

Modelling and Coordination of Dynamic Braking Systems for Multi-Vendor Multi-Terminal HVDC Grids with DC Circuit Breakers

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Abstract

The development of HVDC grids to support the large-scale integration of offshore wind is anticipated to be a key enabler of the energy transition. In this context, multi-vendor (MV) interoperability is essential to ensure system expandability within a competitive framework. The EU-funded InterOPERA project has delivered functional frameworks, design studies, and specifications for a real-time MV multi-terminal (MT) HVDC demonstrator, enabling the integration of different technologies. This work focuses on the dynamic braking systems' (DBS) response in DC grids equipped with DC circuit breakers, and most notably, their associated inductances introduced for fault current gradient limitation. Undesirable responses exhibited by conventional generic modelling approaches are analysed, and alternative representations are proposed. Simulation results demonstrate that adequate DBS representation in design studies can significantly influence the characterisation of dynamic constraints at subsystem interfaces during converter blocking and temporary AC fault events. They also reveal cross-influences between DBS settings and converter control parameters at remote stations, indicating that DBS performance requirements should be conceived as part of the overall DC voltage control strategy. Finally, burden-sharing among DBS units and converter stations is shown to be implementation-dependent, stressing the need for coordinated DBS design and highlighting the relevance of a system-wide approach.

1 Introduction

Multi-terminal HVDC (MTDC) grids are increasingly recognized as an enabler for the efficient integration of large-scale offshore wind generation and strengthening cross-border interconnections. By extending conventional point-to-point (P2P) HVDC links, MTDC grids improve operational flexibility, transmission asset utilization, and system resilience. Their widespread deployment, however, requires the development of robust, scalable, and interoperable multi-vendor (MV) solutions. In this context, the EU-funded InterOPERA project aims to advance MV-MTDC technology through a real-time demonstrator involving major HVDC equipment vendors and transmission system operators (TSOs).

During the preparation phase, an interoperable functional framework was established and applied to the selected HVDC grid topology. This work resulted in detailed technical specifications [1] [2], supported by comprehensive HVDC grid design studies and system-level analyses [3] [4] [5].

Consistent with findings reported in the literature [6], Dynamic Braking Systems (DBSs) were identified as a key component requiring careful specification and design when transitioning from conventional P2P HVDC schemes to MTDC grids. While several DBS technologies and control philosophies are currently available in the industry, they have primarily been

developed for single-vendor P2P HVDC applications featuring a single DBS.

Moving to MTDC grids raises new questions regarding DBS specification, sizing, and placement, while the introduction of multiple vendors may further require the coordination of independent implementations. Moreover, the introduction of DC Circuit Breakers (DCCBs) and associated DC Fault Ride-Through (DC-FRT) requirements fundamentally modifies DC fault management strategies. Combined with the limited overcurrent capability of converter-based technologies, this may require design adaptations, such as increased DC-side inductance, with significant implications for the overall transient and dynamic system response [7].

However, the resulting impact on DBS performance and design remains insufficiently investigated. In particular, the adequacy of current DBS solutions and the potential need for additional functionalities to ensure the desired response in such environments warrant further assessment. In practice, the absence of widely accepted generic DBS models capable of accurately representing different solutions in DCCB-based MTDC grids, challenges the refinement of DBS specification and the identification of potential coordination requirements.

Existing simplified functional DBS models are often considered sufficient for conventional P2P HVDC studies: The expected system-level behaviour, the response of the

simplified models, and the performance of existing technological DBS solutions generally align. In MTDC grids, however, this assumption remains to be verified, as the dynamic behaviour observed with simplified DBS models may not lead to the expected behaviour, and/or it may not match the performance achievable with current industrial implementations, particularly in the presence of DC reactors.

To address these gaps, this paper develops several generic DBS models and evaluates their impact on the system-wide dynamic response of the InterOPERA three-terminal (3T) base case and a variant of the five-terminal (5T) reference topology under a broad range of operating conditions and disturbances. In line with the InterOPERA project's assumptions, DBSs are located at each onshore converter station.

Particular attention is given to potential cross-vendor interactions, examining how design choices within one subsystem may influence the dynamic stress and performance of other equipment. To this end, extensive sensitivity analyses are conducted. The main contributions of this work are threefold: i) the development of generic DBS models suitable for DC grids with large inductances, ii) the demonstration of the need to account for DBS behaviour during in MTDC grid pre-design studies, and iii) the assessment of potential DBS coordination requirements in MV projects.

This paper is organized as follows: Section 2 details the study assumptions, modelling approach, and simulation framework. Section 3 investigates the impact of DC-side inductances on the performance of selected generic DBS models in a P2P sub-topology of the investigated InterOPERA 3T system— i.e., a topology comparable to existing P2P HVDC links. Section 4 presents the results obtained with different DBS models on the InterOPERA 3T base case. Section 5 extends the analysis to the 5T topology. Section 6 addresses DBS coordination aspects and discusses the corresponding results. Finally, conclusions are drawn in Section 7.

2. Modelling and Methodology

Section 2.1 describes the InterOPERA HVDC grid use case, while Section 2.2 reviews the preliminary DBS requirements retained for the demonstrator. Section 2.3 presents the implemented DBS models and parametrization. Lastly, Section 2.4 outlines the simulated scenarios.

2.1 HVDC grid topology and DC fault protection concept

Fig. 1 presents the InterOPERA demonstrator DC grid topology, previously described in [4]. The complete benchmark, shown in Fig. 1 (b), consists of a meshed 5T HVDC system including five DC switching stations (DCSSs). Each converter station consists of a bipole rated at 2 GW and the nominal voltage is set to 500 kV. Depending on the availability of converters and transmission lines, the grid can be operated in different configurations.

While different allocations of onshore and offshore stations have been explored [3] [8], this work assumes that the western

converter stations (north-west and south-west) are connected to onshore transmission systems, whereas the eastern stations (north-east and south-east) are connected to offshore WPPs. Three representative cases are considered in this work:

- **P2P configuration** (Fig. 1 (a)), connecting one onshore and one offshore converter station through three DCSSs and a 400 km cable.
- **3T configuration** (highlighted in Fig 1 (b)), a radial DC grid with an additional onshore converter station and DCSS connected to the central DCSS (#5).
- **5T configuration**, the complete meshed topology, with all converters and lines in service, comprising two offshore and three onshore converter stations.

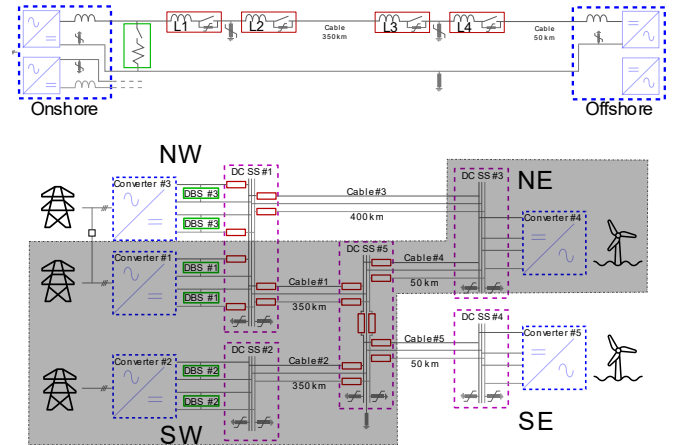


Fig. 1 (a) View of the HVDC grid containing 2T, (b) View of the full 5T topology and the 3T-base case (marked in grey).

This work follows the InterOPERA demonstrator design study approach, which relies on generic models during the preliminary phase to ensure vendor neutrality. The behaviour of these models was reviewed by the participating equipment vendors, who confirmed their functional representativeness and thereby the relevance of the obtained results. As reported in [4] [5], the generic EMT model of the InterOPERA demonstrator includes detailed representations of HVDC converter stations, wind power plants (WPPs), DCCBs with their associated DC reactors, surge arresters, and frequency-dependent DC cable models.

The InterOPERA DC fault protection strategy is based on the concept of Fault Separation Zone (FSZ) and Fault Clearing Zone (FCZ). An FSZ defines the area within which a DC fault can be eliminated by Fault Separation Devices (FSDs) such as DCCBs. An FCZ defines an equal or more restricted area within which the faulty part of the network can be isolated from the healthy part once the fault current has been interrupted. In line with previous studies, DCCBs located in DCSSs #1 and #5 are equipped with 200 mH reactors. In addition, to fulfil the InterOPERA DC-FRT requirements applicable to converter stations, 150 mH DC reactors are installed at each converter DC HV terminal. Their impact is partially assessed in Section 3 through comparison with cases where no converter-side reactor is considered. As shown in several sensitivity analyses, large inductances influence the dynamic behaviour of MTDC networks [1], with the

magnitude of observed phenomena – potentially also DBS-related dynamic phenomena – expected to be dependent on the level of DC inductance [4]. Hence, alternative protection schemes (e.g., studied in [9]) may be less susceptible to the challenges discussed in this paper. However, such investigations lie outside the scope of this work.

The InterOPERA demonstrator insulation coordination is based on maximal continuous pole voltage of 525 kV (1.05 pu, base 500 kV), leading to preliminary Switching Impulse Withstand Voltages (SIWVs) values of 1050 kV (2.1 pu) and Lighting Impulse Withstand Voltages (LIWVs) of 1050 kV (2.1 pu) or 1175 kV (2.35pu) according to IEC and CIGRE [10] [11]. Surge arresters are installed at each DCSS's busbar, modelled using the IEC 60071-11 V/I characteristic, with 10kA Lighting Impulse Protective Level (LIPL) defined at 980 kV [5].

2.2 Initial DBS requirements

As previously stated, in InterOPERA, the DBSs are installed at the converter DC point of connection (DC-PoC) in onshore stations only. In the North-West station, this corresponds to a location between the converter-side and DCCB-side reactors. In the absence of more detailed design studies, each DBS was rated to absorb 1 GW, corresponding to the maximum power export of a converter pole, for a duration of up to 2 s [2].

Since the purpose of a DBS is to contain DC voltage excursions during dynamic events to prevent unintended protection operation of devices connected to the DC grid, its performance specification is closely linked to the capabilities of neighbouring equipment throughout the DC system, most notably the converter station located at the same DC-PoC. Specifically, DBSs are expected to maintain the DC voltage within the steady-state and dynamic operating ranges specified for converter stations under the considered contingencies [3] [4] [5]. Therefore, the DBS activation threshold must be set above the continuous DC voltage operating limit, i.e., 1.05 p.u. Moreover, during dynamic events, the DC voltage shall remain below the insulation coordination level, thereby avoiding surge arrester operation. Regarding the operating principle, the specification was deliberately left open, allowing for different implementations; an approach that may need revision should interaction issues emerge during the demonstration phase.

Finally, although DBSs may, in general, be considered independent subsystems and potentially supplied separately from the converter stations, they are delivered within the converter station scope in the InterOPERA demonstrator. The analysis presented in this work remains valid regardless of the selected approach for subsystem splitting.

2.3 DBS models

This subsection introduces generic DBS models intended for DC grid pre-design studies. These models must remain sufficiently simple and vendor-agnostic, while realistically reproducing the behaviour of industrial implementations to accurately capture the resulting system-wide dynamic response. This enables the derivation of functional

requirements aligned with system needs and compatible with a broad range of vendor-specific solutions. As shown in Fig. 2, four types of DBS models are considered, each allowing for different implementations. Full details are provided in this subsection.

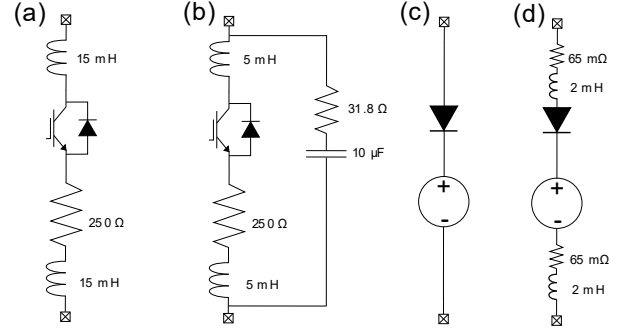


Fig. 2 Schematic representation of four DBS models: (a) Basic_hyst (b) PWM_droop (c) Ideal_droop (d) Ideal2_droop

2.2.1 Basic DBS model (shorten to Basic_hyst): The most widely used generic DBS model consists of a shunt resistor connected through a switching device [2] [6] [12]. The switch is activated when the DC voltage exceeds an upper threshold and deactivated once it falls below a lower threshold.

This operating principle, referred to hereafter as hysteresis control, is illustrated in Fig. 3. The resistor is typically sized to dissipate the rated power at nominal DC voltage. In this work, considering a rating of 1 GW per poles at 500 kV results in a resistance value of 250 Ω. Alternatively, higher values could be selected to absorb 1 GW at the maximum continuous operating voltage of the system (525 kV) or the DBS (540 kV), which is expected to have limited impact on the overall results.

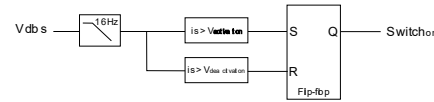


Fig. 3 Schematic representation of DBS basic model control

2.2.2 Switching DBS model (shorten to PWM_droop): To achieve smoother energy absorption during DBS operation, the basic model can be extended by controlling the switching device through Pulse Width Modulation (PWM) [13], allowing the absorbed power to be continuously adjusted as a function of the DC voltage through duty-cycle modulation. In this study, a droop characteristic is implemented between the lower and upper DC voltage thresholds. The control principle is illustrated in Fig. 4. A passive filter is added to suppress harmonics at the PWM frequency switching at 1kHz (see Fig. 2 (b)).

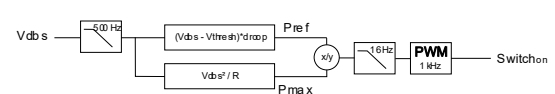


Fig. 4 Schematic representation of DBS PWM model control

2.2.3 Ideal DBS model (shorten to *Ideal_droop*): A new model based on an ideal controlled-voltage source connected in series with a diode is introduced. By directly reproducing the primary function of a DBS, i.e., imposing a fixed DC voltage when activated, it provides a natural implementation-independent idealization of its desired behaviour. In practice, this model can represent an average version of the switching DBS model while covering actual voltage-controlled source implementations. As illustrated in Fig 5, a droop-based control characteristic is also adopted in this case.

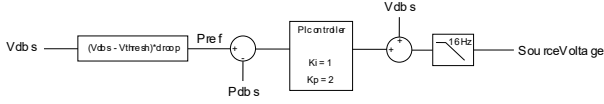


Fig. 5 Schematic representation of the control of droop-based DBS model with an ideal voltage source

2.2.4 Advanced ideal DBS model with power limitation – droop based (shorten to *Ideal2_droop*): This generic DBS model is based on the ideal DC voltage source, an aggregated diode to keep the DBS current unidirectional (same as *Ideal_droop* model), and additional small reactors in series for the current gradient limitation. The control is always droop based – even for a voltage threshold activation option (where the slope is very stiff, representing the DC voltage drop over the DBS circuit resistances in the steady state). Besides the proportional action of the Pdc/Vdc droop characteristics, a current limitation of the DBS unit is also implemented in the control to consider limitations of components in actual DBS realisations.

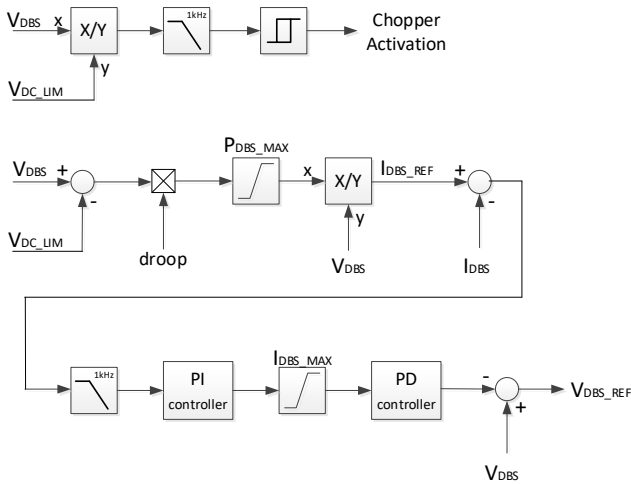


Fig. 6 Schematic representation of the control of droop-based DBS model with an ideal voltage source and current limitation

2.3.5 DBS model settings: Parametric investigations are conducted while maintaining a fixed DBS design and location. The base case settings selected to provide comparable DC voltage containment and energy absorption performance across the different DBS representations are summarized in Table 1. Variants are explored in Section 6.

Table 1 DBS model settings

Hysteresis control	Activation voltage	540 kV (1.08 pu)
	Deactivation voltage	525 kV (1.05 pu)
Droop control	Threshold voltage	537.5 kV (1.075 pu)
	Droop	500 MW/kV

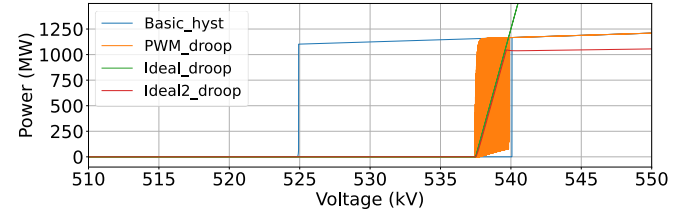


Fig. 7 DBS functional characteristic

The static characteristics of the four DBS models considered in this work are obtained by applying a slowly increasing then decreasing DC voltage at the device terminals. As shown in Fig. 7, power absorption starts at the selected upper threshold (540 kV) in a stepwise manner, and then increases linearly according to the resistive behaviour for the *Basic_hyst* model. The same droop characteristic is used for the three other models, irrespective of their underlying electrical implementation. One limitation of the proposed *Ideal_droop* model is that the absorbed power is not inherently bounded. Consequently, results obtained with this simpler model should be interpreted with appropriate caution.

2.4 Scenarios

For selected initial operating conditions, described in the relevant sections, the following events are considered:

- Three-phase temporary solid AC fault (100 ms) at the onshore PoC of the NW station(s)
- Pole outages of one onshore converter station (at NW), with two cases for the DBS at the affected station:
 - remaining in operation, and
 - out of service with the associated converter.

3 P2P configuration: DC side inductance impact on the DBS generic model performance

Before addressing the behaviour of the DBS in a complex MTDC grid, an initial study is carried out to evaluate the response of the various generic models under onshore AC faults in the presence of large DC reactors near the DBS (Configuration P2P introduced in Section 2.1, see Fig. 1 (a)). The reference case (Case 0) corresponds to a conventional HVDC link connecting an offshore WPP, with no additional DC reactors (L1 and L2) installed in the vicinity of the DBS. However, DCCB reactors located in the central station (L3 and L4), which form part of the InterOPERA design, are maintained in all cases investigated in this section. Section 3.1 focuses on the simple DBS model (*Basic_hyst*), while Section 3.2 compares the results obtained with the alternative implementations.

3.1 Simple model response in the presence of DC reactors

Five cases are considered to illustrates the impact of the progressive addition of inductances:

- Case 0: $L_1=L_2=0\text{mH}$ (no extra reactor near DBS)
- Case 1: 150 mH only on the converter side (L_{conv})
- Case 2: Addition of 200 mH on line side (L_{conv} , L_1)
- Case 3: Another 200 mH on line side (L_{conv} , L_1 , L_2)
- Case 4: Only the 2x200 mH on the line side (L_1 , L_2)

Fig. 8 shows voltage measurements at different locations, including the converter DC-PoCs, the valve side, and the DC cable side. Fig. 9 illustrates the energy absorbed by the DBS and the surge arresters (considered exclusively at the DCSS busbar [5]). It is observed that the voltage measured on the cable side remains relatively smooth and similar across all investigated cases, indicating that the primary objective of limiting the cable voltage is effectively achieved. However, when inductances are added on the line side of the DC-PoC, the simple bulk resistance DBS model (*Basic hyst*) exhibits chattering, resulting in large voltage spikes at the DC-PoC.

Since performance requirements are typically specified at this interface (i.e., the DC-PoC) in MV projects involving separate converter, DCSS, and cable suppliers, dynamic DC voltage limits must be defined at DC-PoC, which may become non-trivial in the presence of recurring high-frequency transients.

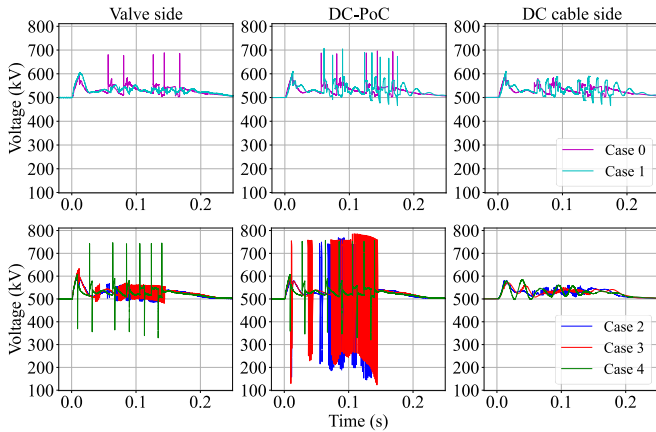


Fig. 8 DC voltage at different locations (onshore station)

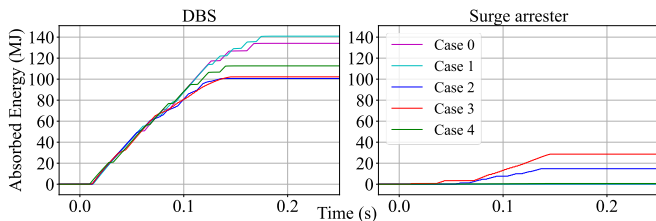


Fig. 9 Absorbed energy in the DBS (left) and for all the surge arresters (right) for the 5 cases described above

This phenomenon is a consequence of the abrupt insertion and removal of the resistance, which introduces high current derivatives that, in turn, generate large voltage drops across reactors. The effect is significantly amplified when the reactors are placed on the line side (typically associated with the DCCBs) as in cases 2, 3 and 4. In these configurations, the limited rate of change of current through the added inductances reduces the voltage stabilisation normally provided by the

cable's capacitance. Furthermore, cases 2 and 3 (with inductances on both, converter and line, side of the DBS) exhibit sustained surge arrester conduction, which is undesirable during such events.

3.2 Other DBS model responses in the presence of DC reactors

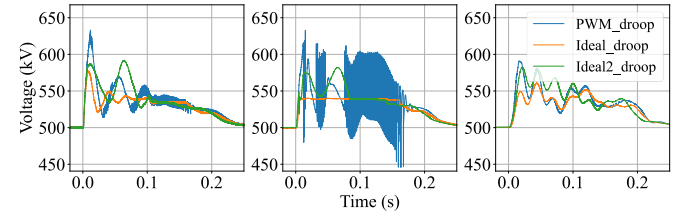


Fig. 10 DC voltages at converter valves (left), DC-PoC (middle) and cable side (right) for different generic DBS models during an AC fault in P2P with DC reactors (case 3)

Fig. 10 demonstrates that all alternative DBS representations significantly reduce the amplitude of the DC voltage spikes, thereby preventing spurious surge arrester conduction. Residual oscillations are still observed in the *PWM_droop* implementation despite the presence of a passive filter, while the ideal voltage-source models exhibit the smoothest response for comparable levels of absorbed energy. These results highlight the limitations of the *Basic hyst* representation when studying MTDC grids containing multiple inductive elements, notably DCCB reactors, and show that they can be overcome by using alternative models.

4 3T configuration: DBS model behaviors

As in P2P applications, DBSs are primarily introduced in MTDC grids to prevent converter overloading when operating in even-terminal topologies where temporary power imbalances cannot be compensated (e.g., 2T and 4T configurations). However, they may also support voltage containment when operating in odd-terminal topologies, such as the 3T InterOPERA base case considered here, potentially relaxing some design constraints, which represents a new utilisation context for DBS.

Dynamic design studies of the InterOPERA 3T base case were presented in previous work excluding DBSs [4]. With only one offshore station, power export can always be maintained following AC faults or pole outages at either of the two onshore stations. Nevertheless, Figs. 11, 13 and 14 show that the resulting dynamic response is characterised by significant DC voltage excursions. The analysis is therefore revisited in this work considering various generic DBS models.

Sections 4.1 and 4.2 present the system response following an AC fault and a pole outage at NW (CNVS #1), respectively, while considering full power export from NE (CNVS #3) to NW, with SW (CNVS #2) compensating for losses. Sections 4.3 and 4.4 then examine the robustness of the observations with respect to the number of DCCB reactors and the converter DC voltage control settings. Section 4.5 assesses the impact of DBS integration on the overall outcomes of the system design study by aggregating results across a wide range of scenarios.

At this stage, identical DBSs (same model type and settings) are assumed at both onshore stations for each simulation.

4.1 AC fault example

Fig. 11 (left) confirms that the observations made for the P2P configuration extend to the 3T topology: the *Basic_hyst* DBS model exhibits high-frequency voltage spikes at the affected station's (CNVS 1) DC-PoC, which are absent with the voltage-source implementations. Moreover, this phenomenon remains confined to the affected station DC-PoC, while the DC voltage at the remote stations follows a similar trajectory irrespective of the DBS model considered (see CNVS 2 in Fig. 11 (right)).

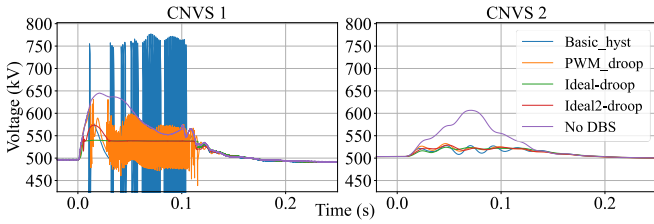


Fig. 11 DC voltage – Temporary AC fault at NW (CNVS 1)

It is also worth noting that only the DBS at the affected station (NW, CNVS 1) is triggered, as the activation threshold is not reached at the other onshore station (SW, CNVS 2) in any of the cases considered. Consequently, no evidence of a need for coordination between DBSs installed at different stations is observed for the InterOPERA 3T base case during AC faults.

4.2 Pole outage example

This section investigates two NW converter pole blocking scenarios, depending on whether the DBS at the affected terminal remains operational or also blocks. Although DBSs are not intended to systematically block following such events, blocking may occur under exceptional conditions and must therefore be considered during system design studies

4.2.1 Converter pole and DBS blocking: With the loss of the DBS at the affected terminal (CNVS 1), the DC voltage excursion at the surviving station (CNVS 2) reaches the DBS activation threshold as observed in Fig. 12.

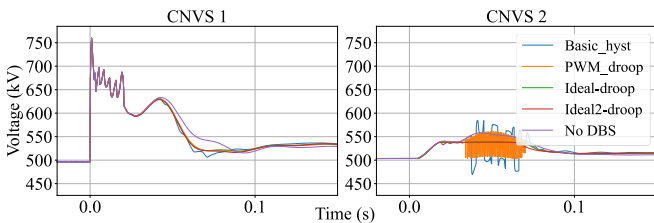


Fig. 12 DC voltage during an unexpected pole outage at NW

This result further illustrates the DBS contribution to overvoltage containment in 3T grids. In contrast, the impact on the DC voltage at the affected terminal remains marginal.

4.2.2 Converter pole blocking and DBS remaining operational: Conversely, Fig. 13 shows the significant impact

that an operational DBS at the affected station can have on the overall system recovery following a converter pole blocking event. As in the temporary AC fault case, only the DBS at the affected station is activated, yet its influence extends across the entire DC grid. In the case of a pole outage, the lost power export cannot be restored locally and must be taken over by the remote onshore station through its primary control response. By limiting the DC voltage excursion, the DBS reduces the input signal driving the DC voltage-power droop on the surviving station, effectively slowing down the active power takeover, prolonging DBS operation, and increasing the absorbed energy, which remains well below the rated value.

The dependency observed between the response of DBS at the affected station and the converter at the surviving station indicates that any future coordination strategy may need to consider both DBS settings and converter DC voltage control functions, rather than treating them as separate design aspects.

Notably, there are two aspects to this: The coordination of the converters' DC voltage control with the DBSs' control, and the choice of the DBS model in order to study this coordination. As the first aspect – i.e., the influence on the active power takeover of the healthy converter station – exists irrespective of the model, qualitative sensitivities in this regard are only studied for a single DBS model type in sections 4.3 and 4.4.

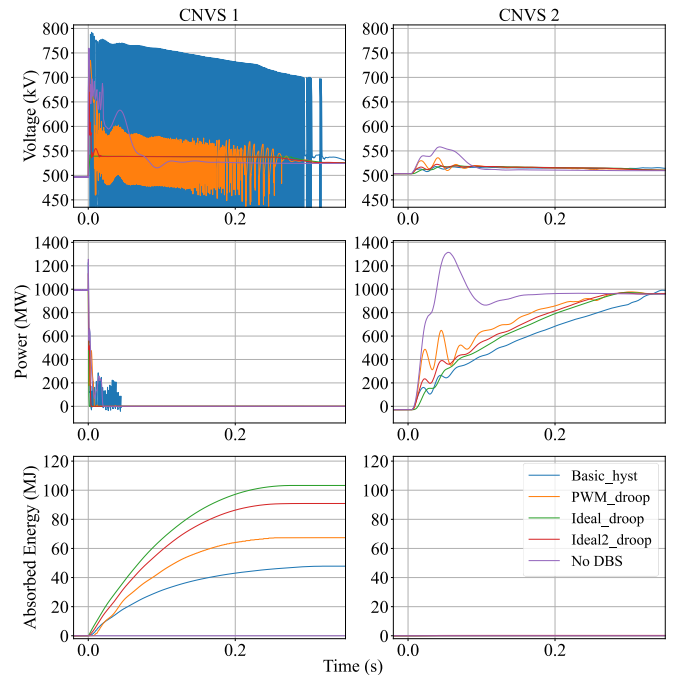


Fig. 13 Blocking of positive pole at NW in the 3T base case. DC voltage at DC-PoC (top), power transmit through converter (middle) and energy absorbed by the DBS (bottom)

4.3 Sensitivity analysis on DCCB reactors for AC faults with the *Ideal_droop* DBS model

The impact of the number of DCCB reactors in the DC grid is investigated using the *Ideal droop* DBS model, with results shown in Fig. 14 and Fig. 15. Two variants are considered in addition to the base case (all DCCBs at DCSSs #1 and #5):

without DCCBs, and with DCCBs only at the busbar coupler of #5. Although the dynamic response is slightly modified, the key observation remains unchanged, with the DC voltage at the remote converter remaining below the DBS activation threshold. The dynamic burden on the DBS is, however, influenced by the level of inductance in the DC grid. By slowing current redistribution between converters, higher inductance delays the power takeover by the remote converter and consequently increases the energy absorbed by the DBS.

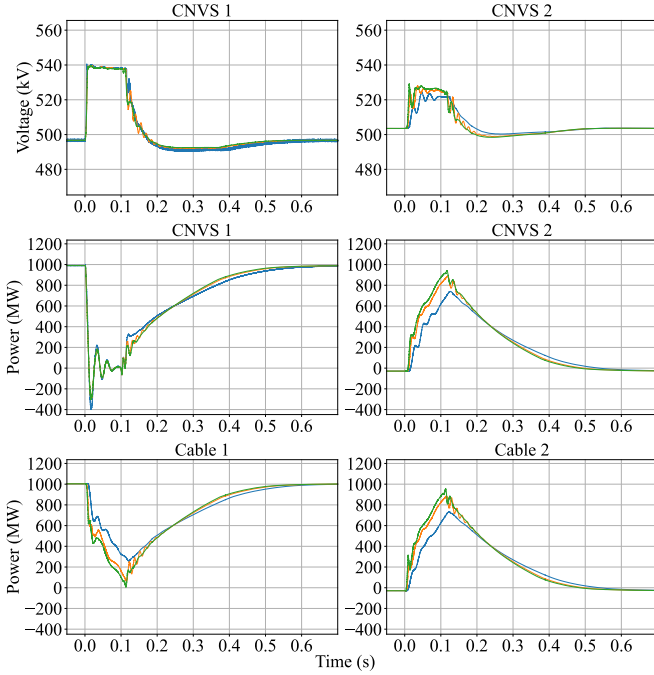


Fig. 14 Temporary AC fault at NW, 3T configuration, DBS model: *Ideal droop*. Converter DC voltage (top), Converter export (middle) and flowing through DC cable (bottom)

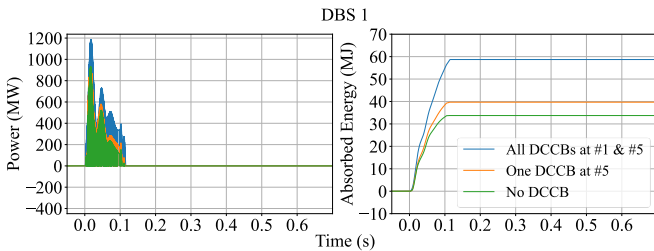


Fig. 15 Temporary AC fault at NW, 3T configuration, DBS model: *Ideal droop*. Absorbed power (left) and Absorbed energy (right) by DBS 1

4.4 Sensitivity analysis of converter control settings following a pole outage with the *Ideal droop* DBS model

This section considers the *Ideal droop* DBS model together with the two converter control variants previously introduced in [4]. The variants consist of a slower the DC voltage control loop (Ctrl var 1) and a reduced contribution from the arm energy control (Ctrl var 2). Fig. 16 shows that the active power takeover by the surviving onshore station is more sensitive to the converter control settings than to the selected DBS model implementation (influence shown in section 4.2). The correlation between the power takeover dynamics and the

energy absorbed by the DBS is nevertheless confirmed: slower converter dynamics result in delayed DC voltage recovery and, in turn, higher absorbed energy.

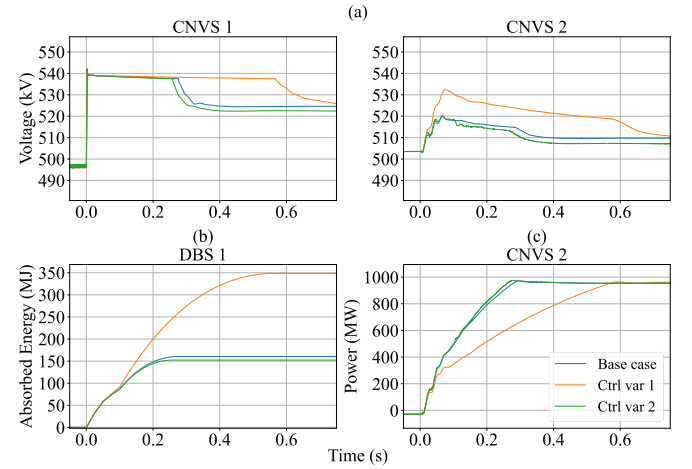


Fig. 16 Blocking of positive pole at NW in the 3T base case, for variation of converter control. (a) DC Voltage at CNVS1 and CNVS 2 (b) Energy absorbed by DBS 1 (c) Power transferred through CNVS 2

4.5 Aggregation of all scenarios

Referring to previous work [4], eight initial operating conditions are considered to cover various DC voltage profiles and active power schedules. All possible pole outages and AC faults are then simulated, resulting in a total of 72 scenarios for each DBS assumption. Temporary over-/under-voltage (TO/UV) profiles are constructed by evaluating the time spent beyond predefined voltage thresholds. Results obtained with different DBS models are compared with those previously reported in [4], where no DBS was included. Here, the DBS at the affected station is assumed to remain operational (even when the converter is blocked). For a meaningful interpretation of dynamic performance requirements, high-frequency transients must be filtered out. The results shown in Fig. 17 are therefore based on DC voltage measurements at the DC-PoC after applying a 200 Hz filter. It is observed that voltage-source based DBS models exhibiting smoother responses (*Ideal droop* and *Ideal2 droop*) effectively reduce overvoltage constraints at the DC-PoC while other DBS models (*Basic hyst* and *PWM droop*) can lead to a higher dynamic voltage range.

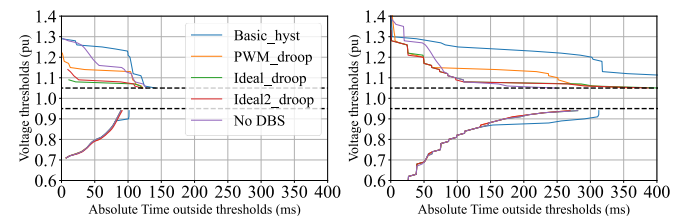


Fig. 17 Aggregation of absolute time outside operational limits for all scenarios in 3T, for AC faults (left) and positive pole trip (right), from measurements filtered at 200 Hz

It can be concluded that the proposed voltage-source DBS models successfully capture the desired capability of DBSs to

mitigate dynamic DC voltage constraints in DCCB-based MTDC grids at DC-PoC. The resulting system-level response can therefore be considered a suitable reference behaviour for DBS functional specification. These models provide a vendor-agnostic basis for early-stage design studies and the assessment of potential coordination strategies.

5 Extension to the 5T configuration

This section investigates the impact of DBS integration on the dynamic behaviour of the full 5T InterOPERA demonstrator topology shown in Fig. 1. In particular, the two onshore converter stations at NW operate in close electrical proximity on both the AC and DC sides. While coupled AC busbar operation introduces common-mode failures leading to overload scenarios, the proximity of the two DBSs creates conditions under which coordination requirements, if any, are expected to become more apparent. The operating point considered assumes full power infeed from both offshore stations, evenly distributed among the three onshore stations, resulting in a converter loading of approximately 70%. For brevity, the assessment is limited to temporary AC fault.

5.1 With opened AC-side coupling

Fig. 18 shows the simulation results following an AC fault at CNVS 1 with the AC busbars decoupled. The DBS activation threshold is reached at the affected station but not at the adjacent one (CNVS 3), due to the DCCB reactors located between the two converters. This demonstrates the ability of appropriately designed DBS to limit transient overvoltage with only marginal impact on neighbouring stations under specific scenarios. In this particular case, the power imbalance is smaller than in the 3T case given the initial power schedule and the recovery is faster, as two surviving onshore stations share the power balancing task. As anticipated, the expanded DC grid exhibits reduced system-wide DC voltage excursions for a single fault, resulting in limited disturbance propagation.

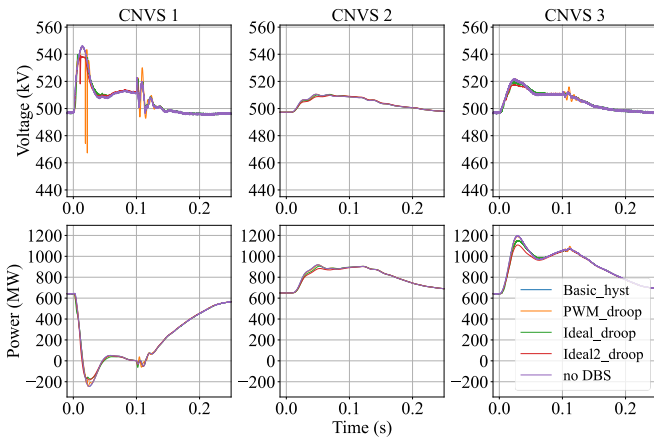


Fig. 18 AC fault at NW, 5T configuration, decoupled busbar, DC voltage and power at DC-PoC

5.2 With closed AC-side coupling

As shown in Fig. 19, coupling the AC busbar of two identical onshore converter stations equipped with identical DBS results

in similar DC disturbances following an AC fault. Specifically, identical voltage measurements are observed at both DC-PoCs (CNVS 1 and 3), naturally leading to equal sharing of the energy absorbed by the DBSs. Interestingly, the remote DBS (SW, CNVS 2) is also activated, but only after fault clearance.

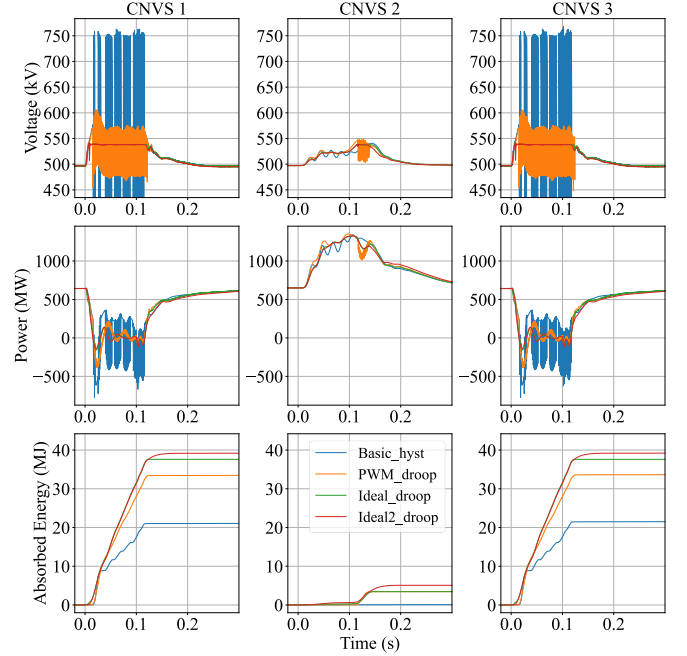


Fig. 19 AC fault at NW, 5T configuration, coupled AC busbar, DC voltage, power and DBS energy at DC-PoC

This somewhat unexpected behaviour is again a consequence of the slow DC current redistribution imposed by the large reactor inductances and highlights the need for a deeper understanding of DBS operation in MTDC grids. Once power is drawn back by the AC system, the DC voltage at the affected station recovers rapidly and the local DBS deactivates before system-wide power balance is fully restored. The resulting temporary power surplus causes the DC voltage at CNVS 2 to rise until the remote DBS activation threshold is reached.

6 Sensitivity analysis of DBS control settings

In practice, DBSs installed at different locations may be supplied by different vendors and therefore rely on distinct technical implementations while complying with the same functional requirements. Having established the suitability of the proposed *Ideal_droop* generic DBS model for vendor-agnostic design studies, this section investigates the sensitivity of the results to selected modelling approaches and settings, including heterogeneous DBS implementations across the system. Section 6.1 investigates the impact of DBS control settings on system recovery following pole outages in the 3T configuration, while Section 6.2 considers the 5T case, where two DBSs operate in close electrical proximity. The focus is primarily placed on high-level parameters that may be subject to system-level coordination, namely the DBS activation threshold and droop gain, since implementation-specific design choices remain outside the scope of interoperability specifications. That said, Section 6.2.3 illustrates that such

implementation differences can also affect individual device solicitation, leaving a residual uncertainty regarding their impact on overall system performance that may ultimately require validation using the final vendor-specific models.

6.1 Converter pole outage in 3T HVDC system

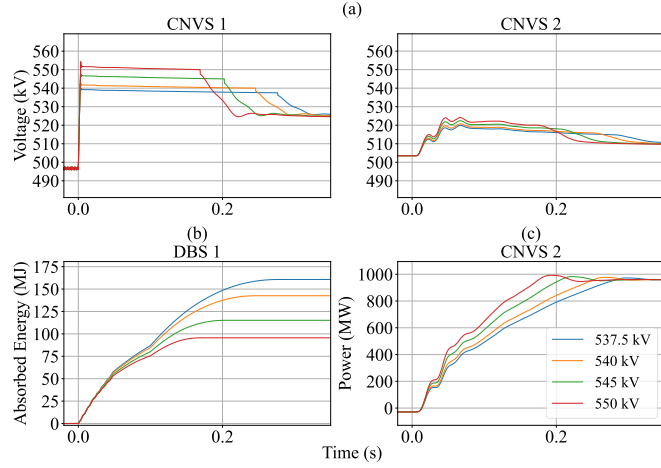


Fig. 20 3T – Sensitivity to activation threshold during pole blocking. (a) DC Voltage at CNVS1 and CNVS 2 (b) Energy absorbed by DBS 1 (c) Power transferred through CNVS 2

In Fig. 20 shows the DC voltage at the DC-PoC, the converter active power, and the energy absorbed by the DBS following the outage of the NW converter (CNVS 1, with DBS remaining operational), corresponding to the scenario considered in Section 4.2.2. The DBS activation threshold is increased from the base-case value of 1.075 pu (537.5 kV) to 1.1 pu (550 kV). As expected, the voltage plateau at the affected DC-PoC shifts upwards accordingly. Interestingly, both the activation duration and the absorbed energy decrease. This behaviour is explained by the increased response of the surviving converter, as the slightly higher DC voltage excursion provides a stronger input signal to the DC voltage-power droop controller, leading to a faster active power takeover. This observation illustrates the reciprocal aspect of the coordination considerations introduced in Section 4.4 (Fig. 16). Just as slower converter controls can increase the energy absorbed by the DBS, DBS settings can influence the control effort required from the converters. Therefore, DBS parameter selection directly influences how the dynamic burden is shared among the different devices participating in DC grid voltage control.

Fig. 21 shows that, for a range of relatively high gains, the DBS droop setting plays a secondary role, as its impact on the system-wide response remains marginal.

6.2 Coordination between DBS electrically close in 5T

This section revisits the scenario examined in Section 5.2 (AC fault and coupled AC-side busbars), introducing asymmetry by varying the activation threshold and droop gain of only one of the DBSs located at NW.

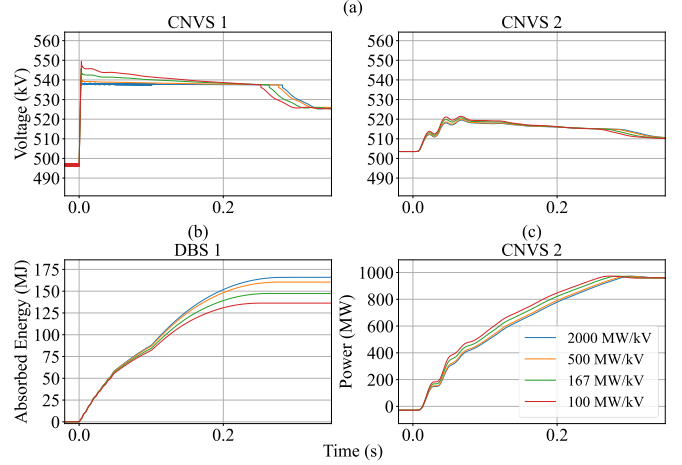


Fig. 21 3T – Sensitivity to DBS droop gain during pole blocking. (a) DC Voltage at CNVS1 and CNVS 2 (b) Energy absorbed by DBS 1 (c) Power transferred through CNVS 2

6.2.1 Voltage threshold variation: Fig. 22 shows the impact of varying the activation threshold of the DBS next to CNVS 1.

As introduced in Section 5.2, the disturbance remains largely local in this case due to its limited magnitude relative to the overall system capability. Consequently, as long as local DBS limits are not reached, the total energy absorbed at the node remains essentially constant. Asymmetry in the activation thresholds therefore mainly influences the sharing of this burden between the two DBSs (Fig. 22 bottom, left and right), with only marginal impact on the overall system response.

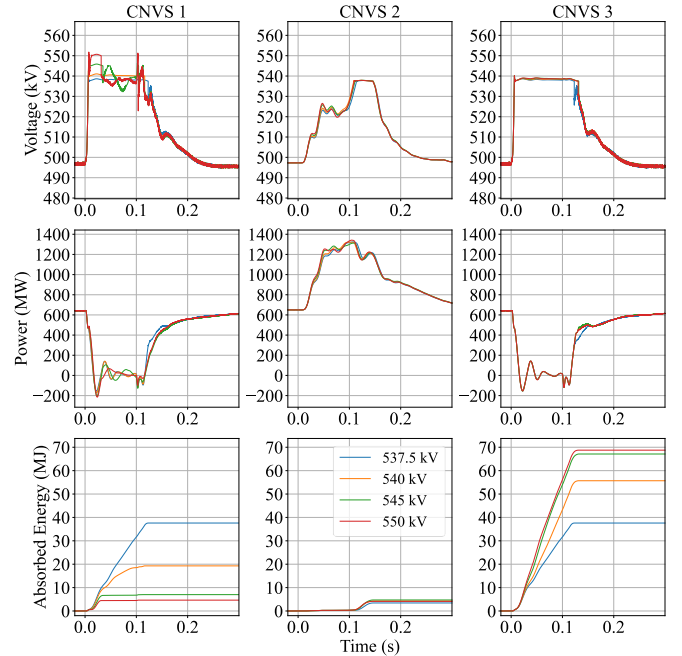


Fig. 22 AC fault at NW. 5T configuration, coupled AC busbar. Asymmetrical DC voltage activation threshold in both DBSs

6.2.2 Droop variation: Fig. 23 shows that analogous results are obtained when introducing asymmetric droop gains between electrically close DBSs by reducing the gain of the

DBS associated to CNVS 1: the burden sharing is modified, while the overall system response remains largely unchanged.

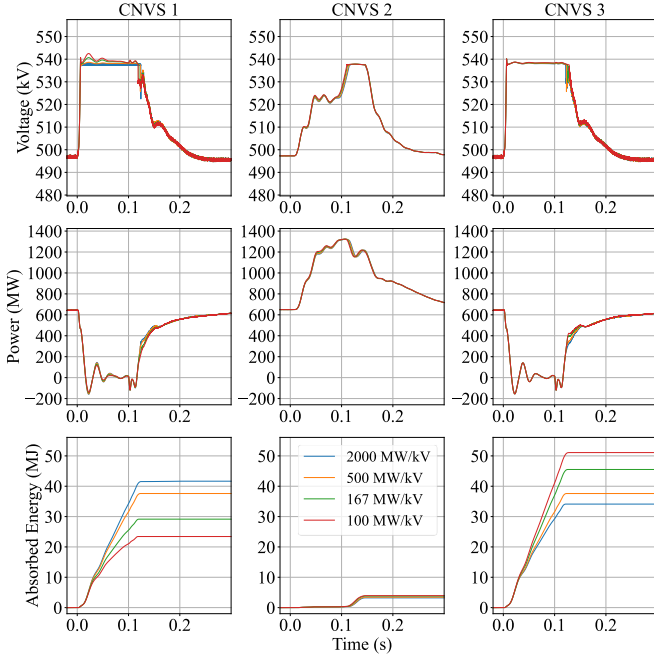


Fig. 23 AC fault at NW. 5T configuration, coupled AC busbar. Asymmetrical Pdc-Vdc droop gains in both NW DBSs

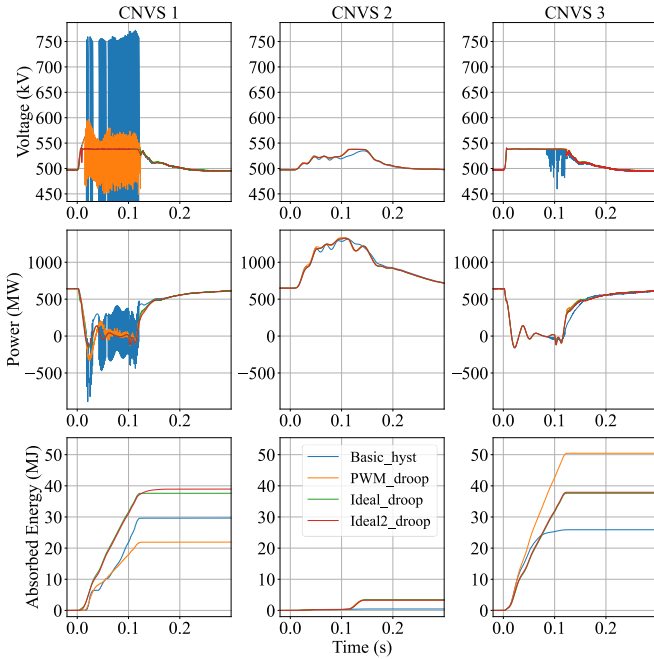


Fig. 24 AC fault at NW. 5T configuration, coupled AC busbar. Heterogenous DBS modelling (associated to CNVS 1)

6.2.3 DBS model variation: Fig. 24 shows analogous results when changing the DBS model associated with CNVS 1. As in the previous sensitivity analyses, the implementation allowing larger DC voltage excursions ultimately absorbs less energy, while the DBS providing stronger voltage containment absorbs a larger share of the dynamic burden. This behaviour is also observed when comparing *PWM_droop* and *Ideal_droop*, despite their equivalent control principle and

settings. These results further confirm that DBS design choices primarily influence burden sharing rather than the overall system response, highlighting the relevance of DC voltage coordination studies, including DBSs, for MV deployments.

7 Conclusion

This paper has demonstrated the importance of considering DBSs in the design of DCCB-based MV-MTDC grids and proposed generic models suitable for vendor-agnostic studies. The results show that large DC inductances, such as those associated with DCCBs, significantly influence DBS dynamic behaviour and may lead to non-representative responses when simplified models are employed. In particular, the conventional hysteresis-controlled resistor model may produce signal chattering, high-frequency voltage spikes, and unintended surge arrester conduction. While these phenomena are a natural consequence of the large voltage drops induced across DC reactors by abrupt DBS switching, they are not desired in a practical DBS implementation.

In contrast, the proposed PWM-based and ideal voltage-source representations successfully capture the capability of DBSs to contain temporary DC overvoltages while avoiding these limitations. Hence, they provide a relevant basis for early-stage MTDC grid pre-design studies and DBS specification. More importantly, the study shows that DBSs can significantly influence the resulting dynamic design constraints. Neglecting their contribution at early project stages may therefore lead to overly conservative specifications or, conversely, to an underestimation of the required system capabilities, potentially increasing costs or compromising performance.

The study further showed that DBS operation is strongly influenced by network topology, DC inductance distribution, and operating conditions. While DBS activation often remains local during AC fault scenarios, converter outages can produce system-wide effects through the DC voltage control response of remote stations, irrespective of whether the DBS at the affected station remains operational or not. Specifically, the results demonstrate that DBS behaviour and the converters' DC voltage controls are closely interrelated: DBS action influences the DC voltage signal driving remote converter responses, while converter control settings directly affect DBS operating duration and absorbed energy. These dependencies are further reinforced by the slower current redistribution between converters in the presence of large DC reactors. As a result, DBSs specification cannot be performed in isolation, but must be integrated into the overall DC voltage control strategy of the MTDC grid.

Sensitivity analyses also demonstrated that individual DBS design choices primarily affect burden sharing rather than the overall system response. Heterogeneous implementations and parameter settings generally lead to comparable system-level performance, in terms of DC voltage containment, indicating a good degree of robustness from a design-study perspective. However, they can significantly alter the distribution of absorbed energy and control effort among neighbouring DBSs and converter stations. In a multi-vendor environment, this

distinction becomes particularly important, as comparable system-level behaviour may conceal substantially different distributions of dynamic stress among participating devices. Striving for a balanced sharing of the burden appears desirable to maximise asset utilisation, avoid unnecessary oversizing of individual components, and improve system resilience, making it a key objective in the development of future functional specifications and coordination principles. In the meantime, burden-sharing aspects should be carefully assessed during the interaction study phase using vendor-specific models.

Finally, the study assumed fixed DBS locations and a predefined DC protection strategy inherited from the InterOPERA framework. Yet, as DBS behaviour has been shown to be strongly dependent on topology and inductance distribution, assessing alternative placements and protection philosophies represents an important topic for future research.

8 Acknowledgements

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