology and should be taken into account when carrying out a cost-benefit analysis in future developments.

Appendix A: Data system
A.1: Data of the test system
Data of the original CIGRE Nordic32A benchmark test system can be found in [39, 48] and a comprehensive description of the system can be found in [49]. Some modifications were made in the test system used in this paper, in order to stress the system and to reduce the damping ratio of inter-area oscillations. The modifications made are detailed in [19]. Converter and HVDC grid parameters are provided in Table 4.

A.2: Parameters of the control strategies for the case study
● P-WAF: \( k_{P,i} = 200 \) pu, \( \Delta P_{\text{max},i} = 1.0 \) pu, \( T_{f,i} = 0.1 \) s, \( T_{W,i} = 10 \) s and \( \alpha_k = 1/3 \). The gains are in nominal p.u. Different values of \( k_{P,i} \) are analysed in Section 4.1.

● Q-WAF: \( k_{Q,i} = 200 \) pu, \( \Delta Q_{\text{max},i} = 1.0 \) pu, \( T_{f,i} = 0.1 \) s, \( T_{W,i} = 10 \) s, \( V_{TH,i} = 0.75 \) pu and \( \alpha_k = 1/3 \). The gains are in nominal p.u. Different values of \( k_{Q,i} \) are analysed in Section 4.1.

● PQ-WAF: The same parameters of strategies P-WAF and Q-WAF are used.

Table 4 Converter & HVDC grid data. Base for pu: VSC's nominal apparent power.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal apparent power</td>
<td>1000 MVA</td>
</tr>
<tr>
<td>DC voltage</td>
<td>±320 kV</td>
</tr>
<tr>
<td>AC voltage</td>
<td>±300 kV</td>
</tr>
<tr>
<td>Configuration</td>
<td>Symmetrical monopole</td>
</tr>
<tr>
<td>Active-power limits</td>
<td>+100 MW</td>
</tr>
<tr>
<td>Current limit</td>
<td>±50 MVar</td>
</tr>
<tr>
<td>DC-voltage limits</td>
<td>1 pu (d-axis priority)</td>
</tr>
<tr>
<td>Max. modulation index (( \alpha_m ))</td>
<td>1.31 pu</td>
</tr>
<tr>
<td>Current-controller time constant (( \tau ))</td>
<td>5 ms</td>
</tr>
<tr>
<td>Connection impedance: ( r_s = r_x + jx_s ) (reactor + 300/400 kV transformer)</td>
<td>0.002 + 0.17 pu</td>
</tr>
<tr>
<td>Active-power control</td>
<td></td>
</tr>
<tr>
<td>Reactive-power control</td>
<td></td>
</tr>
<tr>
<td>DC-voltage drop parameter (( k_{dc,i} ))</td>
<td>0.1 pu</td>
</tr>
<tr>
<td>VSC/ VSC' loss parameters (( c_{\text{dc},i} ))</td>
<td>11.033 / 3.464 × 10⁻³ pu</td>
</tr>
<tr>
<td>DC-line loss parameters (( c_{\text{cc},i} ))</td>
<td>4.40 / 6.67 × 10⁻³ pu</td>
</tr>
<tr>
<td>DC-line shunt capacitance (( C_{\text{cc},i} ))</td>
<td>2.05Ω / 0.140 mH</td>
</tr>
<tr>
<td>VSC Eq. capacitance (( C_{\text{dc},i} ))</td>
<td>1.70/2F</td>
</tr>
<tr>
<td>Total eq. DC-bus capacitance (( C_{\text{dc},i} ))</td>
<td>193.2 mF</td>
</tr>
</tbody>
</table>

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6 References


