

On the damping and coupling impacts of DC fault-limiting reactors in multi-terminal DC grids.

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ABSTRACT

This paper investigates the impact of DC fault-limiting reactors (DCRs) on the dynamics of multi-terminal DC (MTDC) grids, with a particular focus on their damping and coupling effects. The first part examines the instability introduced by large DCR values using a simplified low-frequency model and a comprehensive small-signal analysis of a four-terminal meshed DC grid. A dedicated controller is proposed to stabilize the system and is compared with other mitigation measures, such as modifying the control mode and changing the power flow direction. The second part investigates the coupling effects of DCRs in DC grids, showing that the commonly assumed equivalent DC grid capacitance becomes invalid in the presence of DCRs. This leads to different conclusions regarding DC voltage support between stations, particularly during fast transient responses. All findings are validated through time-domain simulations of a four-terminal DC grid.

1. Introduction

Despite their advantages in providing flexibility and efficiency in offshore wind power integration, Multi-Terminal DC (MTDC) grids present challenges in control and protection. From a protection perspective, DC faults can cause the short-circuit current to rise to several tens of kiloamperes within just a few milliseconds [1]. Fault current interruption is typically achieved using DC circuit breakers (DCCBs). One of the key components of DCCBs are DC reactors, as they help limit the fault current. These reactors can also be installed at converter terminals. Their sizing and placement depend on the chosen protection strategy, cable lengths and grid configuration [2, 3, 4].

While effective for fault current limitation, DCRs also introduce undesirable dynamics that can negatively affect DC voltage stability and damping [5, 6, 7, 8]. In [5], large inductance values are shown to reduce the damping and controllability of the DC voltage. A dedicated outer-loop controller, called DC-PSS, is proposed to mitigate the instability. In [6], a similar outer controller is proposed to modify the active power setpoint of the MMC according to the derivative of the DC voltage. In [7], DCRs were shown to limit the power transfer capability of the MMC, and a the active power control loop is tuned to narrow down its bandwidth in order to improve the DC voltage response. In [8], a Power-Flow Controller (PFC)-based active damping is introduced to improve the transient performance of a VSC-based DC grid with large DCRs. In the current study, after a thorough small-signal analysis, we introduce a simple inner control modification to the zero-sequence current, which can effectively dampen the resonance introduced large DCRs in the grid.

The impact of the DC reactor (DCR) extends beyond inducing negative damping; it also affects the coupling between converter stations. In this context, previous studies

often rely on the concept of equivalent DC grid capacitance [9], assuming that the DC voltages of different MMC stations are dynamically coupled, even at relatively high frequency ranges (i.e., during faster transient responses). This assumption is particularly valid for DC grids with short cable lengths, where the electrical distance between converter stations is small. In such cases, the dynamic behavior of the DC voltage can be considered analogous to the frequency response of AC grids, incorporating both inertial and primary responses. This behavior has motivated the study of MMC energy control structures, ranging from non-energy-based control (NEBC) to energy-based control (EBC) [9, 10, 11, 12]. NEBC operates similarly to a two-level VSC and does not explicitly control the internal energy, resulting in a noticeable inherent capacitance on the DC side. In contrast, EBC actively regulates the internal MMC energy to a constant value, significantly reducing the effective DC-side capacitance. To compensate for this reduction and enhance DC voltage dynamic response, various control strategies have been proposed to introduce a virtual capacitance, thereby increasing the effective electrostatic inertia of the DC grid [9, 10, 13, 14, 15].

In a multi-vendor MTDC grid, the HVDC converter vendors are responsible for the design and implementation of the control systems, which may vary significantly from one converter to another. To ensure interoperability, Transmission System Operators (TSOs) shall establish technical specifications that define the expected behavior of the HVDC converters without acquiring access to control information [3, 16]. From this perspective, MMCs may adopt different control schemes related to internal energy management. If the DC grid is modeled as a single equivalent capacitor [17], then the more MMC stations with either inherent or virtual capacitance, the greater the overall DC inertia, and inertial support can be better shared among converter stations, as the rate of DC voltage change is reduced. However, with longer cable lengths and higher DCR values, such equivalent capacitance assumption becomes less accurate. In fact, the DCRs

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increase the electrical distance between stations, effectively acting as filters for high-frequency dynamics and limiting electrostatic inertial support between distant stations. Previous work within InterOPERA project, aiming at enabling future multi-vendor MTDC grids, by defining functional specifications [3] and minimum requirements for interfaces [18], has investigated the dynamic performance of a three-terminal bipolar DC grid, where large DCR values have been utilized, showing that DCRs can impact the overall response time of the DC voltage. [19].

From the above context, a gap in the literature is identified regarding the unified study of DC reactors in MTDC grids, specifically, their impact on damping and on the sharing of inertial support. This article aims to address this gap through both small-signal analysis and time-domain simulations. The main contributions of this paper are:

- Analyzing the impact of DCRs using a simplified low-frequency MMC model, and proposing a simple controller that effectively mitigates the instability introduced by large DCRs.
- Applying both small-signal analysis and time-domain simulations to a 4-terminal meshed DC grid to validate the analytical results and demonstrate the controller's performance.
- Challenging the assumption of equivalent DC grid capacitance by showing, through case studies, that with the same number of MMC stations controlling their total energy, the maximum DC voltage deviation varies significantly depending on the presence of DCRs in the network.

The rest of this paper is structured as follows: Section 2 introduces the simplified MMC model and analyzes its low-frequency dynamics. Section 3 verifies these findings using a more detailed MMC representation. Section 4 introduces an active damping solution to improve the small-signal stability with a design process. Section 5 applies the analysis to a four-terminal DC grid. Section 6 investigates how DCRs influence dynamic coupling in a 4T DC grid. Finally, Section 7 summarizes the key findings of this study.

2. Simplified low-frequency MMC analysis

To analyze the impact of the DC reactor on the dynamic response of a converter station, this section studies the low-frequency interaction between the DC-side MMC impedance and the DC reactor impedance.

2.1. MMC model for low-frequency analysis

Consider the system in Fig. 1. The MMC model is based on the Average Value Model (AVM) described in [20, 21]. It assumes that all internal variables of the MMC are well regulated, meaning perfect balancing of the submodule capacitor voltages is achieved. Additionally, it assumes perfect balancing between the upper and lower arm capacitor voltages, as well as among the three legs of the MMC. Furthermore,

the second harmonic circulating currents are assumed to be effectively suppressed by the control [20, 22]. Such a control concept is referred to as Non-Energy Based Control (NEBC) [23, 24, 25].

The equivalent capacitance of the MMC is therefore represented by a capacitor $C = \frac{6C_{SM}}{N}$, where C_{SM} is the submodule capacitor and N is the number of submodules per arm. For the purpose of this study, only the DC-side dynamics of the AVM are considered, as the impact on the AC side is not within the scope of this analysis. Consequently, AC-side related controls, such as the Phase-Locked Loop (PLL), are assumed ideal. The AVM provides a reasonable trade-off between accuracy and complexity, as it allows for a low-order representation of the MMC and still captures the essential low-frequency dynamics.

In Fig. 1, L_{arm} and R_{arm} represent the MMC arm inductance and resistance, respectively. The DC reactor is represented by L_{der} , which is connected in series with the MMC DC terminal. The outer control behavior is represented by the controlled current source connected in parallel to the capacitor C . In the general case, the MMC operates under DC Voltage droop control.

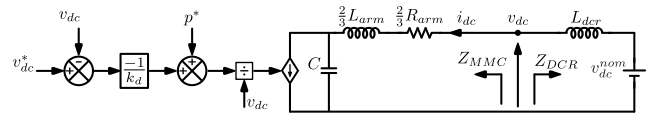


Figure 1: Simplified low-frequency MMC model used for stability analysis. The outer control is represented by a controlled current source, which can be configured to operate in constant power mode or DC voltage droop mode.

To perform the stability analysis on the simplified model in Fig. 1, we write the source-load relationship typically used in the impedance based stability analysis, and find the MMC impedance (see the appendix for the derivation):

$$Z_{MMC}(s) = \frac{V_{dc}(s)}{I_{dc}(s)} = \frac{a_2 s^2 + a_1 s + a_0}{sC + \frac{1}{k_d v_{dc0}} - \frac{P_0}{v_{dc0}^2}} \quad (1)$$

where

$$\begin{aligned} a_2 &= L_{dc} C \\ a_1 &= R_{dc} C + L_{dc} \left(\frac{1}{k_d v_{dc0}} - \frac{P_0}{v_{dc0}^2} \right) \\ a_0 &= R_{dc} \left(\frac{1}{k_d v_{dc0}} - \frac{P_0}{v_{dc0}^2} \right) + 1 \end{aligned}$$

with $L_{dc} = \frac{2}{3} L_{arm}$, $R_{dc} = \frac{2}{3} R_{arm}$, k_d the droop gain, v_{dc0} and P_0 representing the operating point of the MMC.

The DC-grid impedance is represented solely by the DC reactor $Z_g(s) = sL_{der}$. The return ratio $\mathcal{L}(s) = \frac{Z_{MMC}(s)}{Z_g(s)}$

of the simplified setup represents the loop gain of the system, where the stability of the closed-loop system shall be determined¹.

2.2. MMC operating in constant power mode

Considering the MMC impedance expressed in (1), with the MMC operating in constant power mode ($k_d = \infty$), the MMC impedance simplifies to:

$$Z_{MMC}^{Pmode}(s) = \frac{L_{dc}Cs^2 + \left(R_{dc}C - \frac{L_{dc}P_0}{v_{dc0}^2}\right)s - R_{dc}\left(\frac{P_0}{v_{dc0}^2}\right) + 1}{sC - \frac{P_0}{v_{dc0}^2}} \quad (2)$$

It can be seen that $Z_{MMC}^{Pmode}(s)$ contains a real pole at $s = \frac{P_0}{Cv_{dc0}^2}$. If the value of C is considered to be a design parameter, the open-loop stability of $Z_{MMC}^{Pmode}(s)$ can be uniquely determined by the operating point P_0 . The return ratio $\mathcal{L}(s)$ can therefore be expressed as:

$$\mathcal{L}(s) = \frac{L_{dc}Cs^2 + \left(R_{dc}C - \frac{L_{dc}P_0}{v_{dc0}^2}\right)s - R_{dc}\left(\frac{P_0}{v_{dc0}^2}\right) + 1}{sL_{dcr}\left(sC - \frac{P_0}{v_{dc0}^2}\right)} \quad (3)$$

From (3), we observe that L_{dcr} only influences the magnitude of $\mathcal{L}(s)$, while the phase is determined by the physical parameters and the operating point. This is confirmed in Fig. 2, where the impedance profiles of the MMC and the grid (represented by the DCR) for different values of L_{dcr} are shown for the AVM parameters given in Table 1 and the operating power set to $P_0 = 1$ p.u (rated inverter power). Fig. 2 illustrates that, when $P_0 > 0$, increasing L_{dcr} leads to a reduction in the magnitude of $\mathcal{L}(s)$, thereby shifting the gain crossover frequency to lower values, where the phase is more negative due to the RHP pole. This shift reduces the phase margin and increases the risk of instability.

2.3. Impact of DC voltage droop

When utilizing DC voltage droop control ($k_d < \infty$), the return ratio $\mathcal{L}(s)$ can be expressed as:

$$\mathcal{L}(s) = \frac{a_2s^2 + a_1s + a_0}{sL_{dcr}\left(sC + \frac{1}{k_d v_{dc0}} - \frac{P_0}{v_{dc0}^2}\right)} \quad (4)$$

From (4), the addition of DC voltage droop control modifies the system dynamics by adding positive damping at low frequency range, which can be observed in the denominator of (4). Droop control increases the phase margin of the system, lowering the risk of instability. More analysis will be conducted in the next section to verify this notion.

¹To avoid confusion with the symbol L used for inductance, the return ratio is denoted by $\mathcal{L}(s)$ instead of $L(s)$ throughout this paper.

Table 1
MMC parameters.

Parameter	Value
Nominal power [MVA]	1000
Nominal L-L AC-PoC voltage [kV]	400
Nominal DC voltage [kV]	525
Number of submodules per arm	400
Submodule capacitance [μ F]	10
Transformer reactance [pu]	0.18
Transformer resistance [pu]	0.005
Arm inductance [mH]	43
Arm resistance [Ω]	0.8

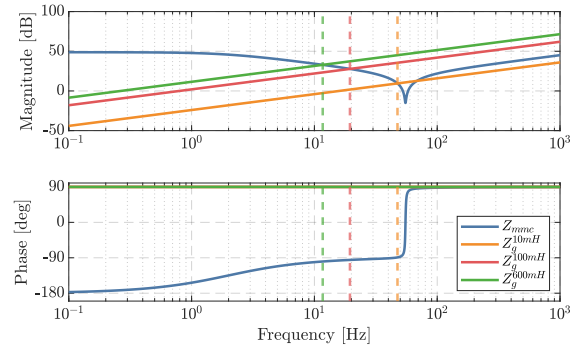


Figure 2: Impedance frequency response of the DC-side MMC AVM in constant power mode, with the grid (pure inductive) impedance for different DC reactor sizes. Increasing L_{dcr} reduces the gain crossover frequency, decreasing the phase margin and potentially causing instability.

3. Standalone MMC response

In order to verify the analysis conducted in Section 2 using the simplified low-frequency MMC model, a test setup shown in Fig. 3 is presented, similar to the one in Fig. 1, but with a more detailed MMC representation. The Arm Average Model (AAM) is utilized to represent each MMC arm by an equivalent capacitor. The state-space representation of the MMC is developed following the approach introduced in [26], by considering double dq frame transformation. The MMC control structure follows a typical hierarchical control, with outer control loops generating the references for the inner current control loops. A pair of PI controllers are used to regulate the second harmonic circulating currents to zero, which is known as Circulating Current Suppression Control (CCSC) [22], see Fig. 4. The physical and control parameters of the MMC are given in Tables 1 and 2. The small-signal MMC DC-side impedance Z_{MMC} is obtained by linearizing the state-space model around the operating point, and choosing the DC voltage as the output variable

MMC control parameters.

Parameter	Value
DC voltage droop gain [p.u./p.u.]	0.1
Active power time response [ms]	50
AC current control time response [ms]	10
CCSC time response [ms]	5

and the DC current as the input variable. The return ratio is then obtained as $\mathcal{L}(s) = \frac{Z_{MMC}}{sL_{dcr}}$.

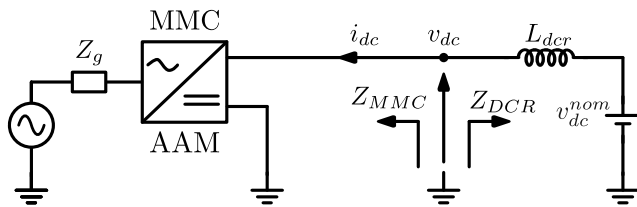
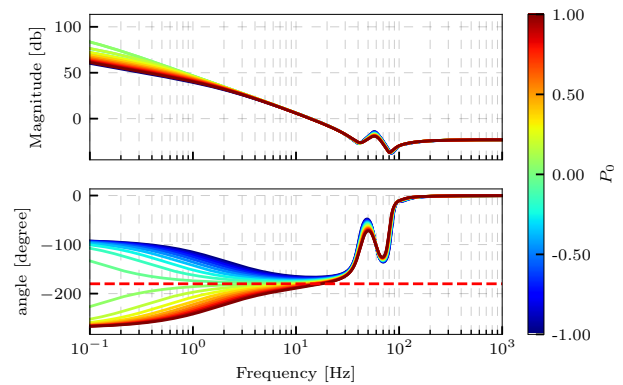


Figure 5: Frequency response of the return ratio for the standalone MMC operating in constant power mode $\mathcal{L}(s)$ for different values of L_{dcr} . Increasing L_{dcr} reduces the magnitude without affecting the phase, leading to instability above a critical value $L_{dcr} = 318$ mH.



4. Active damping by lead compensation

The instability caused by large DCR values is related to the negative phase margin at low frequency range. To mitigate such instability, the MMC impedance can be reshaped

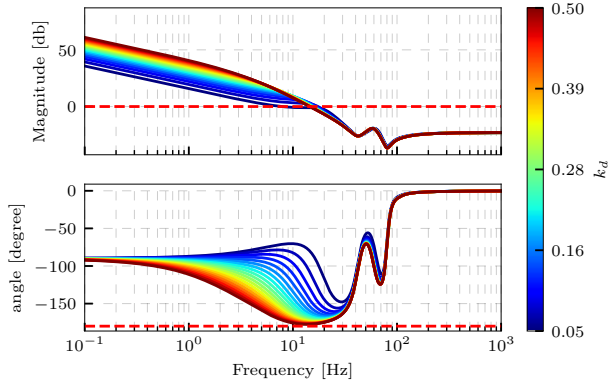


Figure 7: Effect of DC voltage droop control on the return ratio for $L_{dcr} = 400$ mH. A higher droop action (lower k_d) increases the phase margin and improves damping in the low-frequency range.

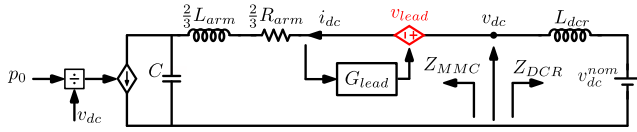


Figure 8: Principle of active damping: a lead compensator generates a voltage signal v_{lead} in response to DC current variations, which can be considered as a virtual impedance.

in that range to introduce positive damping. As shown in Fig. 8, this can be achieved through a voltage source v_{lead} that reacts to variations in the DC current i_{dc} .

In this work, the damping action is applied to the zero-sequence circulating current i_z^Σ , because it is directly related to the DC current by $i_{dc} = 3i_z^\Sigma$. A lead compensator is added to the MMC control structure (Fig. 9) to improve the phase margin around the original crossover frequency. The transfer function of the lead compensator is given by:

$$G_{lead}(s) = \eta \frac{Ts + 1}{\alpha Ts + 1} \quad (5)$$

where η is the gain of the compensator. The lead compensator has a zero at $s = -\frac{1}{T}$ and a pole at $s = -\frac{1}{\alpha T}$.

For the considered L_{dcr} values between 10 mH and 400 mH, the phase crossover frequency of the original system is about 18.1 Hz (see Fig. 5). Following the approach in [27], achieving a 30° positive phase margin requires $\alpha = 0.0334$. The lowest gain crossover frequency within the studied range of L_{dcr} is 14 Hz, corresponding to $L_{dcr} = 400$ mH. Therefore, a value of $T = 15.9$ ms is chosen, which, with the above value of α , corresponds to a zero at 10 Hz and a pole at 30 Hz.

The gain η should be chosen sufficiently small to avoid adding an excessive DC offset to the MMC capacitor voltage v_{cz}^Σ , as the compensator output v_{mz}^Σ directly affects it. In this study, $\eta = 0.05$ is chosen, which improves the phase margin, though below the 30° target, while adding a minimal v_{cz}^Σ offset.

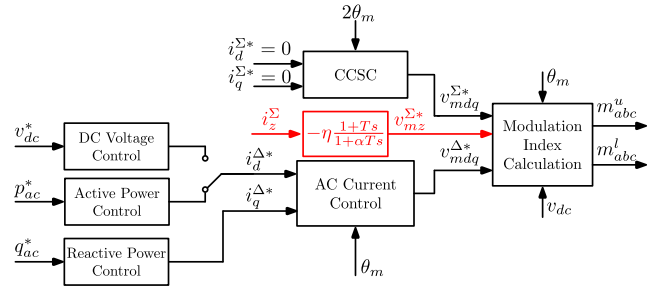


Figure 9: Integration of the lead compensator into the MMC control structure, acting on the zero-sequence circulating current i_z^Σ .

Fig. 10 shows the frequency response of the return ratio $\mathcal{L}(s)$ with and without the lead compensator, considering $L_{dcr} = 400$ mH and $P_0 = 1$ p.u., originally judged unstable in Section 2. It can be seen that the lead compensator indeed improves the phase margin at the critical frequency range, leading to better damping characteristics. It can further be noted that the lead compensator does not alter either the low frequency range (below 10 Hz) or the high frequency range (above 200 Hz). Unlike switching to DC voltage droop control mode, the lead compensator does not affect the steady-state DC voltage response.

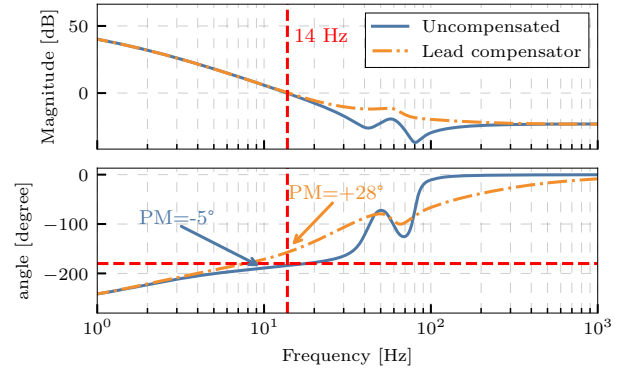


Figure 10: Return ratio with and without lead compensation for $L_{dcr} = 400$ mH and $P_0 = 1$ p.u. Lead compensation improves the phase margin from -5° to 25° , thus stabilizing the system.

A time-domain simulation is conducted to verify the performance of the lead compensator. It compares the response of the MMC in the test setup shown in Fig. 3 under a step DC voltage disturbance, without and with the lead compensator applied. The results presented in Fig. 11 demonstrate that the lead compensator effectively stabilizes the system. The DC voltage response remains stable and free of oscillations, even when $L_{dcr} = 400$ mH.

5. Application to a four-terminal DC grid

In this section, we aim to verify the results obtained in previous sections by means of small-signal analysis and time-domain simulations on a four-terminal asymmetrical

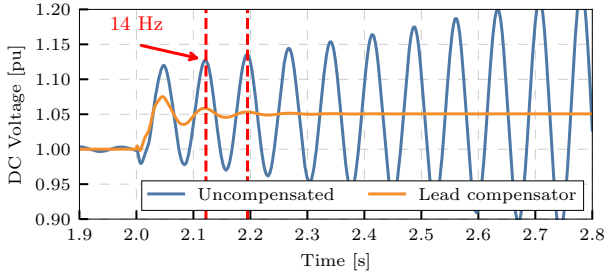


Figure 11: DC voltage response of the MMC to a step disturbance comparing uncompensated and lead-compensated systems with $P_0 = 1$ p.u. and $L_{dcr} = 400$ mH.

monopolar DC grid, shown in Fig. 12. In the considered grid, DC cables of length 100 km interconnect the four MMC stations creating a meshed topology. DCRs are placed at the terminals of the MMC stations. The main parameters of the MTDC grid are the same as in Table 1.

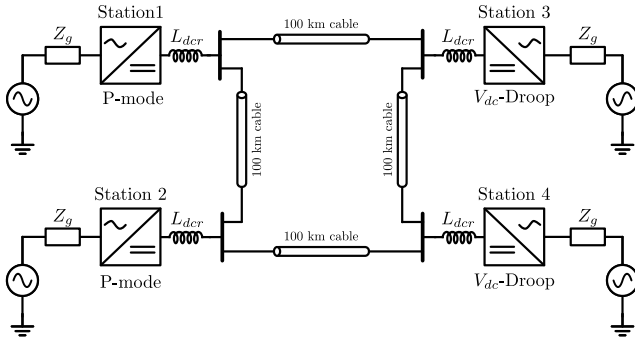


Figure 12: Four-terminal meshed DC grid under study.

The small-signal model of the full grid is needed to analyze the possible interactions and undamped modes. For this, the respective state-space representations of the grid subsystems are built and interconnected according to the proper inputs/output relationships. Starting with the MMC, the same AAM described in Section 3 is utilized. The state-space representation of the DC cable is obtained from the original frequency-dependent π model according to the process proposed in [28]. Three RL branches are used to capture the frequency dependence of the cable dynamics, showing acceptable accuracy up to 400 Hz, which is suitable for the frequency range of interest in this study. The AC grid is modeled with a Thevenin equivalent, with a short-circuit ratio of 10, representing a strong AC grid. The overall non-linear state-space model is obtained by interconnecting the subsystems, namely the MMC stations, DC cables and DCRs. The small-signal model of the 4T DC grid is therefore obtained in MATLAB by linearizing the overall state-space model around the operating point, defined by the power flow and the converter control mode.

Table 3

Operating point 1 of the 4T DC grid.

Converter	Control Mode	v_{dc}^{set} [pu]	p_{dc}^{set} [pu]
Station 1	P-mode (inverter)	N/A	0.95
Station 2	P-mode (inverter)	N/A	0.95
Station 3	DC voltage droop	1	-0.925
Station 4	DC voltage droop	1.007	-1

Table 4

Operating point 2 of the 4T DC grid.

Converter	Control Mode	v_{dc}^{set} [pu]	p_{dc}^{set} [pu]
Station 1	P-mode (rectifier)	N/A	-0.95
Station 2	P-mode (rectifier)	N/A	-0.95
Station 3	DC voltage droop	1	0.855
Station 4	DC voltage droop	0.996	1

5.1. Small-signal analysis of the 4T DC grid

Considering the MMC physical and control parameters shown in Tables 1 and 2, the eigenvalues of the linearized 4T DC grid are plotted as a function of the DCR value, considering operating point 1 defined in Table 3, where the St1&2 operate in inverter mode and St3&4 in DC voltage droop mode.

The results are shown in Fig. 13. It can be seen from Fig. 13a that, as the DCR values increase in all stations, a pair of eigenvalues move to the RHP, indicating that the system becomes unstable. The natural frequency of the unstable eigenvalues is 15 Hz, which is within the frequency range where instability was observed in the simplified MMC model in Section 2 and verified by the standalone MMC behavior in Section 3. A participation factor analysis is performed to find that the unstable eigenvalues (λ_{65} and λ_{66}) are mainly influenced by the states i_{z1}^{Σ} , i_{z2}^{Σ} , v_{Cz1}^{Σ} , and v_{Cz2}^{Σ} , which correspond to the zero-sequence current of Stations 1 and 2, and the zero-sequence components of the capacitor voltages of Stations 1 and 2, respectively.

Consider a change in the power flow direction to reach the operating point 2, defined by Table 4, where the P-mode MMC stations (St1&2) operate in rectifier mode. Fig. 13b shows that, with the same range of DCR variation, all the system eigenvalues lie on the LHP, which is a sufficient condition for system stability. This shows the considerable impact of the operating point on the system dynamics, especially when large DCRs are present in the grid.

To analyze the impact of DC voltage droop control on the system dynamics, the closed-loop system poles are plotted in Fig. 13c for the case where the system is at operating point 1, with St2's control mode switched to DC voltage droop. The results indicate that the system remains stable for all values of DCR. This demonstrates that the DC voltage droop control introduces positive damping to the system.

Finally, the impact of the active damping provided by the proposed lead compensator is analyzed by applying it to St1 and St2 at operating point 1, with both operating in

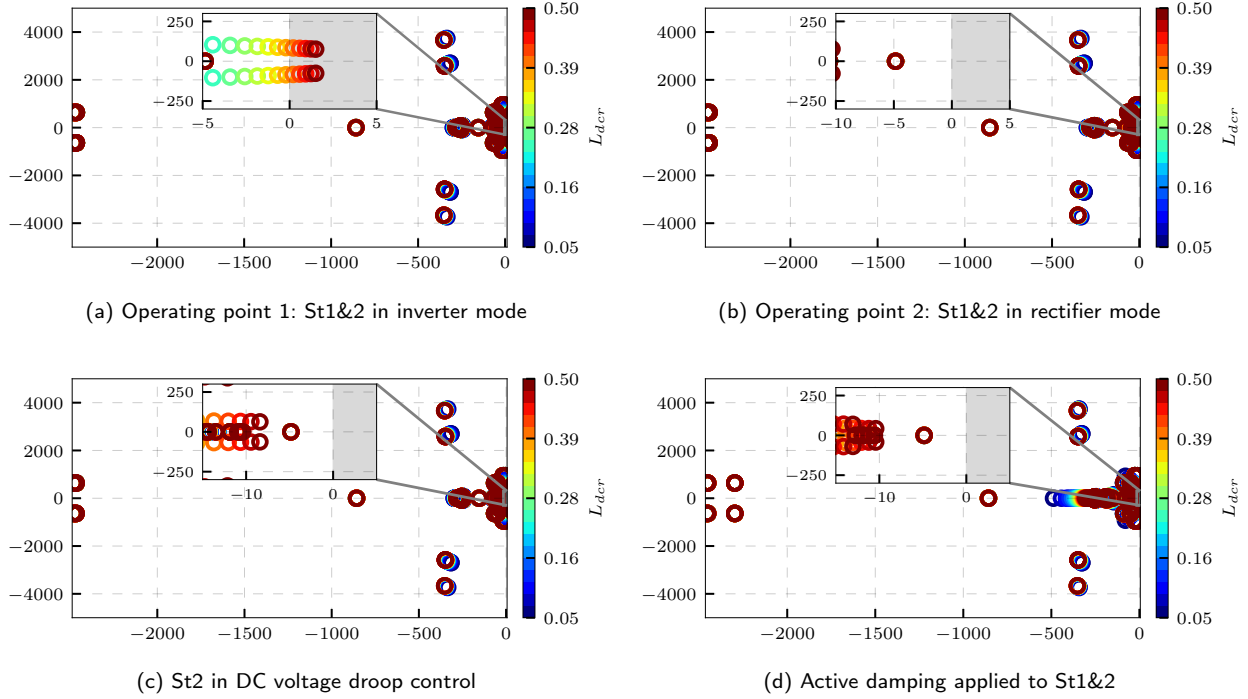


Figure 13: Eigenvalues of the 4T DC grid for varying DCR sizes under different operating conditions.

constant power mode. The parameters of the compensator are the same as the design criterion in Section 4. The results presented in Fig. 13d show that the lead compensator effectively mitigates the instability caused by the large DCR values, even with St1 and St2 operating in inverter mode, with no poles moving to the RHP.

The above results shown in Fig. 13 are consistent with the analytical predictions conducted in Section 2 and the standalone MMC results in Section 3. Moreover, the same design parameters of the lead compensator presented in Section 4 are utilized on the 4TDC grid case, showing the effectiveness of the damping controller.

5.2. Time-domain simulations of the 4T DC grid

Time-domain simulations are conducted in EMTP-RV to verify the small-signal analysis results in Section 5.2. The same control and physical parameters are utilized for consistency. The AAM is used for the MMC stations. The wideband cable models are used to represent the DC cables. In all simulations in this part, the DCR values are set to 400 mH for all stations, which is higher than the critical value obtained in the small-signal analysis, in Section 3.

The results shown in Fig. 14 indicate the following:

- In Fig. 14a, at operating point 1, St1 and St2 exhibit growing DC voltage oscillations at 14 Hz.
- In Fig. 14b, at operating point 2 with St1 and St2 in rectifier mode, the system remains stable after a 500 MW step decrease in St1 AC power setpoint at $t = 4$ s. While all DC voltages reach steady state, St1 and St2 (P-mode) exhibit more oscillations compared to St3

and St4 (droop control), indicating that, regardless of the operating point, the DC voltages of P-mode stations are generally less damped than those of stations operating under DC voltage droop control.

- In Fig. 14c, for operating point 1, DC voltage droop is activated at $t = 5$ s. It can be observed that switching St2 control mode from constant P-mode to DC voltage control restores system stability. It can also be seen that the steady-state operating point is slightly changed. This behavior is expected since DC voltage droop control changes the active power output of the station.
- In Fig. 14d, for operating point 1, applying the lead compensator to St1 and St2 at $t = 5$ s stabilizes the system. The DC voltage responses exhibit well-damped behavior, even with St1 and St2 operating in inverter mode, confirming the effectiveness of the lead compensator. We also observe that the steady-state behavior remains unchanged after introducing the lead compensator (note the response of St3 and St4), which verifies that this damping controller does not alter the DC voltage steady-state response.

Table 5 summarizes the discussed mitigation measures to the stability issues introduced by the DCRs in the 4T DC grid, with the respective practical considerations for each solution.

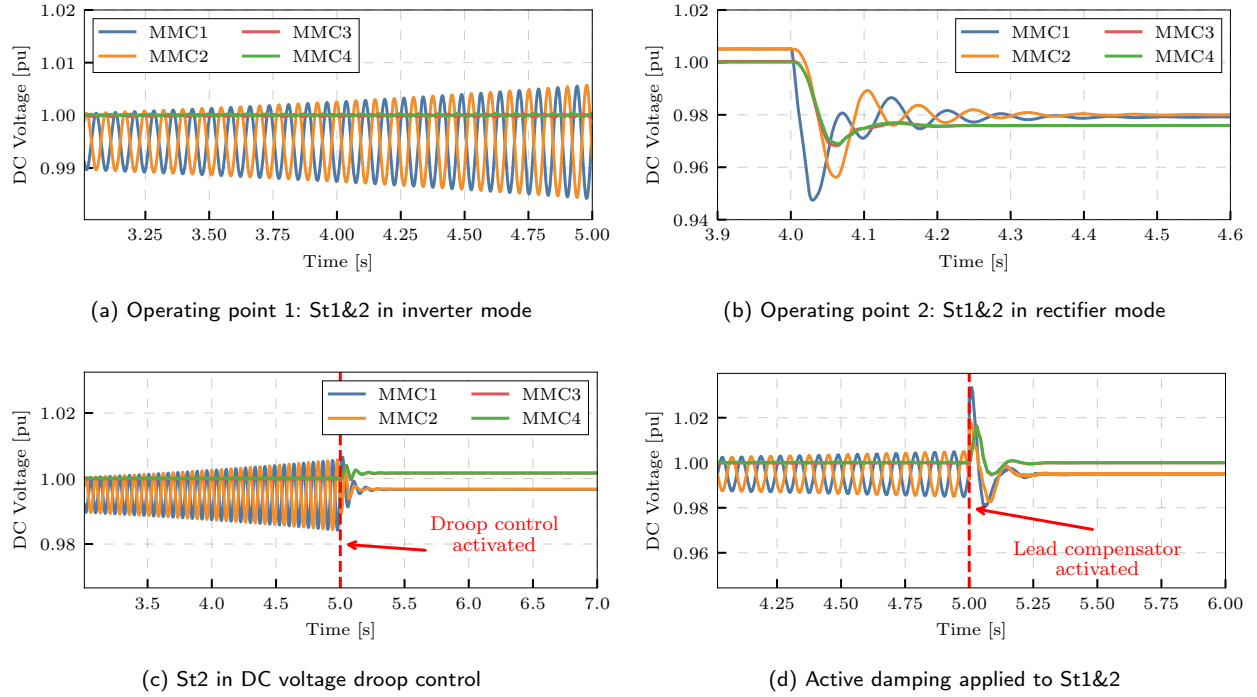


Figure 14: Time-domain DC voltage responses of the 4T DC grid with 400 mH DCRs for the four cases considered in the small-signal analysis.

Mitigation solution	Practical considerations
Increasing the number of DC voltage droop stations	• Adding more droop stations can enhance damping and improve dynamic stability. • For small and sparse grid configurations, the number of droop-controlled stations is often dictated by the system's steady-state voltage regulation needs. • Less flexibility in DC grid planning.
Operating P-Mode Stations Primarily in Rectifier Mode	• For offshore stations, rectifier operation is realistic. • For onshore stations, however, constraining P-mode operation to rectifier mode imposes limitations on power flow direction • Proper system-level design is needed.
Active damping by lead compensation	• Offers improvement in system damping without restricting operational flexibility. • Requires careful design and testing to evaluate the impact on other transient response considerations (e.g. impact on high-frequency dynamics, system response time)

Table 5

Mitigation measures to the stability issues introduced by DCRs in the 4T DC grid, with practical considerations for each solution.

6. Impact of DCRs on DC voltage coupling between converter stations

In this section, we examine another implication of introducing DCRs in DC grids, specifically, their impact on converter coupling and DC voltage support. We consider the same 4T DC grid presented in Section 5, using operating point 2 as defined in Table 4, where St1 and St2 operate

in rectifier mode. Two control modes related to internal energy regulation are considered: Non-Energy-Based Control (NEBC) and Energy-Based Control (EBC). The choice between these two controllers is motivated by their influence on maximum transient DC voltage deviation following a given disturbance. Our objective is to investigate whether

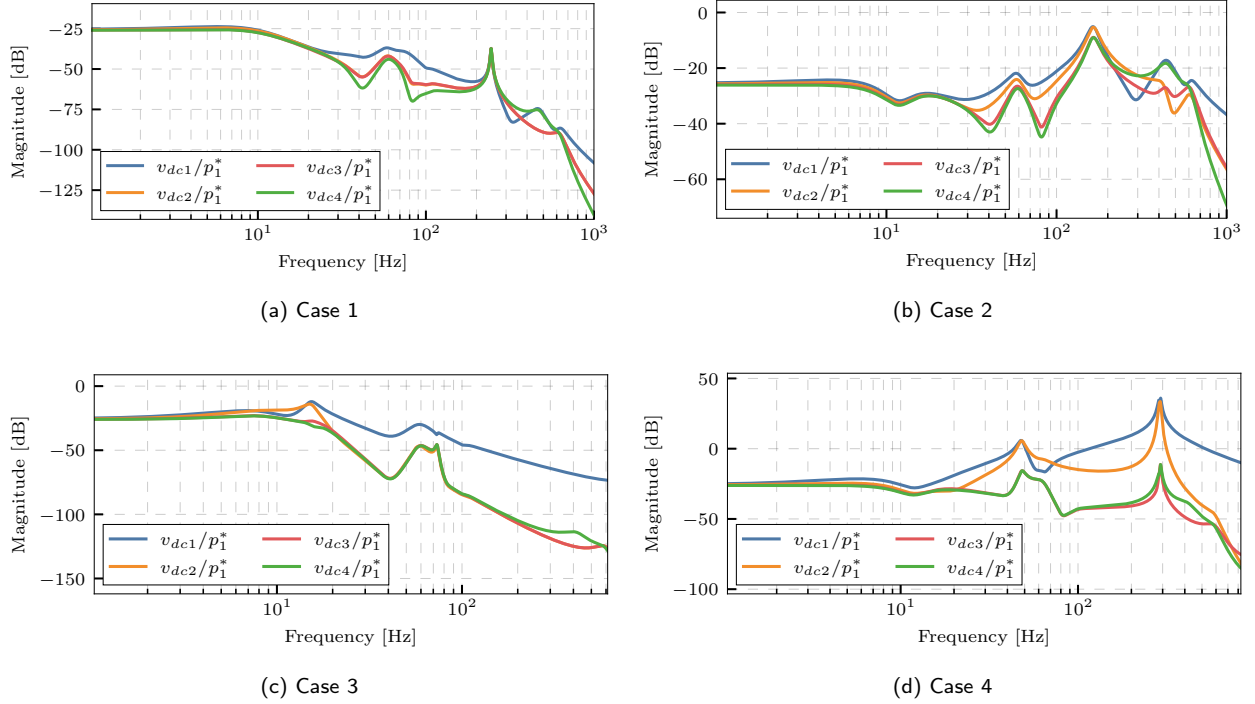


Figure 15: Magnitude frequency response from AC power reference of St1 to DC voltages at each station, for four cases. DCRs reduce coupling between station DC voltages, especially with EBC

the presence of DCRs affects this metric and whether the different stations exhibit similar dynamic behavior. To analyze this impact, four case scenarios are considered and described below, with Stations 3 and 4 controlling the DC voltage using NEBC in all cases.

- Case 1: St1&2 in NEBC, with no DCRs.
- Case 2: St1&2 in EBC, with no DCRs.
- Case 3: St1&2 in NEBC, with DCRs of 300 mH.
- Case 4: St1&2 in EBC, with DCRs of 300 mH.

Figs. 15a and 15b clearly show that, for cases 1 and 2, the frequency responses of the four DC voltages in the grid are quite similar. This indicates that the DC voltage at each station is equally sensitive to changes in the AC power reference of St1, due to the short electrical distances between them (the stations are interconnected using 100 km cables). However, higher resonant peaks are observed in the high-frequency range (above 100 Hz) in Case 2 compared to Case 1, suggesting that the DC voltages are more sensitive to the disturbance when St1 and St2 operate in EBC mode.

When DCRs are introduced in Cases 3 and 4, the frequency response of St1 voltage exhibits a different behavior compared to the other stations, indicating that the remaining stations are less responsive to the disturbance introduced by St1, as shown in Figs. 15c and 15d. It is also clear that the high-frequency responses of St3 and St4 are significantly worse, exhibiting higher resonant peaks, when EBC is used

(Case 4) compared to NEBC (Case 3). This suggests that the decoupling effect among converter DC voltages, caused by the introduction of DCRs, worsens the DC voltage response when EBC is utilized.

EMT simulations are performed on the 4T DC grid to verify the results obtained from the small-signal analysis. For consistency with the small-signal analysis conditions, a step change in the active power reference of St1 is introduced at $t = 3$ s, and the DC voltage responses of all stations are shown for the four cases previously described.

Figs. 16a and 16b show that when no DCRs are present, the time-domain behavior of the DC voltages of all stations are similar, supporting the equivalent capacitor assumption of the grid. In Case 2, due to the increase of the number of energy control stations, the DC voltage response exhibits higher transient excursions.

The results of Cases 3 and 4, shown in Figs. 16c and 16d, indicate that, since the DC voltage of St1 is closer to the original disturbance, the maximum DC voltage deviation is higher than the other stations, with an even higher deviation in Case 4, where EBC is used.

The results shown in Fig. 16 reveal that the choice of energy control structure for MMC stations primarily affects the response of the individual stations where it is implemented. Increasing the number of stations where the converter acts as a capacitor has no significant impact on the overall system response, as the presence of DCRs decouples the DC voltage dynamics between stations. For faster transient responses,

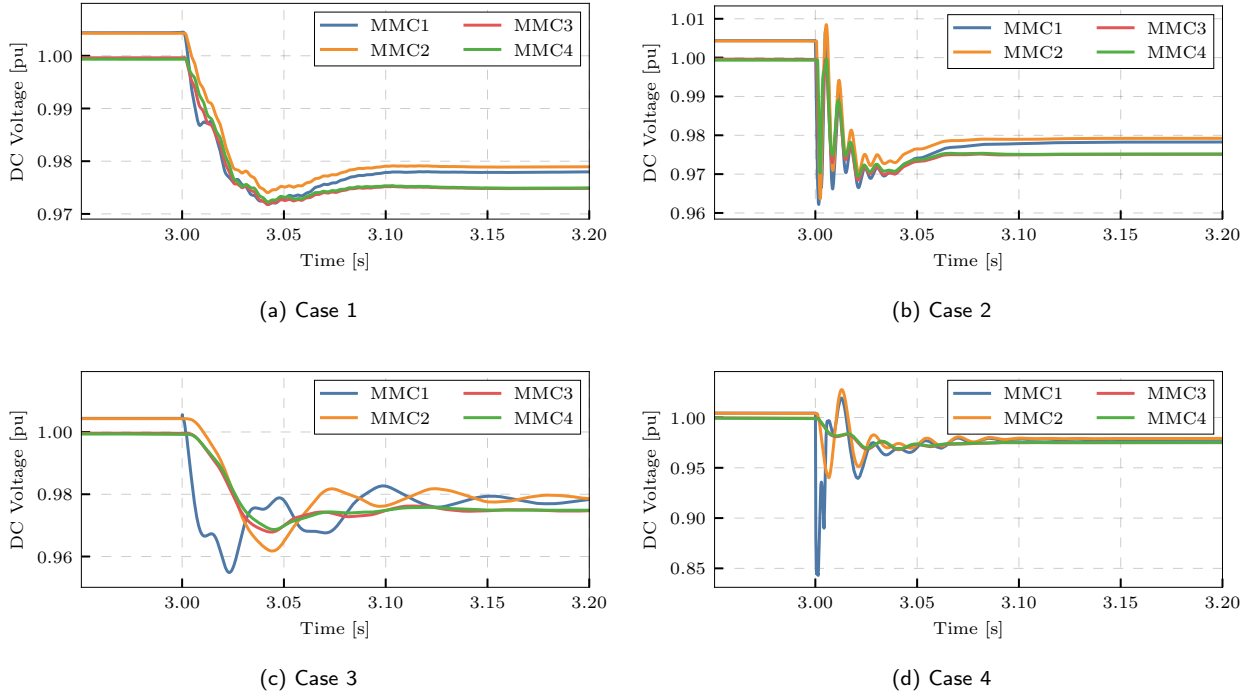


Figure 16: Time-domain DC voltage responses to a power step at St1 for the four cases considered. Without DCRs, DC voltages respond similarly; with DCRs, responses are decoupled, and EBC increases voltage deviation at the station closest to the disturbance (St1).

each converter behaves independently, and no inertial support is exchanged or shared among stations when DCRs are present. Nonetheless, the individual compliance of each stations should be ensured, in order for the DC voltage not to exceed the maximum allowed deviation with respect to the time-frame of interest [3].

7. Conclusion

This paper has presented a comprehensive analysis of the impact of DC reactors (DCRs) on the stability of MMC-based DC grids. The study has shown that DCRs can lead to instability issues, particularly when the MMC operates in P-mode and the DCR values are high. The analysis was conducted using a simplified low-frequency model of the MMC, which was validated through standalone full MMC model, and a four-terminal meshed DC grid. A simple lead compensator was proposed to mitigate the instability issues caused by the DCRs, and its effectiveness was verified through small-signal analysis and time-domain simulations. Moreover, the study has highlighted the impact of DCRs on the coupling between converter stations and the DC voltage support, showing that DCRs can decouple the DC voltage dynamics between stations, leading to different responses depending on the control strategy used.

A. Derivation of the MMC impedance

The impedance of the simplified MMC model in Fig. 1 can be derived by considering the voltage across the

capacitor C denoted here by v_c , which can be expressed as:

$$C \frac{dv_c}{dt} = i_{dc} - i_{mmc} \quad (6)$$

where i_{mmc} is the current of the controlled current source, which can be written as:

$$i_{mmc} = \frac{P}{v_c} \quad (7)$$

(7) is linearized around the operating point v_{c0} and P_0 to obtain:

$$\Delta i_{mmc} = \frac{\Delta P}{v_{c0}} - \frac{P_0}{v_{c0}^2} \Delta v_c \quad (8)$$

The DC voltage droop relates the active power to the DC voltage as follows:

$$\Delta P = \frac{1}{k_d} \Delta v_c \quad (9)$$

where k_d is the DC voltage droop gain. Substituting (9) into (8) gives:

$$\Delta i_{mmc} = \left(\frac{1}{k_d v_{c0}} - \frac{P_0}{v_{c0}^2} \right) \Delta v_{dc} \quad (10)$$

The capacitor voltage in (6) can be expressed in linearized form, and substituting the value of Δi_{mmc} from (10) gives:

$$C \frac{d\Delta v_c}{dt} = \Delta i_{dc} - \left(\frac{1}{k_d v_{c0}} - \frac{P_0}{v_{c0}^2} \right) \Delta v_{dc} \quad (11)$$

Converting to Laplace domain gives:

$$sC\Delta V_c(s) = \Delta I_{dc}(s) - \left(\frac{1}{k_d v_{c0}} - \frac{P_0}{v_{c0}^2} \right) \Delta V_{dc}(s) \quad (12)$$

Solving for the DC-side impedance $Z_c(s) = \frac{\Delta V_c(s)}{\Delta I_{dc}(s)}$ gives:

$$Z_c(s) = \frac{1}{Cs + \frac{1}{k_d v_{c0}} - \frac{P_0}{v_{c0}^2}} \quad (13)$$

The total impedance of the MMC is then obtained by adding the arm inductance and resistance:

$$\begin{aligned} Z_{MMC}(s) &= L_{dc}s + R_{dc} + Z_c(s) \\ &= \frac{L_{dc}Cs^2 + \left(R_{dc}C - \frac{L_{dc}P_0}{v_{c0}^2} \right)s - R_{dc} \left(\frac{P_0}{v_{c0}^2} \right) + 1}{sC + \frac{1}{k_d v_{c0}} - \frac{P_0}{v_{c0}^2}} \end{aligned} \quad (14)$$

Notice that we have the assumption that $v_{c0} \approx v_{dc0}$, which considers that R_{dc} is sufficiently small.

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