

MULTI-TERMINAL MULTI VENDOR HVDC GRID DESIGN STUDIES – PART I: LOAD FLOW STUDY AND CONTINGENCY ANALYSIS

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Abstract

Multi-Terminal (MT) HVDC networks have been studied for over a decade, with recent efforts increasingly focusing on enabling multi-vendor interoperability to support a competitive and scalable deployment framework. Concurrently, protection selectivity is receiving renewed attention in the context of large-scale offshore connections based on 2 GW bipolar building blocks, where the maximum loss of infeed has become a critical planning constraint. This three-part series addresses early-stage system-level studies of MT HVDC grids using generic models, which are essential to support primary design. As part of the InterOPERA project, involving HVDC vendors traditionally responsible for DC-side design in point-to-point schemes, a methodology is proposed to instantiate project-specific technical requirements at subsystem DC point-of-connection. This first part focuses on steady-state studies to determine *secure* DC voltage ranges and primary control settings, ensuring N-1 compliance. For the considered three-terminal topology, different configurations of converter station connections (to onshore grids and offshore wind farms) are analysed. The case with two onshore and one offshore station exhibited the narrowest margins, prompting the definition of configuration-specific settings for the InterOPERA demonstrator. The same approach is shown to be relevant for degraded modes arising from permanent asset unavailability, with particular attention to pole-to-ground voltages under asymmetrical operation.

1 Introduction

Driven by the increasing scale of Offshore Wind Farms (OWFs) and the growing need for greater cross-border inter-connection capacity, bipolar High Voltage Direct Current (HVDC) systems based on Modular Multilevel Converter (MMC) technology are expected to play a key role in future transmission networks. However, concerns regarding the techno-economic feasibility of relying exclusively on Point-to-Point (P2P) links have prompted the industry to address the challenges of transitioning to Multi-Terminal (MT) grids.

In this context, the InterOPERA project was launched to enable future HVDC systems from different suppliers to operate together, paving the way for the actual implementation of Europe's first MT, Multi-Vendor (MV), multi-purpose HVDC projects. InterOPERA has already achieved several key milestones, including the development of common functional specifications [1] and minimum interface requirements [2]. A Real-Time (RT) demonstrator is currently being deployed to validate and refine the proposed methods and processes, ensuring their practical applicability. This work focuses on activities supporting the implementation of the RT demonstrator, particularly HVDC grid design studies using vendor-agnostic generic models, that provide input to detailed subsystem specifications.

1.1 InterOPERA HVDC Grid Design Studies

The topology of the InterOPERA demonstrator, based on 2 GW bipoles, was first proposed in [3]. In parallel, general functional requirements, focusing on new DC-side capabilities to maximise interoperability by design, were jointly defined by project stakeholders [1]. Building on these inputs, detailed technical specifications for the demonstrator were developed [4], supported by dedicated system design studies that established appropriate numerical values for specific requirements. Three study packages were defined, as schematised in Fig. 1.

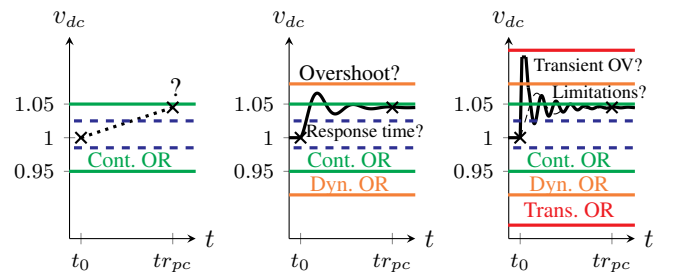


Fig. 1 Schematic representation of the scope of design studies: DC load flow and contingency analysis (left), dynamic (centre), and transient (right), with $t_{r,pc}$ the response time of the primary DC voltage control, OR Operating Range, and OV OverVoltage

In summary:

- DC Load Flow (LF)-based contingency analysis verifies the existence of *acceptable* final states (i.e., within the continuous operating range) following selected outages;
- dynamic studies confirm the existence of an *acceptable* trajectory (i.e., stable operation without inadvertent protection triggering) following selected contingencies;
- transient studies ensure that maximum equipment stresses remain *acceptable* (e.g., below specified withstand levels).

1.2 Design Study Scope Separation and Sequence

For classic P2P links primary design typically starts with main circuit parameter calculations based on LF analysis, followed by transient simulations with detailed models covering both internal and external faults to specify high-voltage equipment. Dynamic studies, focusing mainly on control and protection, are usually carried out last. Industry consensus exists on the boundaries—if not formally defined in terms of a time window, then at least on the phenomena of interest—guiding relevant modelling choices and scenario definitions. For instance, grid-side AC faults are generally addressed in dynamic investigations, whereas converter-side short circuits are treated in transient studies, since in insulated-cable P2P HVDC links the entire DC system is tripped under such faults [5]

As illustrated in the companion papers [6, 7], the traditional boundary between dynamic and transient studies becomes less distinct in MT grids with DC fault-handling capability, since adequate dynamic performance is required to enable recovery of unaffected system parts after DC fault clearance. Similarly, DC Switching Units (DCSUs) equipped with DC Circuit Breakers (DCCBs) typically include an inductance to limit the rate of fault current rise, which significantly affects system dynamics. Consequently, an overlap arises between the scopes of the two study packages, particularly regarding the events to be analysed. The distinction lies in their focus: time frame and whether affected units or only surviving assets are considered. In addition, DCSU reactors introduce losses and voltage drops, also influencing steady-state performance [8]. Furthermore, an operational *reserve* must be maintained in terms of DC voltage and power headroom to ensure acceptable final states following selected contingencies, while relying solely on specific remedial actions, in line with classical operational security principles applied in large-scale AC systems [9]. This requirement creates the need for a contingency analysis, which can be performed using DC LF calculations covering a wide range of operating modes and conditions, to ensure that N-1 security can be achieved in operation with the proposed design; precisely the focus of this first part.

1.3 MT MV HVDC Grid Design Studies: A Three-Part Series

Key findings from the InterOPERA HVDC grid design studies are presented in a series of three papers reflecting the three predefined study packages:

1. **Part I – DC load flow study and contingency analysis** (this paper) verifies that primary DC voltage control capabilities and continuous operating ranges defined for the InterOPERA demonstrator support the application of intended operational principles, e.g., the classical N-1 rule.
2. **Part II – Dynamic study** quantifies temporary excursions of key electrical quantities, notably DC voltage at subsystems' DC Point-of-Connection (DC-PoC), with a focus on AC/DC converters. Selected contingencies include single and bipole outages caused by converter blocking and subsequent trip, as well as temporary grid-side AC faults. The study derives minimum operating ranges for all DC-connected subsystems, within which continuous operation must be ensured, from observed dynamic bands.
3. **Part III – Transient study** evaluates transient stresses on subsystems during DC faults and throughout the fault separation process, particularly on AC/DC converters and DC Switching Stations (DCSSs), while accounting for insulation coordination. It confirms preliminary requirements for minimum equipment withstand levels and, for the purposes of system design studies, validates assumptions regarding surge arrester protective levels, pole cable DC-Temporary Overvoltage (TOV) and neutral system design, including the rated voltage of the Dedicated Metallic Return (DMR) and the minimum value of the grounding resistor.

In practice, the InterOPERA HVDC grid design studies followed the sequence adopted in this paper series: dynamic studies preceding transient studies, with the transient model originally created as a refinement of the *preliminary dynamic model*. This order was chosen primarily due to the project's emphasis on control interaction issues, typically addressed in dynamic investigations, and to initial uncertainties regarding key assumptions on the protection scheme and fault separation device capabilities. While in other contexts the reverse order may be equally valid, an iterative process is always required to confirm design outcomes. In this paper series, the dynamic study is therefore conducted using the *final transient model*.

As an additional disclaimer, each study package focused on specific events to limit workload. Identified gaps were addressed through clauses in the demonstrator specification; for instance, transients associated with blocking events were fully contained within the Original Equipment Manufacturer (OEM) scope [4]. Furthermore, the absence of widely accepted generic models for advanced functionalities, such as temporary blocking—which AC/DC converters may use to support DC fault ride-through—prevented a complete evaluation of system recovery. Insights on these topics are expected from the demonstration phase, relying on vendor-specific solutions. For actual projects, a more comprehensive assessment is recommended. An important realisation from applying the proposed design study process is that interoperability risks extend beyond control interaction issues, encompassing more fundamental capability incompatibilities that cannot be resolved through software updates at later project stages. Such risks must therefore be anticipated early, as they may directly affect the primary design of equipment.

In InterOPERA, certain device-specific capability limits were taken into account from the outset to avoid potential redesigns that could have conflicted with the project's timeline and resources. In more general contexts, where not all OEMs are involved at the system design phase, such early access to detailed data may be unrealistic. To address this, the present series incorporates selected parametric investigations.

The remainder of this paper is organised as follows. Section 2 outlines the proposed methodology and key modelling assumptions. Section 3 summarises the main findings from the DC LF study and contingency analysis, with detailed results previously reported in [8] and provided in Appendices A and B for reference. Section 4 extends the investigation to include losses, degraded operating modes (accounting for permanent asset unavailability and changes in the DC grid grounding location), and neutral voltage shifts associated with asymmetrical operation. Finally, Section 5 presents the conclusions.

2 Assumptions, Methodology and Tools

The detailed HVDC grid design study task included an assumption alignment phase involving subsystem vendors to refine the demonstration scope and establish relevant generic parameter values. A Three-Terminal (3T) base case, shown in Fig. 2, was defined, comprising three AC/DC converter stations, without upfront assumptions on whether stations are onshore or offshore, and four DCSSs. Only the North-West (NW) and the central DCSSs (#1 and #5) are equipped with DCCBs (black-filled squares).

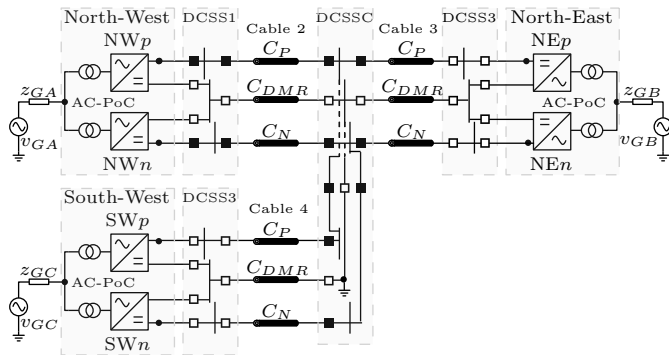


Fig. 2. InterOPERA Demonstrator 3T DC grid topology

Three configurations were explored, with "G" denoting Grid (onshore) and "W" denoting Wind (offshore). The order of stations is NW, South-West (SW) and North-East (NE).

- GGG: all three AC/DC converter stations connected to asynchronous onshore grids;
- GGW: one station (NE) connected to an OWF;
- WWG: only one onshore station (NE), operating in fixed DC voltage control mode, with its outage excluded.

2.1 Key Assumptions for LF-Based Design Studies

As mentioned earlier, the purpose of the DC LF-based design studies is to confirm that a feasible set of operational settings

exists for the base design; otherwise, equipment upgrades may be required. For this purpose, the operational principles must be clearly defined. Additional key assumptions concern the DC grid grounding location, minimum required electrical data (limited to resistance values, particularly for DC cables and DCSUs), and basic subsystem capability requirements.

2.1.1 InterOPERA Demonstrator Operational Principles:

- Operational Security Limits (OSLs), establishing system-level ranges for unlimited operation, are defined based on the technical capabilities of existing 2 GW AC/DC converter stations and 525 kV DC cables. For design studies, the DC voltage continuous operating range, shown in green in Fig. 1, is set to $\pm 5\%$ of the nominal DC grid voltage. With a conservative $U_{DC, Nom}$ of 500 kV, the maximum continuous operating voltage is 525 kV (1.05 pu, with $U_{DC, Base} = U_{DC, Nom}$). In practice, slightly different values may be adopted following a techno-economic assessment. Higher DC voltages are generally preferable, as they reduce transmission losses and mitigate the risk of modulation constraints on AC/DC converter stations at low voltages; however, they impose additional demands on cable design.
- In line with AC system practices from the European System Operation Guidelines (SOGL) [9], five system states are defined for the HVDC grid: normal, alert, emergency, blackout, and restoration [1, 4]. Only the first is relevant in this work: *Normal State means a situation in which the system is within OSLs in the N-situation and after the occurrence of any contingency from the Contingency List, taking into account the effect of the available remedial actions.*
- Remedial actions available to maintain the normal state are here limited to pole-wise primary control schemes applied to onshore stations only, including both continuous and limited DC Voltage Sensitive Modes (DCVSMs) [1]. While alternative schemes could be beneficial in practice, they were excluded for the InterOPERA demonstrator design studies, as the 3T topology inherently provides sufficient active power headroom. This approach may, however, be impractical in other cases (see Section 5.2). Specifically:

- Redispatch and Secondary Voltage Control (SVC) by the DC Grid Controller (DCGC) are treated as alert-state measures, intended to *restore* N-1 compliance, typically after an incident, not to *immediately* respond to the initial outage. In InterOPERA, the DCGC does not autonomously act within the normal range; set points may be manually updated to emulate an operator request. In future applications, performance optimisation tasks may also be assigned if desired by the system operator.
- OWF curtailment is considered an emergency measure, activated via a dedicated scheme once OSLs have been breached (emergency state, akin to AC system defence plans to prevent cascading outages). The coordinated Overvoltage Power Control (OVPC) scheme specifically defined for the InterOPERA demonstrator relies on communication through the DCGC, which weakens the analogy with AC side defence mechanisms.

- Based on these inputs, the system must be designed to ensure N-1 security, i.e., to remain within the continuous operating range under all listed contingencies while relying solely on the defined primary DC voltage control scheme.
- The Contingency List includes both the single outage of any individual asset (ordinary contingencies, as defined in [9]) and the loss of an entire bipole, which accounts for potential common failure modes associated with bundled cables and coupled busbar topologies (exceptional contingencies [9]). In practice, these contingencies are implemented through specific disturbances at each study level. For DC LF-based studies, the outage of a converter unit, a cable pole, or a DCSU is considered equivalent.

2.1.2 Electrical Parameters – DC cable: the InterOPERA design studies' assumption-alignment phase included a consolidation of DC cable parameters and models across the different project work packages. For simplicity, and without loss of generality, a single submarine DC cable type was adopted for all connections, whether to onshore or offshore grids. Variations in cable material, cross-sectional area, or layout, while relevant in practice, are considered out of scope. This assumption is not expected to affect the demonstration of interoperability between subsystems from different vendors, which represents the central objective of the project. Furthermore, system-level design studies focus on electrical stresses at subsystem interfaces rather than along the cable itself. All cable models used across the study levels were based on a single, agreed-upon datasheet, with minor adaptations from [10]. For DC LF-based studies, the grid is represented by a simple resistance, set to **8.63 mΩ/km**, corresponding to a 2500 mm² copper conductor at 70 °C in accordance with IEC 60228 [11]. Voltage and current values are derived from assumed power injections.

2.1.3 Electrical Parameters – DCSUs: reactors introduce both voltage drops and ohmic losses. For LF-based design studies, a conservative approach has been adopted, using a deliberately high yet realistic equivalent resistance of **285 mΩ** per pole, as agreed by the relevant stakeholders. To ensure sufficient design margin, fault separation capability is assumed for all DCSSs, representing a deviation from the InterOPERA demonstrator's selectivity assumption (see Part III – Transient Study [7]). In the DMR, only a busbar and a disconnector are present, their resistance can be neglected for DC LF-based design studies.

2.1.4 Capability Requirements at DC-PoC: this approach removes the study's dependency on converter loss assumptions, as the operating point can be directly defined on the DC side. For onshore stations, the same power rating is assumed in both sending and receiving directions. For offshore stations, only the maximum power rating in the sending direction is considered, with a very limited allowance for power reversal [4].

2.1.5 Neutral System Reference to Ground: under normal operation, the HVDC system is grounded at the central DCSS (#5). Grounding units are available at all DCSSs to support degraded

operating modes and the energisation process [4]. At any given time, only one grounding point is applied.

2.2 Modelling: Primary DC Voltage Control

DC voltage control is implemented pole-wise using a multi-slope droop-type controller based on pole-to-neutral voltages. No station-level (bipole) control is applied. In line with [1], two types of DCVSMs are considered, both employing the classical droop equation (1), but operating within specific voltage bands and applying dedicated settings (s_i , see Fig. 3). Power and voltage setpoints ($P_{DC,0}$, $V_{DC,0}$) are provided by the DCGC:

$$p_{DC} = P_{DC,0} + \frac{1}{s_i}(V_{DC,0} - v_{DC}) \quad (1)$$

- DCVSM operates under normal conditions to maintain continuous power balance and regulate the DC voltage while distributing the control effort across participating units.
- Limited DCVSM (LDCVSM) provides stronger DC voltage support when the voltage approaches OSLs, typically during severe disturbances that create large power imbalances.

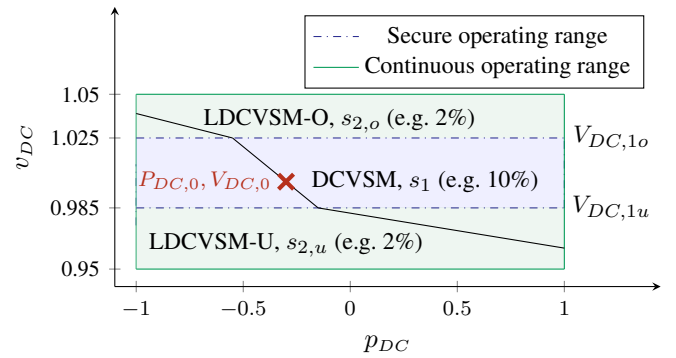


Fig. 3 Continuous and secure operating ranges and DCVSMs slope differentiation in the p_{DC} - v_{DC} plane (GGG case) [8]

The *normal* operating range, as defined in [1], accounts for voltage fluctuations resulting from power flow variations, typically due to changes in load or wind generation. In this work, the *secure* range, shown in blue in Figs. 1 and 3, is introduced to represent the DC voltage range within which the system meets operational security criteria. Both terms are used side by side, following the approach retained in [4]. The knee points of this primary control scheme, where the slope changes, lie at the boundaries of the normal (secure) range, so that the available power headroom varies with the operating point.

2.3 Methodology for DC LF-Based Design Study

To verify that the in-built margins available with the predefined continuous operating range are sufficient for secure operation without unnecessary oversizing, the DC LF study provides:

- a secure operating range, shown in blue in Fig. 3 and delimited by $V_{DC,1u}$ and $V_{DC,1o}$;
- preliminary DC voltage control droop gains (s_1 and s_2), with $s_{2,u}$ arbitrarily set equal to $s_{2,o}$ here for simplicity.

These outcomes can be obtained through an iterative approach:

1. Make an initial guess for the DC voltage secure range.
2. Define scenarios suitable for contingency analysis based on DC power and voltage setpoints ($P_{DC,0}$, $V_{DC,0}$) at relevant locations, thereby emulating the DCGC.
3. Perform DC LF calculations to determine voltages and powers at unspecified nodes (defining candidate initial operating conditions, i.e., N situations) and branch currents.
4. Set preliminary primary DC voltage control droop gains.
5. Conduct contingency analysis by sequentially removing individual assets and recalculating the DC LF to determine post-contingency steady states reflecting the droop response of remaining units.
6. Assess whether the proposed secure range and droop settings allow maintaining all final states within OSLs.
7. If OSL violations occur for DC voltage, power, or current, iterate by refining droop gains and, if necessary, adjusting the secure range limits.
8. If no feasible solution is found, consider hardware upgrades, such as shifting or expanding OSLs.

2.3.1 Preliminary Definition an Initial Secure Range (STEP 1): operating at the lower limit of the DC voltage continuous operating range (0.95 pu) does not provide a valid operating point for contingency analysis, as any outage would lead to OSL violations. Nevertheless, LF results for maximum power transfer under these conditions provide a first estimate of the maximum voltage drop, thereby supporting the definition of the minimum secure range width. For the 3T base case, this corresponds to setting the NW station DC voltage to 475 kV while importing 2 GW from SW (or vice versa), with NE acting as the slack bus compensating losses. With a maximum DC current of 2105 A (1 GW/475 kV per pole), the associated voltage drop can be approximated to 16.92 kV ($2105A \times (700km \times 0.00863\Omega/km + 7 \times 0.285\Omega)$). As an initial assumption, the secure range width is set to 4% (20 kV). The DC voltage margins may be distributed symmetrically between the lower and upper limits, or slightly shifted toward higher voltages to reflect a more realistic operational strategy. In practice, the DCGC generates setpoints based on an optimal power flow that can pursue multiple objectives. In future applications, minimising losses—typically achieved by operating at the highest practical DC voltages—is expected to be a primary consideration, balanced against security requirements. The secure range [$V_{DC,1u}$, $V_{DC,1o}$] is initialised here at [492.5, 512.5] kV ([0.985 1.025] pu). Design studies are conducted with a DCVSM droop of 10%, although, as discussed in Section 4.2, larger values in operation are not excluded but must be carefully assessed. The LDCVSM droop is set to 2% (see Fig. 3), ensuring full power adjustment within the resulting DC voltage margin (2.5% between $V_{DC,1o}$ and the maximum continuous operating voltage). It should be noted that current limitations may also apply, as in InterOPERA, where a DC cable current rating of 2030 A was considered. This constraint ultimately dictated the lower bound of the secure range (492.5 kV) to ensure full power transfer ($\approx 1GW/2030A$) [4].

2.3.2 Scenario Definition (STEP 2): with the minimum (resp. maximum) DC voltage set to 492.5kV (0.985pu) at the receiving end (resp. 512.5 kV, 1.025 pu, at the sending end, the limits of the secure range), six scenarios are constructed by permuting the receiving (resp. sending) end among the three AC/DC converter stations: 1 (NW), 2 (SW), and 3 (NE). An infinite number of variants could be defined based on different power-sharing assumptions among the remaining stations. For the 3T topology, two extreme cases, denoted (a) and (b), depending on the power-flow direction, are retained, resulting in a total of twelve N situations, listed in Appendix A (Tables 4 and 5, cells in **bold**). Only eight scenarios apply to the GGW configuration and four to the WWG case, since inverter-mode operation at maximum power for the offshore station is excluded.

2.4 EMTP DC LF Calculation Tool

The DC LF resolution method has been implemented within the EMTP® simulation tool by leveraging its AC LF calculation capabilities [12]. An iterative process runs multiple LF calculations until the correct operating point is reached. Two types of constraints are available for the DC LF calculation:

- **Fixed DC power injection mode:** a reference active power ($P_{DC,0}$) is imposed, which can be either positive or negative.
- **DC voltage droop control mode:** the multi-droop characteristic described in Section 2.2 is implemented using native EMTP® AC LF devices. This mode defines the relationship between DC voltage and power according to the droop gain.

3 Results from the Contingency Analysis

Results from the DC LF analysis, fully defining N situations (STEP 3 in Section 2.3), were reported in [8] and are provided in Appendix A for completeness (*italic*). The contingency analysis indicates that the numerical results are specific to the system configuration, whereas the methodology itself remains generally applicable. The outcomes of this first design study level also supported the definition of these settings as operational parameters, established at the system level by the DCGC [4], thereby providing operational flexibility and mitigating their contribution to MV interoperability risk.

3.1 GGG Configuration

Applying the preliminary settings proposed in Section 2.3.1 to all AC/DC converter stations ensures compliance with the security criteria for the GGG case (stop at STEP 6 in Section 2.3):

- Secure range: [492.5, 512.5] kV ([0.985, 1.025] pu)
- DCVSM droop gain (s_1) set to 10%
- LDCVSM droop gain ($s_{2,u} = s_{2,o}$) set to 2%

3.2 GGW Configuration

For the GGW case, OSL violations at the offshore station occurred toward the upper bound when default settings were applied. Even very low LDCVSM droop gains (<1%) proved insufficient to manage full power transfer by the surviving

onshore station during maximum OWF production scenarios. To address this, the secure operating range was adjusted to allow more upward regulation (STEP 7) [8], resulting in a tighter range (3.5%) at the limit of the estimated maximum voltage drop. The preliminary settings for the GGW configuration are:

- Secure range: [487.5, 505] kV ([0.975, 1.01] pu)
- DCVSM droop gain (s_1) set to 10%
- LDCVSM droop gain ($s_{2,u} = s_{2,o}$) set to 1%

3.3 WWG Configuration

The default secure range and droop gains (applied exclusively to NE) also satisfy the design criteria for the WWG configuration, as in the GGG case. However, fixed DC voltage control at the onshore station is considered more suitable for this topology (3T with two stations in *constant power*, Vf, mode) and is adopted in the dynamic and transient studies [6, 7].

4 Extended Analysis: Losses, Neutral Voltage Shift and Degraded Modes

Achieving N-1 compliance in the GGW case requires operating the offshore station at a DC voltage close to 1 pu (500 kV). The impact of this constraint on losses, and consequently on operational costs, is discussed in Section 4.1. Section 4.2 highlights the role of the multi-slope droop scheme, which allows higher gains within the normal range while maintaining operational security. The limitations of the results under degraded modes are illustrated in Sections 4.3 and 4.4, emphasising their effect on DC voltage measured to ground.

4.1 Losses Considerations

Tab. 1 compares losses when operating at the upper bound of the secure range (512.5 kV for GGG and 505 kV for GGW) with those at the OSL limit (525 kV). Reported values include DC grid losses but exclude AC/DC converters, and are therefore solely associated with the higher current flowing through the assumed DC cables and DCSU resistances.

At the maximum continuous operating voltage (525 kV), losses amount to 2-3% of the nominal power (1 GW per pole), depending on the power direction. Maintaining a 0.025 pu voltage margin in the GGG case to accommodate steady-state excursions from droop-based primary DC voltage control increases losses by 0.09-0.16% of nominal power (e.g., from 3.01% to 3.17% in N4a).

Table 1 Losses (in % of P_{Nom}) in different scenarios

Scenario (Power direction)	525 kV	512.5 kV	505 kV
4a (NW → SW)	3.01	3.17	3.24
4b (NW → NE)	1.89	1.98	N/A
5a (SW → NW)	3.00	3.16	3.23
5b (SW → NE)	2.00	2.09	N/A
6a (NE → NW)	1.93	2.02	2.09
6b (NE → SW)	2.04	2.14	2.21

In the GGW case, enforcing a 0.04 pu DC voltage margin increases losses by 0.23%, corresponding to relative increases of approximately 5% and 7% compared with the base case, which may motivate the exploration of alternative operational principles and control schemes (refer to Section 5.2).

4.2 On the Importance of the LDCVSM Mode

It was previously noted that the definition of LDCVSMs enables the use of larger values of s_1 . Fig. 4 shows that if all AC/DC converter stations relied solely on DCVSM, OSL violations would occur once droop gains exceed 5%.

- The red cross (x) indicates the initial operating point of each terminal for situation N4a (NW → SW @ 512.5 kV).
- The orange circle (o) represents the final operating point of the healthy pole (positive in this case) for $s = 5\%$.
- The orange plus (+) indicates the final operating point of the affected (negative) pole for $s = 5\%$.
- The black plus (+) indicates the final operating point of the affected (negative) pole for $s = 10\%$.

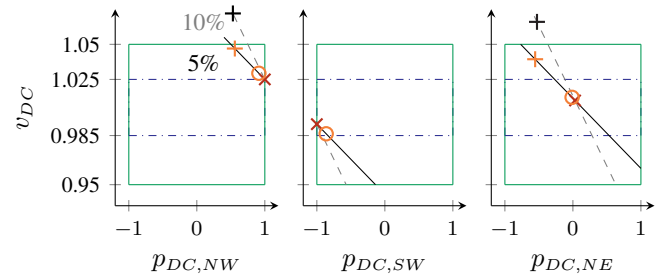


Fig. 4 NW (left), SW (middle) NE (right). DC voltage control response: N4a, outage of the SW negative pole

In practice, applying low droop gains introduces additional challenges, such as greater sensitivity to natural fluctuations from uncontrollable injections and measurement noise, potentially increasing instability risks. By contrast, enabling LDCVSM with a 2% gain in selected stations preserves operational security across all outages while still allowing higher droop gains in the normal operating range.

4.3 Full Asymmetric Monopole Operation

Asymmetrical monopole operation increases transmission voltage drops due to current returning through the DMR, potentially compromising the ability to remain within the predefined secure range, particularly under maximum power transfer. Specific settings or power limitations may therefore be required in these degraded modes to maintain operational security. Fig. 5 shows the positive-pole voltage profiles across the network in a fully asymmetric configuration, where only the positive pole is energised. STEP 1 of Section 2.3 is repeated: the receiving-end voltage is set to the lower bound of the continuous operating range (475kV, 0.95pu) to estimate the maximum voltage drop.

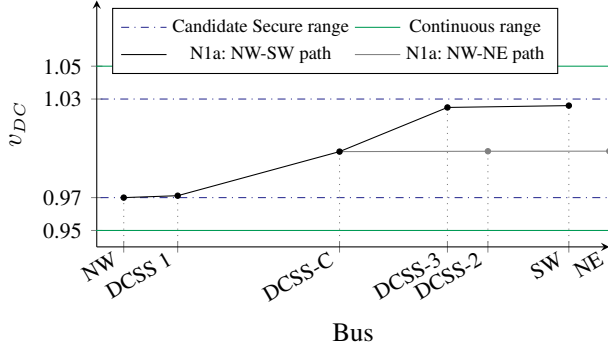


Fig. 5 DC grid voltage profile under fully asymmetrical (positive-pole) operation. Power from NW $\rightarrow$ SW @485 kV

Considering an equivalent cable cross-section, the DMR resistance equals the pole resistance, effectively doubling the total cable resistance and resulting in a 28 kV (5.7%) drop, which exceeds the initial 4% secure range width. A possible secure range for this degraded mode would therefore be [485, 515] kV ([0.97, 1.03] pu). As before, a contingency analysis can be used to validate preliminary droop settings.

4.4 Grounding Location and Maximum Neutral Shift

Special attention must be given to pole-to-ground voltages, as significant neutral voltage deviations during asymmetrical operation may cause pole-to-ground voltages to exceed the OSL, thereby jeopardising DC cable insulation integrity. Previous results, reiterated in Fig.9 (Appendix A), show that during a single-pole outage, the neutral voltage shift can reach 5 kV when grounding is located at the central DCSS, corresponding to 10 % of the continuous operating range. If pole-to-ground voltages must also remain within OSLs while relying solely on the primary DC voltage control scheme, additional margins are necessary, for example, by enforcing pole-to-neutral voltages within the [0.96, 1.04] pu band. This further constrains the design space and may necessitate countermeasures (STEP 8). Table 2 presents final states after an SW station outage under N4a conditions (NW $\rightarrow$ SW, 512.5 kV at NW), with all stations participating in DC voltage regulation (GGG configuration).

Table 2 Load Flow results for N4a following SWn outage (pu)

Pole	U_{NW}	P_{NW}	U_{SW}	P_{SW}	U_{NE}	P_{NE}
Positive	1.028	0.874	0.984	-0.866	1.010	0.030
Negative	-1.036	0.445	-1.045	0	-1.032	-0.443

While these results are unaffected by the grounding location, the neutral voltage shift varies when grounding is moved to the SW DCSS (see Table 3). In this case, the maximum shift approaches 8 kV at NW, bringing the positive pole voltage close to its OSL. In practice, neutral system design is typically assessed in detail during transient studies. This example highlights the need for a coordinated and iterative approach between study packages and supports the selection

Table 3 Neutral and pole-to-ground voltages, N4a (SWn out)

Pole	U_{NW}	U_{SW}	U_{NE}
Neutral (GN DCSS # 5) (kV)	-2.54	5.32	-0.4
Positive (GN DCSS # 5) (pu)	1.033	0.973	1.011
Negative (GN DCSS # 5) (pu)	-1.031	-1.035	-1.031
Neutral (GN DCSS # 3) (kV)	-7.86	0	-5.72
Positive (GN DCSS # 3) (pu)	1.043	0.984	1.022
Negative (GN DCSS # 3) (pu)	-1.02	-1.045	-1.02

of the central DCSS as the default grounding location for the InterOPERA demonstrator. An alternative to preventive measures—such as introducing additional margins when defining the secure range—to address cable constraints under steady-state asymmetrical operation is to apply corrective actions via higher-level controls, such as the DCGC.

5 Conclusion, Discussion and Next Steps

This work introduces a paper series proposing a methodology for conducting HVDC grid design studies, developed within the InterOPERA project and structured in three packages, each addressed by a specific part of the series. Building on previous work [1, 3, 8], a 3T base case is defined and key assumptions are outlined. In many respects, the InterOPERA settings, designed to maximise demonstration capabilities, pose greater challenges than would typically be encountered in a real-world project. For example, the study considers multiple configurations (GGG, GGW, and WWG), in which a converter station may shift from connecting to a strong AC system to an OWF—a scenario that would be unlikely in practice. Nonetheless, this exercise enables exploration of diverse use cases and supports the development of common requirements by station type (onshore and offshore), independently of their physical location or the specific stations to which they connect, i.e., to a limited extent, regardless of topology. It also validates the general applicability of the proposed design study process.

5.1 InterOPERA DC LF-based Design Study Takeaways

This first Part focuses on DC LF studies, including a contingency analysis required within the MT framework when operational security principles from the AC world are applied to DC networks. The inclusion of DCCBs also affects steady-state performance, introducing voltage drops and losses that must be accounted for. The analysis confirms the existence of secure pole-to-neutral DC voltage ranges within the predefined continuous operating limits while evaluating possible droop control settings, thereby validating preliminary ratings. It further highlights the importance of configuration-specific operational parameters and underscores the particular challenges associated with the GGW case.

The effectiveness of multi-slope droop schemes in supporting operational security while facilitating normal operation is demonstrated, confirming the suitability of the functional requirement proposed in [1], based on two DCVSMs, and supporting its adoption in relevant standards.

The study also emphasises the need to plan for degraded modes, such as asymmetrical operation, while carefully considering grounding strategies and their impact on pole-to-ground DC voltages. Finally, trade-offs between maintaining N-1 compliance and operational losses are highlighted.

5.2 Discussion on Remedial Actions

This section presents an open discussion on alternative operational and control strategies for future investigation. While primary control schemes are typically designed to bring the system to a stable equilibrium without communication, maintaining continuous operation at this new operating point is not strictly necessary. In InterOPERA, this conservative assumption was adopted due to the limited maturity of DCGC-based actions and uncertainty about their capability to **ensure**—not merely *restore*—operational security (Alert state).

Relying exclusively on primary control to maintain the system within the Normal state can, however, impose significant design constraints, particularly in topologies such as the InterOPERA full five-terminal configuration with very long cables [3, 4]. In practice, communication-based SVC or alternative automatic schemes could also serve as valid remedial actions to **maintain** the system in the Normal state, as commonly employed in AC system security management.

These approaches require nonetheless careful design, as they involve admitting temporary DC voltage excursions beyond the secure range, and in some cases even beyond the continuous operating range. This could necessitate defining a new *abnormal* range (similar to exceptional AC voltage limits), allowing short-term OSL violations—potentially for durations longer than dynamic events—to accommodate Dynamic Braking System (DBS) activation for instance, thereby postponing the declaration of an Emergency State and the deployment of, typically more drastic, remedial actions.

Further work is required to assess SVC performance, potentially including redispatch strategies, as relying solely on DC voltage shifts may not suffice to maintain and fully restore operational security. Alternatively, autonomous adaptation controls, based on local measurements and excluded from InterOPERA, could be integrated into primary control scheme. How to model these advanced functionalities within DC LF tools remains an open question; meanwhile, their assessment could be conducted within the scope of dynamic design studies; precisely the focus of the next paper in this series: Part II – Dynamic Study [6].

A N Situations: Load Flow Results

Tabs. 4 and 5 show in **bold** the imposed quantities that define the scenario, and in *italic* the results of the LF calculation. Active power is considered positive when injected into the DC grid. Fig. 6 illustrate DC LF results for N1a and N5a situations.

Table 4 N situations – Low voltage cases (pu)

OCs	N1a	N1b	N2a	N2b	N3a	N3b
U_{NW} (pu)	0.985	0.985	<i>1.017</i>	<i>1.002</i>	<i>1.006</i>	<i>0.991</i>
P_{NW} (pu)	-1	-1	1	<i>0.022</i>	1	<i>0.022</i>
U_{SW} (pu)	<i>1.017</i>	<i>1.001</i>	0.985	0.985	<i>0.991</i>	<i>1.007</i>
P_{SW} (pu)	1	<i>0.021</i>	-1	-1	<i>0.021</i>	1
U_{NE} (pu)	<i>1.001</i>	<i>1.006</i>	<i>1.002</i>	<i>1.007</i>	0.985	0.985
P_{NE} (pu)	<i>0.032</i>	1	<i>0.032</i>	1	-1	-1

Table 5 N situations – High voltage cases (pu)

OCs	N4a	N4b	N5a	N5b	N6a	N6b
U_{NW} (pu)	1.025	1.025	<i>0.993</i>	<i>1.009</i>	<i>1.005</i>	<i>1.020</i>
P_{NW} (pu)	1	1	-1	<i>0.021</i>	-1	<i>0.021</i>
U_{SW} (pu)	<i>0.993</i>	<i>1.010</i>	1.025	1.025	<i>1.020</i>	<i>1.003</i>
P_{SW} (pu)	-1	<i>0.020</i>	1	1	<i>0.020</i>	-1
U_{NE} (pu)	<i>1.010</i>	<i>1.005</i>	<i>1.009</i>	<i>1.004</i>	1.025	1.025
P_{NE} (pu)	<i>0.032</i>	-1	<i>0.032</i>	-1	1	1

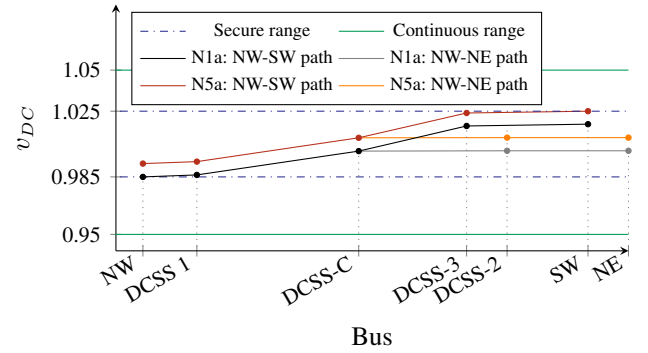


Fig. 6. Voltage profile in the DC grid. N1a and N5a situations

B Previous Contingency Analysis Results

Figs. 7 and 8 include the contingency analysis results from [8] for the GGG and GGW configurations, respectively. Fig. 9 illustrates neutral shift and pole-to-ground voltages.

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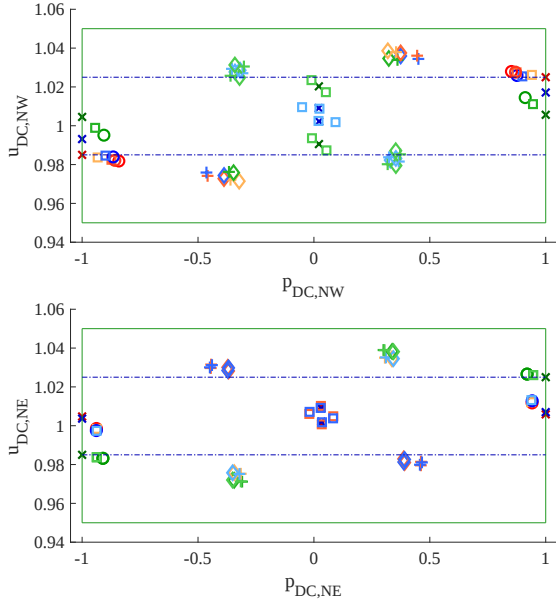


Fig. 7. GGG: contingency analysis. NW (top), NE (bottom)

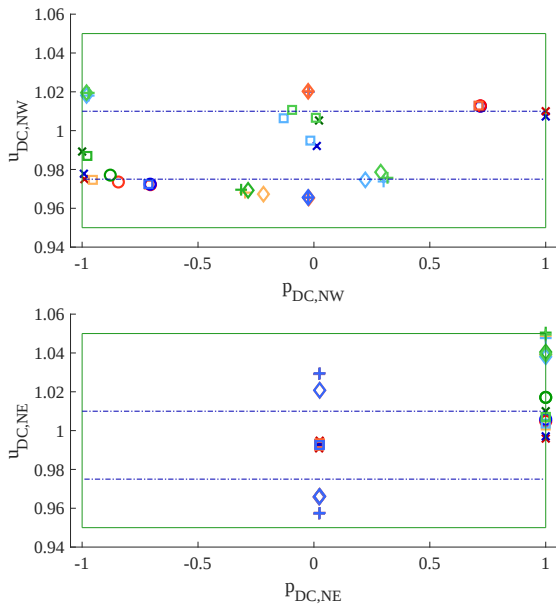


Fig. 8. GGW: contingency analysis. NW (top), NE (bottom)

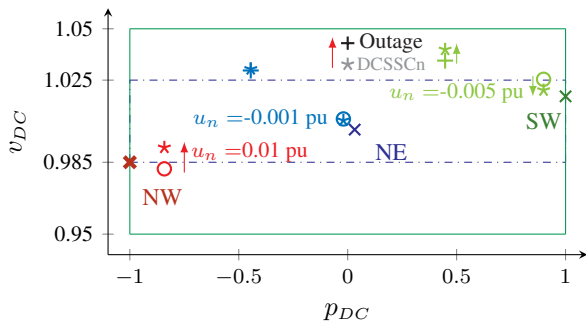


Fig. 9 Pole-to-ground DC voltage: N1a, outage of the NW negative pole [8]

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