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Getting Ready for Multi-Vendor and Multi-Terminal HVDC Technology

Jaqueline Cabañas Ramos [1,*,†,‡], Marc Moritz [1,‡], Nico Klötzl [2,‡], Ceciel Nieuwenhout [3,‡], William Leon Garcia [4,‡], Ilka Jahn [5,‡], Dimitar Kolichev [6] and Antonello Monti [1,*]

[1] Institute for Automation of Complex Power Systems, RWTH Aachen University, 52074 Aachen, Germany; marc.moritz@eonerc.rwth-aachen.de
[2] TenneT TSO GmbH, 95448 Bayreuth, Germany; nico.kloetzl@tennet.eu
[3] Groningen Centre of Energy Law and Sustainability, University of Groningen, 9700 AB Groningen, The Netherlands; c.t.nieuwenhout@rug.nl
[4] SuperGrid Institute, 69100 Villeurbanne, France; william.leongarcia@supergrid-institute.com
[5] Division of Electric Power and Energy Systems, KTH Royal Institute of Technology, 100 44 Stockholm, Sweden; ilka@kth.se
[6] T&D Europe, B1030 Brussels, Belgium; policy@tdeurope.eu
* Correspondence: jaqueline.cabanas@eonerc.rwth-aachen.de (J.C.R.); amonti@eonerc.rwth-aachen.de (A.M.)
† Current address: Institute for Automation of Complex Power Systems, Mathieustrasse 30, 52074 Aachen, Germany.
‡ These authors contributed equally to this work.

Abstract: Interoperable multi-vendor High-Voltage Direct-Current (HVDC) grids are a key enabler for the integration of renewable energy (in particular offshore wind) and its transmission over longer distances to consumers. However, most HVDC systems today are single-vendor and point-to-point. Various technical and non-technical aspects need to be considered, for example, (real-time) testing, legal aspects (intellectual property and regulation), and the multi-vendor interoperability process. This paper presents findings from the READY4DC project, which is a larger and open European effort involving diverse stakeholders, including HVDC manufacturers, transmission system operators, wind developers, academia, and research institutes. It summarizes key technical recommendations, emphasizing comprehensive interaction studies and the development of a structured legal framework to facilitate the development and operation of a multi-vendor, multi-terminal HVDC grid. The READY4DC project highlights the need for increased harmonization, transparent communication among stakeholders, and future-oriented research to ensure the robustness and interoperability of interconnected grids. Collaborative efforts are key for addressing technical complexities and advancing the deployment of multi-vendor multi-terminal HVDC technology.

Keywords: HVDC; multi-vendor; multi-terminal; interoperability; interaction studies; legal aspects; demonstration

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1. Introduction

Looking ahead to 2050, Europe aims to be the first climate-neutral continent, and achieving this requires significant changes in the way we handle electricity, leading to more electrification across different sectors. The push for more renewable energy, especially offshore, is crucial. A key player in this shift is a more advanced and interconnected High-Voltage Direct-Current (HVDC) transmission. Here, the concept of multi-terminal multi-vendor (MTMV) HVDC systems becomes essential [1]. While technical aspects are being addressed by operators and providers, political leaders must also shape the necessary rules and regulations [2].

Offshore wind farms have high reliability and public acceptance [3]. The North Sea Wind Power Hub (NSWPH) Project serves as an example of offshore wind as a significant component for achieving a fully carbon-neutral power system [4]. Additionally, the innovative 2 GW Program significantly contributes to European offshore wind targets and introduces an advanced and standardized multi-vendor HVDC platform model [5].

In the broader context of offshore transmission and generation development, the transition to multi-terminal (MT) HVDC grids is identified as the keystone. In the beginning, a multi-terminal system is thought to have three terminals, which can be expanded in the future. The challenges in making widespread DC grids happen are mostly connected to the idea of having several HVDC terminals [6]. The question emerges if there is a need for an HVDC "supergrid" spanning multiple European countries and serving as transmission infrastructure in coexistence with the pan-European AC transmission grid. In several visions for the future European grid, the role of HVDC in power transmission varies. While earlier visions, e.g., [7] came with a flavor of a top-down planning and building approach for a possible European HVDC "supergrid", more recent visions propose an incremental approach to integrating multi-terminal HVDC projects into the European transmission grid, such as [8]. Furthermore, we see the first multi-terminal HVDC systems appearing today that may be expanded to HVDC grids piece-by-piece.

Realizing such a step-by-step MT-HVDC grid development holds several unresolved challenges. Meeting the EU targets requires simultaneous planning and development of offshore generation assets and MT-HVDC grids to ensure deliverability, extensibility, flexibility, and cost-effectiveness of power. The implementation of cost-effective and open solutions for MT-HVDC grids, particularly as multi-vendor systems, is necessary. Interoperability of HVDC systems emerges as a critical need, both technically and legally, for the widespread deployment of MTMV HVDC systems.

Addressing these challenges was the scope of the READY4DC project, a collaboration that involved key industry associations, transmission system operators (TSOs), HVDC and wind technology suppliers, wind farm developers, academia, and research institutes. This cooperation created a platform for stakeholders and key industrial partners to co-develop and establish necessary strategic consensus, paving the way for the first-of-its-kind MTMV HVDC demonstration project in Europe.

In the initial stages, READY4DC identified as additional challenges that each actor in MV projects independently defines models, making sharing difficult, and that openness conflicts with confidentiality requirements. In the realm of testing, READY4DC recognized the critical need to define meaningful and realistic scenarios at an industrial scale for the maturity of DC technology. In addition, the concept of interoperability and an interoperability process evolved within READY4DC.

The identified challenges were tackled in four working groups. Those working groups elaborated on the following contributions:

- Establishing a transformation shift with the suggestion of a generic, vendor-independent framework for modeling HVDC systems. Through the agreement on model characteristics, this key objective aimed not only to foster openness but also to facilitate meaningful tests.
- Clear definition of roles and responsibilities in MTMV networks, and clarification of criteria for meaningful industry-scale MTMV HVDC testing.
- Suggesting guidelines on the implementation of a first MTMV demonstration project.
- Providing a long-term vision for the role and development of HVDC technology.

These objectives collectively define the essence of READY4DC, showcasing a significant stride in advancing HVDC technology within a collaborative and well-defined framework.

This paper is organized in accordance with the project's structure. At first, Section 2 provides an overview of the current state of multi-terminal and multi-vendor HVDC, the technology state of the art, and defines identified challenges. The subsequent sections present the findings on each working group's objective: Section 3 deals with the modeling, simulation framework, and data sharing for MTMV HVDC interaction studies and large-scale electromagnetic transient (EMT) simulations; in Section 4, the legal framework for realizing an MV HVDC system is explored; Section 5 delves into planning the first

MTMV HVDC demonstration project, placing demonstrators in the European grid, and extending beyond a demonstration project; Section 6 presents a long-term view of HVDC technology and its role in the European energy system. Lastly, Section 7 summarizes the elaborated conclusions and recommendations.

The content presented in this paper is based on whitepapers of the READY4DC project [6,9–13].

2. Multi-Terminal Multi-Vendor HVDC Systems

Today, most HVDC systems are designed by European HVDC suppliers as point-to-point transmission systems and are provided by a single vendor. As a result, READY4DC stresses the need for European multi-terminal HVDC systems to be future-proof and expandable to multiple vendors.

MTMV HVDC grids play a crucial role in the cost-effective transition of the energy system toward climate neutrality. This is because they address various objectives within a single technical solution. These objectives include connecting offshore generation to the EU transmission system, enhancing interconnection capacity between diverse market zones (as detailed in [3]), reinforcing grid stability and meeting other system requirements, ensuring scalability and cost-effectiveness, and facilitating an accessible EU HVDC market for all present and future technology suppliers.

Several advantages of MTMV HVDC systems may boost the reliability, efficiency, and stability of the grid in comparison to a solution consisting of several single-vendor point-to-point HVDC arrangements. Furthermore, the implementation of an MT-HVDC system will improve the flexibility of the offshore grid in terms of power allocation. A multi-terminal HVDC system can also provide higher utilization of HVDC lines.

2.1. Multi-Terminal HVDC Technology—State of the Art

The rapid expansion of large-scale and remote renewable energy sources has helped the economic viability of MT-HVDC networks. Therefore, substantial investments have been directed toward research efforts by both industry and academia. These efforts aim to develop technologies capable of effectively addressing the challenges associated with MT-HVDC networks. The first European multi-terminal HVDC grid developments are:

1. The Caithness-Moray-Shetland System in Scotland [14]
   The project initially comprises a 2-terminal HVDC link, encompassing approximately 260 km of cabling, with the majority situated in the North Sea. It includes a 320 kV/132 kV substation and HVDC converter station at Upper Kergord, Shetland. Additionally, a necessary HVDC switching station at Noss Head, Caithness, facilitates connection to the existing transmission system (Figure 1). As part of its dynamic development, the project is designed with flexibility, allowing for the expansion into a 3-terminal configuration. Currently, the project is at stage 4 of 5, marked by the mobilization of personnel, contractors, and equipment, indicating significant progress. Approved in 2020 after a decade-long development journey, the Shetland HVDC link is integral in connecting Shetland to the GB transmission system, unlocking its renewable potential, decarbonizing its energy supply, and supporting future energy needs. Upon completion in 2024, the link will facilitate the connection of the 443 MW Viking Wind Farm to the GB grid, playing a pivotal role in the transition to net-zero emissions. The selection of HVDC technology underscores its efficiency in transmitting substantial power over long distances, enhancing the sustainability and efficiency of power supply systems.
2. Project Aquila in Scotland [15]
   As a key component of the ‘Pathway to 2030’ investments, SSEN Transmission is set to launch ‘Project Aquila’, a pioneering HVDC Switching Station at Peterhead aimed at expediting offshore wind development (Figure 2). This project, identified as a successful ‘Pathfinder’ initiative by the UK Government, integrates HVDC systems with MT and MV interoperability. By reducing the necessity for onshore converter

stations, Project Aquila not only curtails costs but also minimizes environmental and community impacts. Positioned as a world-leading venture, Project Aquila establishes an MTMV HVDC hub in Peterhead, laying the groundwork for HVDC grids in Great Britain. The project involves collaboration with a GB HVDC Interoperability Expert Working Group, ensuring that insights that have been gained contribute to future HVDC networks. Led by The National HVDC Center, the interoperability working group focuses on specifying and demonstrating interoperable converter stations in partnership with major HVDC manufacturers. Real-time joint simulations, set to be completed in late spring/early summer 2024, will showcase the multi-terminal, multi-vendor control functions' reliability and resilience. This development is pivotal in facilitating the National Grid ESO's planned grid and connecting renewable energy sources to meet ambitious net-zero targets.

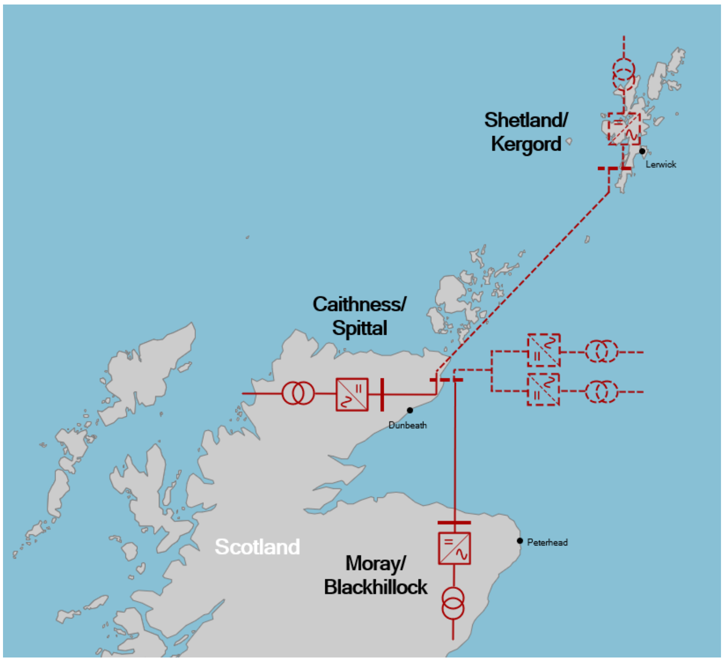


Figure 1. The Caithness Moray HVDC link in northern Scotland (solid), including the ongoing expansion to Shetland and possible offshore connections (dashed) [14].

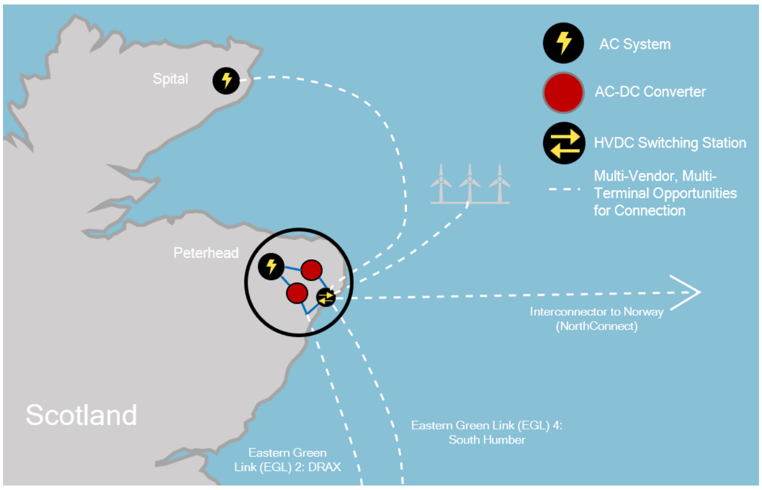


Figure 2. Illustration of project Aquila [15].

3. The Heide hub in Germany [16,17] In a strategic collaboration, 50 Hertz, formerly known as Vattenfall Europe Transmission, and TenneT, the Dutch transmission system

operator, have joined forces to facilitate the integration of wind power from the North Sea into the German power grid (Figure 3). This initiative, a key component of the 2035 grid development plan endorsed by the Federal Bundesnetzagentur (BNetzA) in 2021, involves the establishment of an innovative multi-terminal hub in the Heide region of Schleswig-Holstein, along with an HVDC link to Mecklenburg-Vorpommern. The project aims to accelerate the transport of sea-generated electricity to meet future demand, aligning with Germany's goal of achieving climate neutrality by 2045. The project consists of the construction of a multi-terminal hub, promoting an innovative HVDC switchgear, to connect two offshore direct-current connection systems, each with 2 GW capacity, to an onshore HVDC link. Additionally, a converter will facilitate the conversion of DC to AC, serving the region's offshore hydrogen electrolyzers and supporting the decarbonization of local industries. A 200 km underground cable split between 50 Hertz and TenneT responsibilities will connect the multi-terminal hub to a converter near Schwerin. The innovation reduces costs, minimizes land usage, and enhances load flow flexibility, contributing to the accelerated expansion of offshore wind energy, as envisioned by the German government's new policies. The comprehensive project is set to connect four gigawatts of offshore wind energy from the North Sea to the Heide area by 2032.

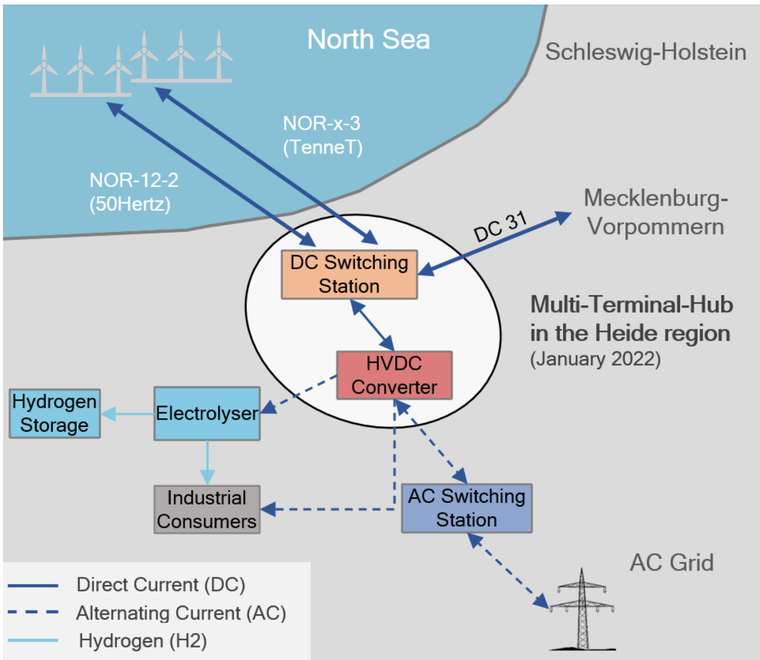


Figure 3. Plans for the Heide hub in Germany [16,17].

4. Project Bornholm Energy Island [18]
Bornholm Energy Island (BEI) (Figure 4) emerges as a pioneering renewable energy and hybrid interconnector project, a collaborative effort between Danish TSO Energinet and German TSO 50 Hertz, expected to be finished in the Baltic Sea by 2030. BEI's initial phase consists of offshore wind farms with a total of 3 GW capacity, connecting to the AC substation at Bornholm Island. Notably, BEI holds the potential to be Europe's inaugural operational MTMV HVDC link, with HVDC interconnectors extending to Zealand (Denmark) and Germany, with future expansions to additional countries. The technological focus involves a VSC multi-terminal HVDC system, offering superior flexibility for distributed network expansion and power transportation capacity. Initially proposing a double-input-single-output HVDC system, BEI explores system control and stability. Despite existing technological challenges, such as multi-vendor interoperability and competitive tendering for HVDC circuit break-

ers, the excellent controllability of VSC technology positions it as a viable option for present-day construction of multi-terminal HVDC grids.

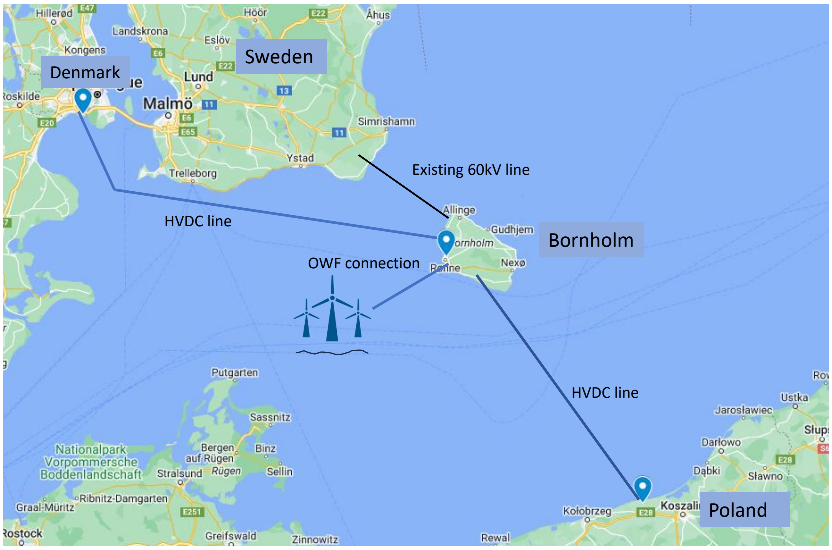


Figure 4. Bornholm Energy Island [18]. (Image courtesy of Google My Maps).

5. The Italian Hypergrid [19]
   Terna's 2023 Development Plan introduces the Hypergrid network (Figure 5), a groundbreaking initiative utilizing HVDC technology to advance the energy transition and security goals. With a significant investment of EUR 11 billion, the plan includes the construction of five electricity backbones, incorporating both overhead and undersea HVDC connections. The Hypergrid aims to double exchange capacity between market zones from 16 GW to over 30 GW, fostering renewable energy integration and minimizing land use. The Hypergrid's key projects, spanning regions such as Lombardy, Tuscany, Sardinia, Sicily, Apulia, Emilia Romagna, and Marche, involve undersea connections, innovative pylons, and converter substations on decommissioned industrial sites. These strategic investments prioritize grid reliability, resilience, and the integration of renewables, contributing to a projected reduction of up to 12.000 kt/year in CO_2 emissions by 2040. The modular approach adopted by Terna facilitates flexible infrastructure development aligned with evolving energy scenarios, ensuring timely implementation to accommodate the surge in new renewable capacity.

Figure 5. Hypergrid project in Italy [19].

2.2. Challenges

The realization of MTMV HVDC systems presents a complex set of challenges that demand close attention to various aspects of system development. One key challenge involves specifying the ratings of essential components, addressing the intricate control and diverse configurations of multi-vendor elements [1]. Functional requirements for HVDC grid protection, converter fault-ride-through behavior, DC circuit breakers (DCCBs), and DC protection intelligent electronic devices (IEDs) also necessitate a clear definition. Standardizing interfaces and communication protocols becomes important to achieve syntactic and semantic interoperability in HVDC grid protection. Additionally, optimizing DCCB elements such as capacitors, inductors, varistors, and charging units is crucial for enhancing interruption speed and reducing overall size and costs [20]. More challenges related to interoperability are present, as experiences from various HVDC projects reveal. The need for a harmonized and standardized approach in multi-terminal, multi-vendor, and multi-purpose HVDC projects becomes apparent, particularly in ensuring interoperability of converters from different vendors under varying grid operational modes. Challenges include devising detection and mitigation methods to protect against adverse control interactions and managing system stability under high penetration of power electronics. While recent projects demonstrate that these issues are solvable through detailed real-time testing and exhaustive offline simulations, the current approach is complex, time-consuming, and not easily scalable for multiple installations.

The challenges inherent in MTMV projects underscore the critical importance of detailed specifications across various facets of system development. Establishing criteria that maximize interoperability in integrated systems involving multi-vendor, multi-terminal, and multi-stakeholder HVDC-connected offshore wind power plants requires a comprehensive understanding of the state-of-the-art technological developments in HVDC power system engineering, electromagnetic transients modeling and simulation, and supporting multi-vendor interoperability studies. This intricate landscape demands a tailored approach to ensure the seamless integration of diverse components and stakeholders in the evolving field of MTMV HVDC systems.

3. Multi-Vendor HVDC Interaction Studies

3.1. Introduction

The increase in size and number of connection points between HVDC and HVAC systems in the perspective of a DC meshed multinational or pan-European grid demands thorough interaction studies to ensure robust operation among components expected to be provided by different vendors in an open market environment. This section is based on the work done by Working Group 1 in the READY4DC Horizon CSA project to explore the integration challenges in complex multi-vendor environments from the perspective of such type of power system studies (see Figure 6).

In a scenario where multiple vendors contribute to the same multi-terminal multi-vendor HVDC grid, it becomes imperative to maintain the system's performance and prevent any adverse effects due to vendor-specific implementations, such as differences in modeling, control tuning, and parameterization. Interaction studies are the main tool for TSOs to predict the effects that different HVDC converters will have on each other and their collective impact on the network. Positive interactions can enhance stability, while negative ones may lead to system performance deterioration. However, it can become a complex task to achieve as it needs coordination among stakeholders with diverse interests, from Transmission System Operators (TSOs) to vendors and developers and third-party simulation labs.

While interactions through the AC network—focused on how the HVDC system interfaces with the AC grid and other nearby HVDC components—is a well-known field, the introduction of multiple vendors and the increase of HVDC interconnectors with the perspective of pan-European meshed multi-purpose interconnections adds new complexity factors, for instance, the integration of models from various sources. Furthermore, on the

DC grid side, multi-terminal grids exhibit fast dynamics and transients, which adds more complexity to the interaction studies.

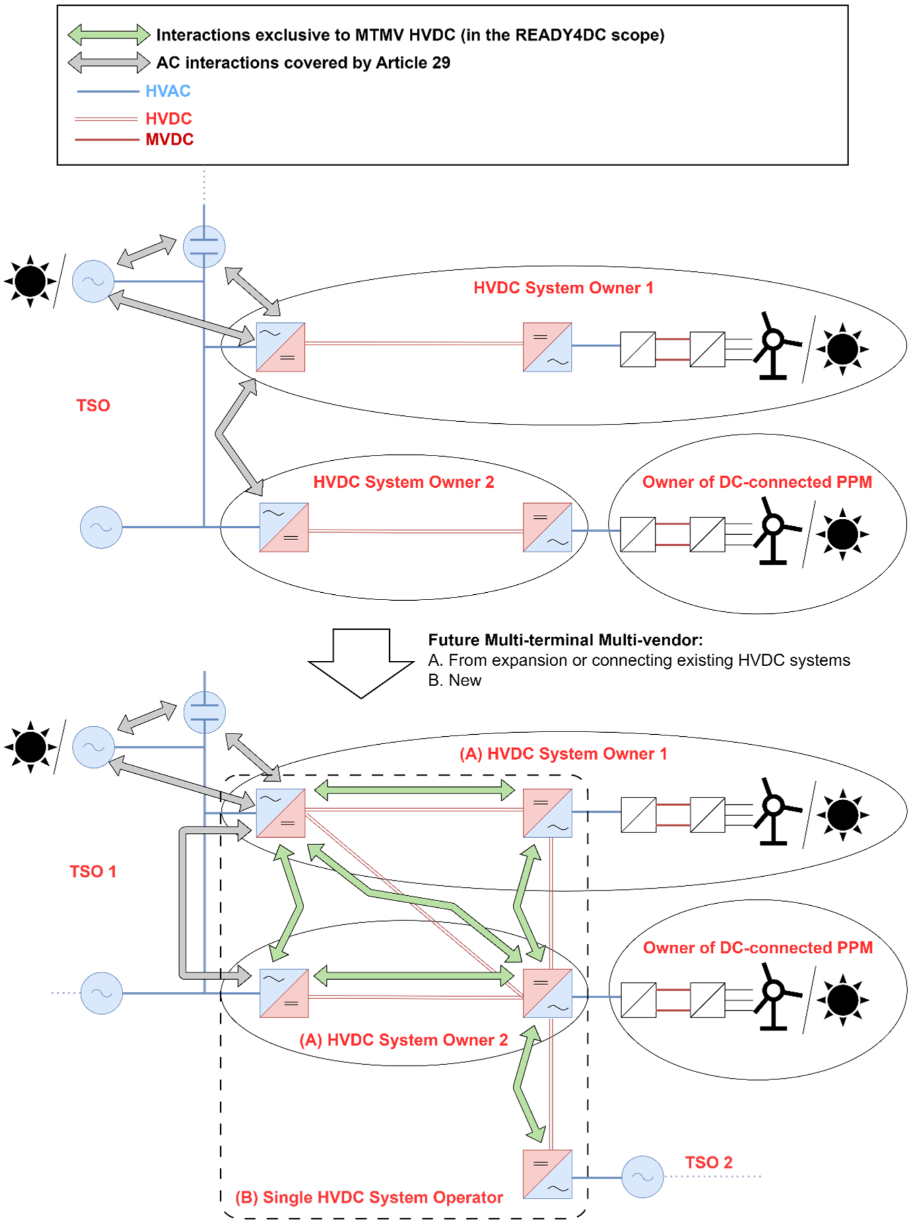
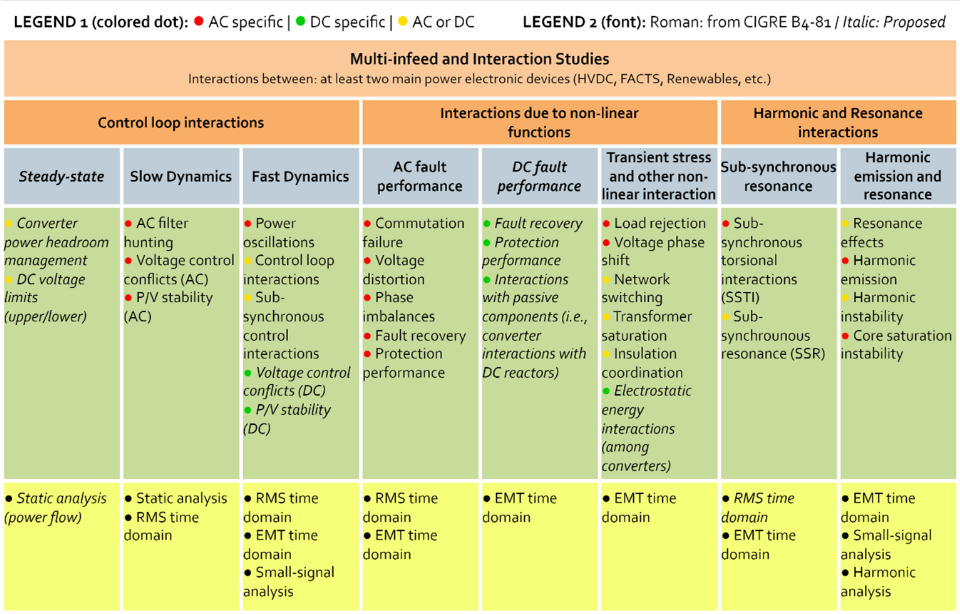


Figure 6. Interaction studies considered in CR (EU) 2016/1447 and identified gaps for MTDC grids [9].

For instance, energy interactions among converters for DC voltage stability and interactions with DC protection components like reactors are areas of focus. High-frequency studies also play a part in examining harmonic distortion and switching transients that can affect system performance. Current efforts in this area are underpinned by a series of publications and ongoing studies, including influential brochures from CIGRE, such as B4.81, B4.82, and B4.85, and guidance notes from GB ESO. The present work also builds upon the foundation laid by earlier documents like the T&D Europe White paper [21] and ENTSO-E guides [3]. Notably, the T&D Europe white paper categorizes interaction studies, following the proposition in CIGRE B4.81. As a continuation of those efforts, new interaction studies are proposed for this classification and shown in Figure 7 also marking whether these are expected to be seen in the AC or DC grid sides. A European code has also stated some rules and is the base for the following of this article as illustrated in Figure 8.



LEGEND 1 (colored dot): 🔴 AC specific | 🟢 DC specific | 🟡 AC or DC **LEGEND 2 (font):** Roman: from CIGRE B4-81 / *Italic: Proposed*

Multi-infeed and Interaction Studies

Interactions between: at least two main power electronic devices (HVDC, FACTS, Renewables, etc.)

Control loop interactions			Interactions due to non-linear functions			Harmonic and Resonance interactions	
Steady-state	**Slow Dynamics**	**Fast Dynamics**	**AC fault performance**	***DC fault performance***	**Transient stress and other non-linear interaction**	**Sub-synchronous resonance**	**Harmonic emission and resonance**
🟡 *Converter power headroom management* 🟡 *DC voltage limits (upper/lower)*	🔴 AC filter hunting 🔴 Voltage control conflicts (AC) 🔴 P/V stability (AC)	🔴 Power oscillations 🟡 Control loop interactions 🟡 Sub-synchronous control interactions 🟢 *Voltage control conflicts (DC)* 🟢 *P/V stability (DC)*	🔴 Commutation failure 🔴 Voltage distortion 🔴 Phase imbalances 🔴 Fault recovery 🔴 Protection performance	🟢 *Fault recovery* 🟢 *Protection performance* 🟢 *Interactions with passive components (i.e., converter interactions with DC reactors)*	🔴 Load rejection 🔴 Voltage phase shift 🟡 Network switching 🟡 Transformer saturation 🟡 Insulation coordination 🟢 *Electrostatic energy interactions (among converters)*	🔴 Sub-synchronous torsional interactions (SSTI) 🟡 Sub-synchrounous resonance (SSR)	🟡 Resonance effects 🔴 Harmonic emission 🟡 Harmonic instability 🔴 Core saturation instability
• *Static analysis (power flow)*	• Static analysis • RMS time domain	• RMS time domain • EMT time domain • Small-signal analysis	• RMS time domain • EMT time domain	• EMT time domain	• EMT time domain	• *RMS time domain* • EMT time domain	• EMT time domain • Small-signal analysis • Harmonic analysis

Figure 7. Categories of interaction studies proposed in CIGRE B4.81, amendments proposed for sub-categories and phenomena [9].

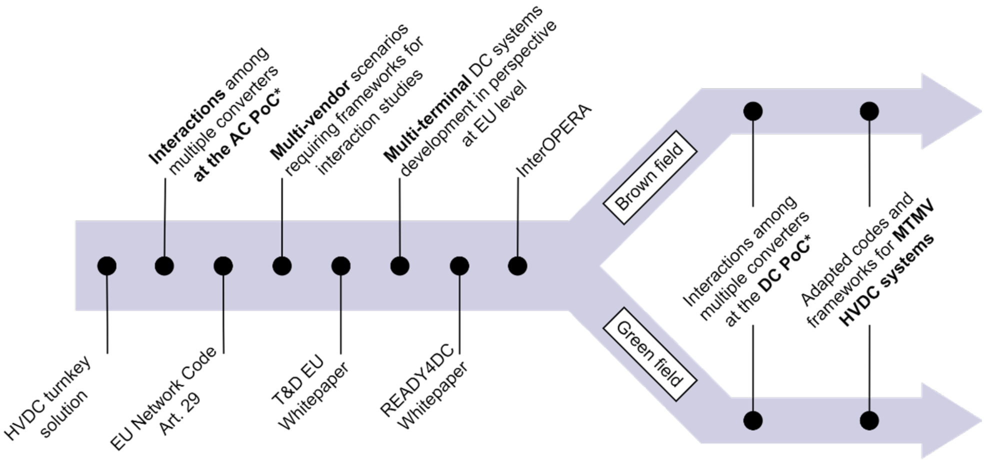


Figure 8. Rationale of the interaction study workflow analysis *PoC: Point of coupling [9].

3.2. Interaction Studies Framework

In READY4DC, we addressed the definition of roles and responsibilities necessary for successful interaction studies and the importance of clear guidelines and workflows for model sharing and the use of tools. We stress the need for collaboration and transparent communication among all stakeholders to ensure the safe and efficient operation of HVDC assets and the continuity of electricity transmission. The generic and straightforward process to perform an interaction study is illustrated in Figure 9.

This process outlines the coordinating and mediating needed in HVDC interaction studies. The six-step process begins with "Specification", where HVDC system operators define validation plans for interaction studies. These plans include the identification of necessary studies, case studies to be tested, agreed-upon acceptance criteria, and key performance indicators. Next is "Interaction Tests", where actual studies take place according to the validation plan. This involves integrating models from various entities, preparing simulations, conducting test scenarios, and documenting results for any issues identified. "Analysis" is the third step, focusing on finding the root cause of any interoperability problems from the tests. This requires a detailed review of simulation outcomes, further testing if needed, and a coordinated approach to tackle issues, particularly in multi-vendor contexts. The fourth step is "Solution Proposal", where stakeholders consider the analysis findings and propose feasible solutions, followed by "Solution Approval", where these solutions are reviewed and approved by all stakeholders. This step balances the need for documentation with the flexibility for vendors to make updates or modifications. Finally, "Mitigating Action" involves implementing the approved solutions, like updates to controls, protection systems, or other components. This step also includes monitoring the performance of the updated equipment to ensure it meets the required specifications.

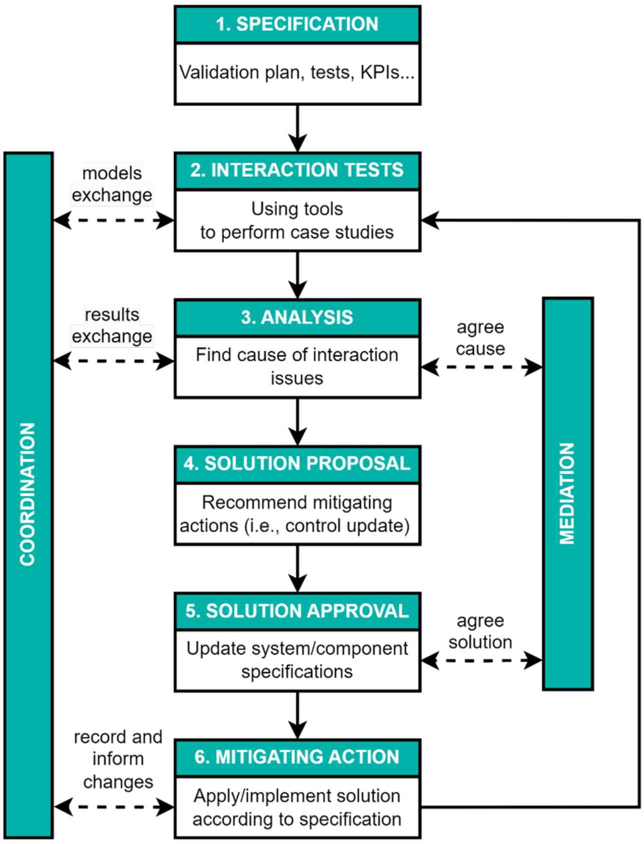


Figure 9. Flowchart of the multi-vendor interaction studies process [9].

3.2.1. Assessing Roles and Collaboration in MTMV HVDC Interaction Studies

These studies can be conducted at different stages of a project's life cycle (see Figure 10), either before or after the project has been awarded. The decision on when to conduct these studies is influenced by various factors, including the complexity of the project, the number of vendors involved, and the desired outcome of the study.

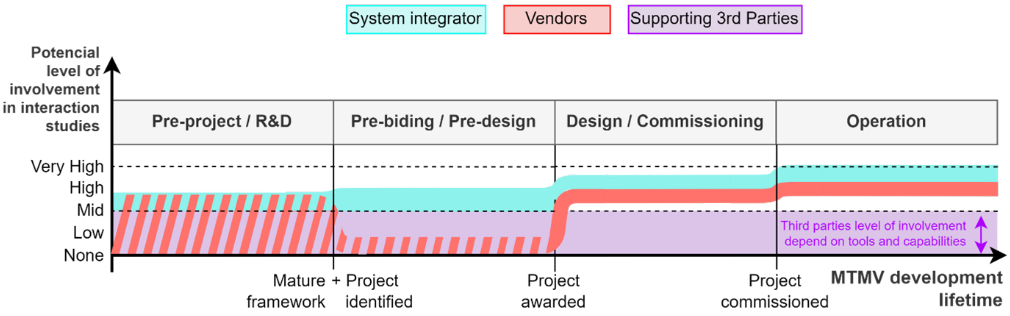
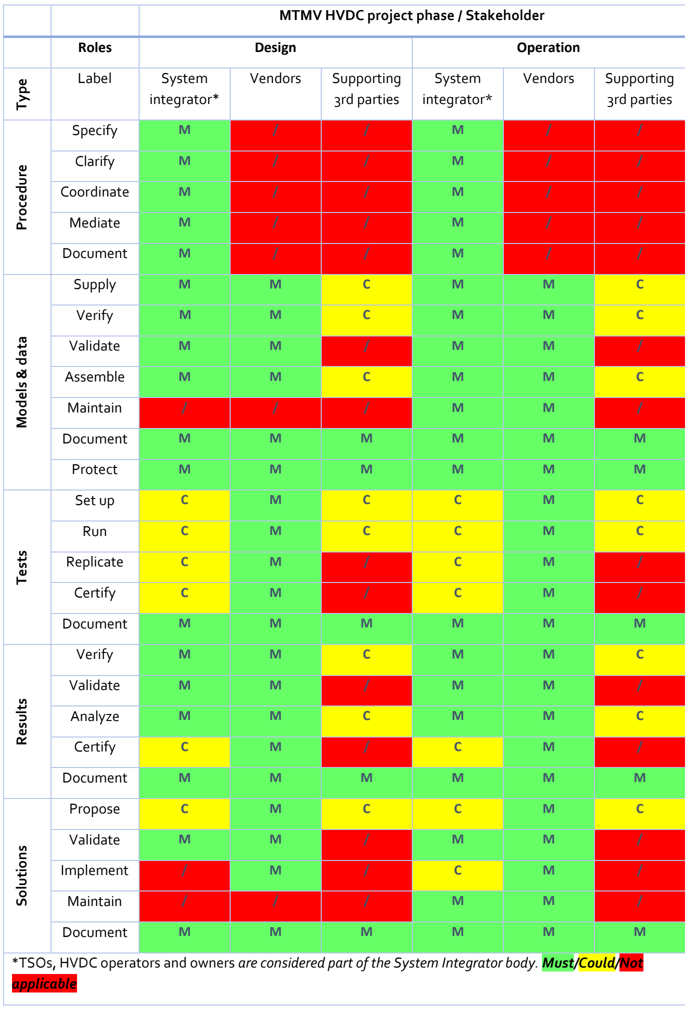


Figure 10. Potential levels of involvement of main stakeholders in interaction studies before and after contract award [9].

3.2.2. Conducting Interaction Studies Post-Award

The most critical and common phase for conducting interaction studies is after the project award. In this phase, detailed and specific models are available, allowing for a more accurate and thorough examination of how different system components will interact. At this stage, the roles and responsibilities of system integrators, vendors, and supporting third parties are more clearly defined and crucial to the success of the project, as proposed by the roles map in Figure 11.

- System integrators, typically Transmission System Operators (TSOs), HVDC operators, or owners, take on a primary role in specifying the processes, coordinating the studies, mediating between parties, and maintaining the overall documentation of the studies. Their involvement is constant and significant throughout the design and operation phases of the project.
- Vendors, on the other hand, are responsible for supplying detailed models, verifying and validating these models, and setting up and running tests. They are instrumental in proposing and implementing solutions that arise from the interaction studies. Their role is vital not only in the design phase but also during the operation of the HVDC system, ensuring ongoing compatibility and performance.
- Supporting third parties, which could include academic institutions, research labs, or specialist consultancies, may also be involved. Their participation varies but can add value in modeling, analysis, and proposing innovative solutions, especially when specialized expertise is required.



		MTMV HVDC project phase / Stakeholder					
	Roles	**Design**			**Operation**		
Type	Label	System integrator*	Vendors	Supporting 3rd parties	System integrator*	Vendors	Supporting 3rd parties
Procedure	Specify	M	/	/	M	/	/
	Clarify	M	/	/	M	/	/
	Coordinate	M	/	/	M	/	/
	Mediate	M	/	/	M	/	/
	Document	M	/	/	M	/	/
Models & data	Supply	M	M	C	M	M	C
	Verify	M	M	C	M	M	C
	Validate	M	M	/	M	M	/
	Assemble	M	M	C	M	M	C
	Maintain	/	/	/	M	M	/
	Document	M	M	M	M	M	M
	Protect	M	M	M	M	M	M
Tests	Set up	C	M	C	C	M	C
	Run	C	M	C	C	M	C
	Replicate	C	M	/	C	M	/
	Certify	C	M	/	C	M	/
	Document	M	M	M	M	M	M
Results	Verify	M	M	C	M	M	C
	Validate	M	M	/	M	M	/
	Analyze	M	M	C	M	M	C
	Certify	C	M	/	C	M	/
	Document	M	M	M	M	M	M
Solutions	Propose	C	M	C	C	M	C
	Validate	M	M	/	M	M	/
	Implement	/	M	/	C	M	/
	Maintain	/	/	/	M	M	/
	Document	M	M	M	M	M	M

*TSOs, HVDC operators and owners *are considered part of the System Integrator body.* ***Must/Could/Not applicable***

Figure 11. Potential roles of stakeholders in interaction studies after contract award [9].

3.3. Model Sharing and Tools for Interaction Studies

EMT simulations are essential during the project engineering design stages for developing and validating system behaviors, as well as for training experts in HVDC operations. EMT time-domain simulations are widely recognized for their ability to capture various interaction phenomena. These simulations are categorized into two main types: offline simulations and real-time simulations, each serving distinct purposes and offering different advantages in complex data, models, and replica environments as in Figure 12.

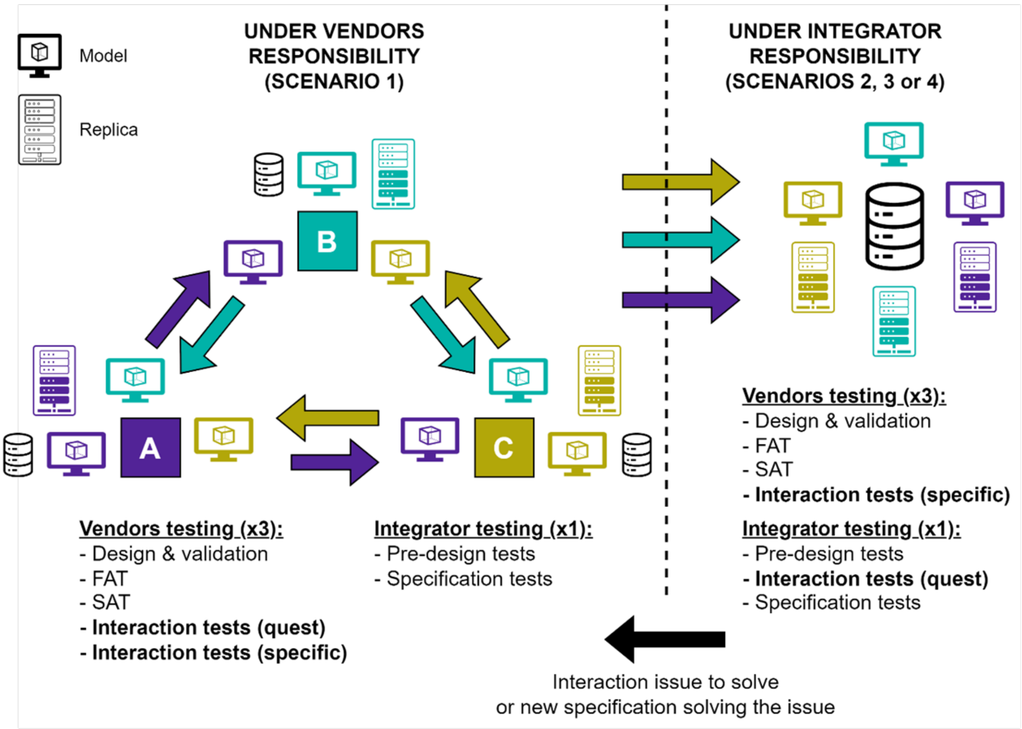


Figure 12. Data, models and replica environment among vendors and integrators for interaction studies [9].

3.3.1. Offline Simulations and Model Integration

Offline simulations provide a detailed examination of system dynamics without the constraints of a real-time clock, allowing equations to be solved at wide ranges of time steps dependent on computational power. The advantages of offline simulations include cost-effectiveness, high accuracy due to the capability for detailed calculations, and relatively easy setup. This mode is particularly useful for scenarios that do not require synchronization with actual time. It naturally suits interaction studies involving extensive power system zones, where detailed modeling requires significant computational resources. The integration of models in offline simulations involves several steps:

1. Model Development: Creating a model, whether manually crafted, automatically generated, or selected from existing libraries, that accurately reflects the physical system.
2. Verification: Ensuring the model meets technical specifications and behaves as expected within the simulation environment.
3. Validation: Confirming the model's accuracy by comparing simulated outcomes to real-world operational data or the results from other simulation tools.
4. Integration: Incorporating the model into a larger simulation framework, where it can interact with other models to simulate extensive system dynamics.

The model integration process in interaction studies should focus on ensuring compatibility across various simulation tools, handling disparities in file formats and compilers, and harmonizing time steps. A standardized process is recommended to establish clear and agreed specifications for simulation compatibility in offline studies, which will ensure that models from different vendors can be seamlessly integrated into the simulation environment. For instance, a model specification table could be developed, outlining key characteristics necessary for seamless model integration. This table would include the model's name, vendor, version, file format, compiler requirements, dependencies, time step requirements, inputs/outputs, usage rules, and model documentation. Such a framework ensures that the first import and subsequent integration of the model is successful and that any updates are managed effectively. Furthermore, solutions facilitating interoperability of models exist, such as the use of common file formats like Library (LIB) files or Dynamic Link Libraries (DLL) that eliminate compiler constraints.

3.3.2. Real-Time Simulations and Replica Integration for HIL Studies

Real-time simulations are indispensable for HIL setups where maintaining synchronicity with an actual clock is crucial. These simulations enable the testing of control and protection systems to transient events, ensuring the response time is reflective of real operational scenarios. Real-time simulations require robust simulation capabilities and often rely on parallel computing to handle the complexity of intelligent electronic devices within a power system. HIL studies necessitate the physical integration of replicas, which are authentic representations of hardware control systems. This integration is geared towards validating the interaction between the control systems and the simulated electrical environment, which includes:

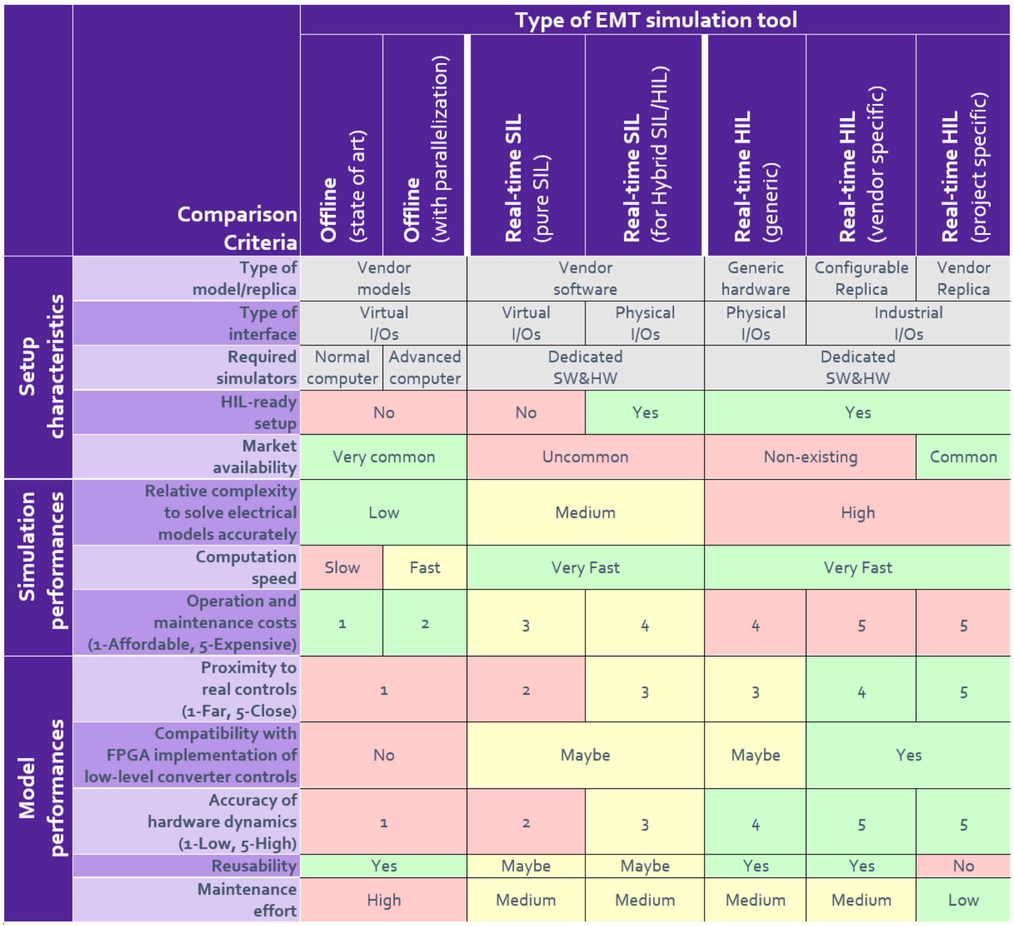
1. Replica Fabrication: Building replicas to match the specifications of the actual hardware used in field operations.
2. Validation: Testing replicas under varied conditions to verify their performance matches that of the real hardware.
3. Real-Time Integration: Connecting replicas to a real-time simulation environment that emulates the electrical grid, ensuring they respond accurately and within the necessary time frame to dynamic conditions.

The creation of an HIL simulation center, as demonstrated by entities like the National HVDC Center and RTE International, has helped TSOs develop skills while building confidence in the HVDC systems that are installed and operated on real sites. These centers offer a network analysis environment where confidential TSO network models, developed in real time, can be combined with vendor-specific models or replica hardware from vendors. Such environments ensure data integrity and IP protection through controlled access, cyber and physical security measures, and co-signatory status in System Technical Codes for data exchange.

3.4. Comparative Analysis of EMT Tools

Offline simulations, regarded for their detailed system dynamics analysis, are suitable for extensive power system zones and are characterized by their lower cost and high model accuracy. Real-time simulations are crucial for HIL setups, excel in syncing with actual operational timings, and are essential for transient event testing.

The debate between using offline models throughout the project or switching to replicas is nuanced. In large-scale projects, the practicality of using black-boxed offline models is evident due to the prohibitive number of physical replicas required. Yet, the choice hinges on specific project stages, system size, and requirements. The goal is to strike a balance—employing sufficient replicas or models to simulate the project accurately while also considering cost-effectiveness and space efficiency. Figure 13 summarizes the main comparison criteria the stakeholders should take into account in such a decision.



	Comparison Criteria	Type of EMT simulation tool						
		Offline (state of art)	**Offline** (with parallelization)	**Real-time SIL** (pure SIL)	**Real-time SIL** (for Hybrid SIL/HIL)	**Real-time HIL** (generic)	**Real-time HIL** (vendor specific)	**Real-time HIL** (project specific)
Setup characteristics	Type of model/replica	Vendor models		Vendor software		Generic hardware	Configurable Replica	Vendor Replica
	Type of interface	Virtual I/Os		Virtual I/Os	Physical I/Os	Physical I/Os	Industrial I/Os	
	Required simulators	Normal computer	Advanced computer	Dedicated SW&HW		Dedicated SW&HW		
	HIL-ready setup	No		No	Yes	Yes		
	Market availability	Very common		Uncommon		Non-existing		Common
Simulation performances	Relative complexity to solve electrical models accurately	Low		Medium		High		
	Computation speed	Slow	Fast	Very Fast		Very Fast		
	Operation and maintenance costs (1-Affordable, 5-Expensive)	1	2	3	4	4	5	5
Model performances	Proximity to real controls (1-Far, 5-Close)	1		2	3	3	4	5
	Compatibility with FPGA implementation of low-level converter controls	No		Maybe		Maybe	Yes	
	Accuracy of hardware dynamics (1-Low, 5-High)	1		2	3	4	5	5
	Reusability	Yes		Maybe	Maybe	Yes	Yes	No
	Maintenance effort	High		Medium	Medium	Medium	Medium	Low

Figure 13. Preliminary evaluation of EMT simulation tools for testing interactions in MTMV HVDC systems [9].

Converter Modeling and Its Impact on Offline and HIL Studies

As converters become more functionally complex and their roles in system stability more critical, the level of detail in their modeling becomes essential. As stakeholders, including TSOs, delve into the impact of converter functions on both components and the entire system, they must grasp how these functions prevent negative interactions and ensure system integrity. Suppose converter functions are analyzed from a multi-layered perspective. In that case, they can be classified from those impacting the inner physical components—such as sub-module balancing and valve switching—to a high level with those affecting the system's overall behavior—like DC voltage control or power management. The limit between those layers may be fuzzy since some functions may affect both component and system levels. The READY4DC-WG1 white paper introduces three degrees of converter control openness (low, medium, high) based on the approach taken for the C&P functional architecture—from a monolithic one to a high degree of modularity—which may influence the effectiveness of stakeholders to perform interaction studies or assessments. The schematic provided in Figure 14 illustrates the three different approaches.

In the first approach, C&P function architecture is monolithic, with a single vendor developing the complete sub-system. The rest of the system connects through I/O pins. While this approach may improve the efficiency of the C&P functions execution and provide a maximum level of secrecy of all C&P functions, including vendor-owned and not vendor-owned, it may hide the source of interactions for an integrator performing such studies.

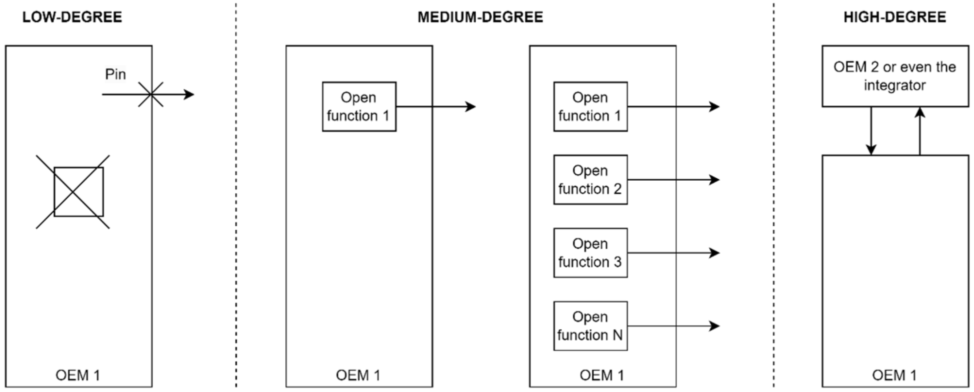


Figure 14. Converter functional openness illustrated [9].

The medium-degree openness shows a separate module containing functions that are considered open due to its low severity on converter health and relevant role for the system. This function or algorithm can be either provided by the same OEM or a different stakeholder but uses the same hardware support as the rest of the architecture. A drawback is an increase of C&P design complexity for the vendor, and the choice of such functions must be subjected to technical standards that define responsibilities and expected performance, not to mention the need to correlate the effect of such functions in producing interactions.

In the last option, not only the function algorithmic but also the hardware support can be open, which requires an external I/Os interface and protocols at the boundaries of both functional blocks. While this may further liberalize the development of certain functional layers in MTMV systems, it is an approach that still requires analysis by technical communities to develop frameworks.

3.5. Summary and Recommendations

As the power industry progresses toward a highly interconnected, multinational DC grid, the complexity of interaction studies escalates, especially in a multi-vendor environment. The READY4DC Horizon CSA project underscores the necessity of collaborative efforts in conducting interaction studies to maintain the robust operation of these complex systems. This chapter, drawn from the insights of Working Group 1 in READY4DC, accentuates the importance of comprehensive interaction studies to manage the effects of various HVDC converters on the DC grid provided by different vendors in an open market.

The interaction studies framework developed in READY4DC aims to facilitate the seamless integration and operation of HVDC assets, emphasizing the crucial role of transparent communication among all stakeholders. The process extends from the initial specifications and interaction tests to the analysis, solution proposal, and implementation, necessitating continuous coordination among TSOs, vendors, and third-party labs. Identifying interaction risks and scheduling studies at the correct project stage—specification, design, validation, or operation—is important.

Traditionally, TSOs have not been involved with vendors from the initial specification phases of such complex projects. However, the landscape is changing. Under R&D innovation agreements, a new configuration is emerging where TSOs and vendors are encouraged to collaborate from the outset. This proactive approach enables all parties to understand the system requirements fully and to work together to address any potential issues from the early stages of the project.

4. Legal Framework for Implementing Multi-Vendor HVDC Systems

Developing an MTMV HVDC grid is only possible with a stable legal and regulatory framework. This is the basis for the coordination and governance, standards, and protection of intellectual property (IP), which is an essential basis for investment in HVDC technology and infrastructure. The legal framework to facilitate HVDC technology ideally consists of a public law framework that takes into account the differences between regular grid investments and MTMV HVDC grids and an agreement between the relevant actors (based on private law) to set the conditions for cooperation [10].

4.1. Interoperability and Competition Law

Developing an MTMV HVDC grid requires companies to cooperate both between client and supplier (vertical) and between competing suppliers (horizontal). Cooperation between companies is allowed but regulated by competition law. The cooperation needed to reach an interoperable HVDC grid includes the development of standards, projects, and possibly joint R&D investments. It is important to note that companies may not cooperate in such a way that disturbs or distorts the market (art. 101 on the Treaty on the Functioning of the EU, TFEU) and that companies in a dominant position may not abuse that position (102 TFEU). Both principles are relevant to the development of a MTMV grid. For example, when multiple companies decide to use a certain technology rather than another technology, this decision needs to be transparent and beneficial to consumers and the market. Abuse of a dominant position can take place when a company that holds a certain patent that is essential to a standard asks a price that is not fair and reasonable for sharing it. Infringement of the rules can come with high fines [10].

READY4DC concludes that the development of standards and other cooperation to reach interoperability should be open and transparent, for example, concerning the allocation of voting rights. There are a few questions that should be clarified by the European Commission, such as how to deal with non-essential but complementary technologies, what the scope and duration of the ‘good faith effort’ to disclose relevant IP rights are in this context, and how the value of a certain IP right should be determined (as excessive pricing is not allowed) [10].

4.2. IP Law

Vendors of HVDC technology have invested significantly in the development of their systems. They protect their intellectual property (IP) via a combination of patents and trade secrets. In a single vendor, turn-key HVDC system, valuable information can be black-boxed inside the converter stations and/or respective simulation models and replicas. However, moving towards multi-vendor HVDC systems, parts of the black box may have to be released to allow for interoperability between different vendors’ equipment. This means that for MTMV HVDC technology, the reliance on trade secrets to protect IP must be reduced, and vendors need to find other ways to protect their IP, for example, via patents (and possibly copyright for software codes). This decision should be taken on a case-by-case basis as not all types of IP rights lend themselves to all types of IP [10].

Another issue identified within READY4DC is that some patents may be essential for reaching a certain standard. EU competition law requires vendors to give access to standard-essential patents on “Fair, Reasonable and Non-Discriminatory” (FRAND) terms. It is not clear how access to trade secrets should be treated in the context of standardization. This should be taken into account by standard-setting organizations, and the European Commission could clarify this issue further.

Sharing confidential information, trade secrets, and patents can take place bilaterally or via a pool. For trade secrets, the value lies in their secrecy, which can be enforced better in bilateral non-disclosure agreements (NDAs) than in a pool-based system. It is possible to license patents in a pool-based system while having a parallel bilateral system for trade secrets. This only works if the patents and trade secrets are clearly separable [10]. Whether this is the case depends on the design of the technology.

4.3. Risks and Liability

The change in roles, duties, and responsibilities in HVDC projects with multiple vendors and multiple owners has a significant impact on liability and warranty in the overall system. With independent, turn-key systems, the contractor is responsible for the design and execution within the boundaries of the contract. The contract usually includes engineering, procurement, construction, and even installation (EPCI). Moving from single-vendor turn-key HVDC systems to MTMV systems will shift part of the design and execution responsibility from the manufacturer to the owner and operator of the DC grid. Owners and operators will need to individually specify each module (e.g., converter stations) while being liable for the performance and the security of the overall system. In READY4DC, the different steps in the development of an HVDC system are investigated from the angle of the shift of risks and liability [10]. Based on READY4DC's work, three main conclusions on this topic are:

1. To minimize risks and associated liabilities in multi-vendor HVDC systems, it is important to clearly define roles and responsibilities in procurement contracts and establish clear guidelines for system integration and testing. Additionally, thorough testing of interoperability can help identify and address potential faults or damages before they become major issues.
2. For the first meshed HVDC projects, an intermediate step is proposed: the connection of several turn-key HVDC systems from different vendors in such a way that if interoperability issues occur, the systems can be separated and operated as individual turn-key systems. This limits the consequences of interoperability issues while still allowing testing interoperability in real projects.
3. Finally, having a clear plan for allocating liability in the event of a fault or damages is essential to minimize disputes and ensure that the appropriate party is held responsible [10].

4.4. Summary and Recommendations

An enabling legal framework is essential in reaching an interoperable MTMV grid. The public law framework needs to be updated to include HVDC grids and accounts for the differences between HVDC and regular grid investments. Parties also need to form an agreement on which to base their cooperation. In developing a legal framework and standardization process, parties should take into account competition law concerns. The IP strategy of vendors may need to change when not all information can be black-boxed anymore. This can be done by replacing trade secrets with patents and by concluding NDAs. Patents can be shared within a patent pool. Regarding risks and liability, the shift from single vendor, turn-key systems to MTMV systems brings a shift in risks and liability from the vendor to the developer of the system. The roles and responsibilities need to be clearly defined in advance, as well as how liability is allocated in the event of faults or damages. Finally, to limit the impact of failures in the first projects, it is suggested that various turn-key HVDC projects of different vendors be connected, which can operate in separate modes when failures occur.

5. Definition and Demonstration of Multi-Vendor Interoperability Process

The motivation for MTMV HVDC grids is covered in Section 2. Selection criteria are needed to enable optimal placement within the European transmission grid for the initiation of the first MTMV demonstrator project. At the same time, current standards are comprised of point-to-point HVDC connections. This requires a procedure for achieving functional specifications for the first MTMV demonstrator and beyond. Section 5.1 provides an outlook on how such a procedure can be obtained.

For the implementation of the first MTMV demonstrator, a joint effort between the different stakeholders, vendors, TSOs, and regulators is required. A stepwise approach with key milestones is proposed in Section 5.2.

After the successful implementation of the first MTMV demonstrator, a roadmap towards rolling out the future expandability of multi-vendor projects will be beneficial for network planning purposes as well as innovation directions. This roadmap is provided in Section 5.3 with the technical requirements and the roles of key actors being mentioned. The content of the following subsections is based on [6].

5.1. Guidelines for Placing the Demonstration Project in the European Transmission Grid

Historically, innovations in electrical power grids went (mostly) in parallel with grid code development. HVDC MT systems and, especially, multi-vendors require grid codes to be added to the AC side and requirements for the DC side. Due to the speed of transformation and technical complexity paired with intellectual property rights, current grid codes [22] do not cover all aspects of HVDC MTMV grids. Hence, selection criteria need to be found to place a possible MTMV demonstrator project within the European transmission grid. These criteria may, in the first step, be described functionally. Table 1 provides an overview of potential functional requirements together with the design impact on the MTMV demonstrator. Also, recommendations are provided in the table to follow current initiatives in HVDC MT grid design.

Table 1. Selection criteria for the first MTMV demonstrator [6].

Functional Requirement	Design Impact	Recommendations
Compliance with system operations guidelines	DC fault protection	• Introduction of DC-FSD • Enable connection of new terminals
	DC control	• Minimizing dependencies on communication • Behavior is predictable
Fulfillment of transmission request	DC voltage options	• 320 kV or 525 kV • DC control easier with one voltage level
	Selection of active power per converter station	• TRL level for 2 GW considered market ready • No specific power rating recommended • For verification purposes minimum active power rating of some hundred MWs

Based on Table 1, a general approach to derive functional specifications is described in Figure 15. This process is dependent on information provided by the TSOs on their planned MTMV projects. If enough information is available, the advantage of the proposed approach is to follow the needs of planned real-life projects. The stepwise approach may be used in follow-up projects to identify relevant MTMV specifications.

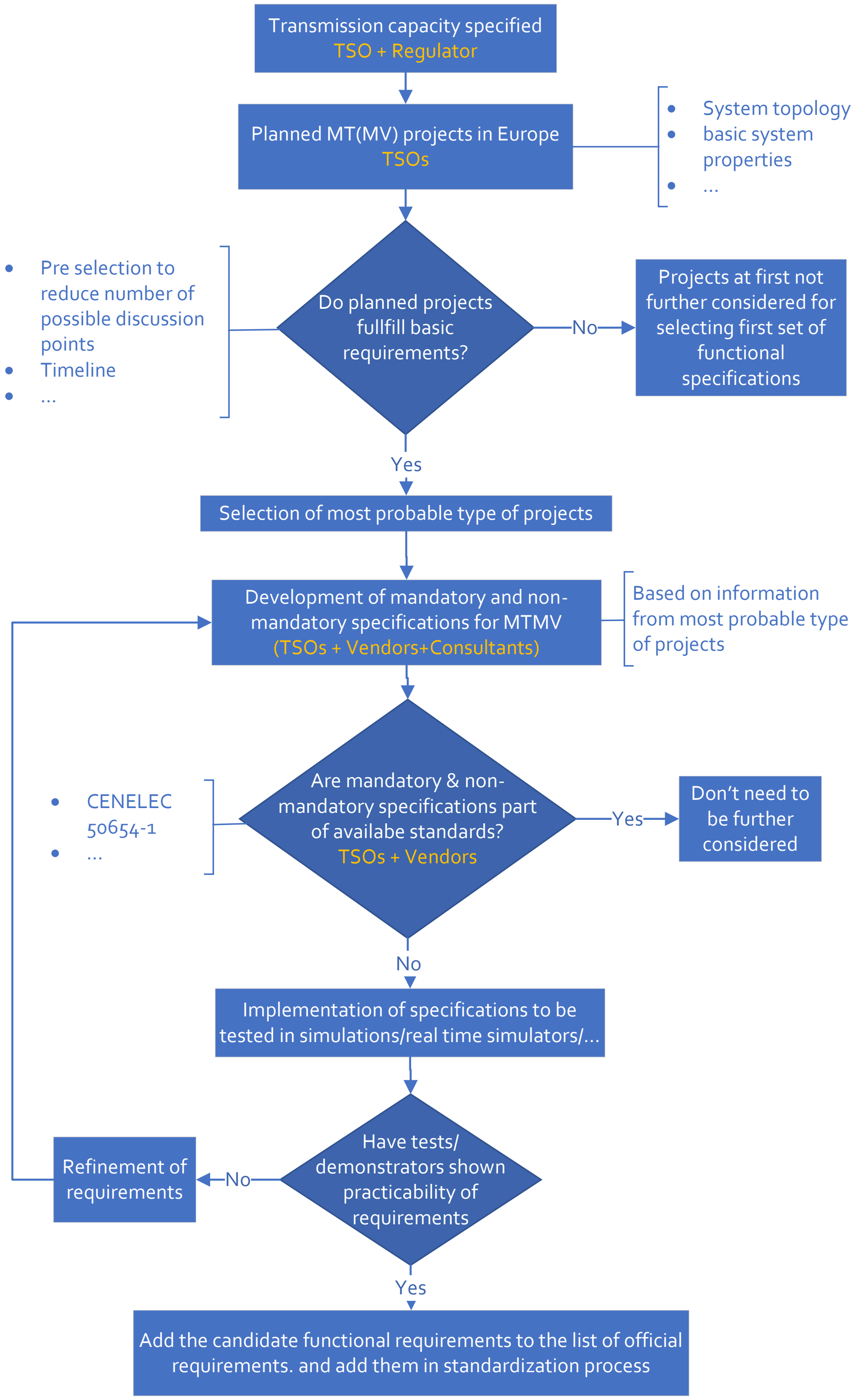


Figure 15. Procedure for selecting functional specifications [6].

5.2. Key Milestones in Implementing the First MTMV Demonstrator

The next steps towards a first MTMV demonstrator can be described by:

1. Preconditions and assumptions before the planning phase
2. Planning & Development of a MTMV HVDC system

3. From a conceptual to a project-specific MTMV system design
4. Final steps from construction to the end of lifecycle

Step 1 comprises (1) the clarification of key roles, (2) the setup of a legal and regulatory framework which includes the alignment of different system operation guidelines and the proposal of an MTMV demonstrator project as project common interest (PCI) in the TYNDP/grid development plans, (3) a standard language for MTMV projects: Herein interface definitions are proposed about model sharing and grid/station level control, (4) the need for system adequacy studies to ensure optimal placement of the demonstrator.
Step 2 is focused on the planning and development of a MTMV system. At first, basic MT functional requirements are to be collected and converted into a basic MT specification. In the following, a conceptual MTMV system design will be provided by the TSOs as a first draft. Vendors are supposed to review the proposal, and by iterative refinement, a coordinated result is achieved. This results in basic MTMV functional requirements and specifications. After that, a prequalification of vendors can be conducted. This includes checking if vendors can fulfill MTMV interoperability based on the defined functional specifications. It might also lead to iterative adjustments of the specifications so that, in the end, detailed MTMV functional specifications are obtained. The detailed specifications might include aspects like energization/shutdown, protection concepts, coordinated control, operating requirements, etc. The following tendering procedure will reveal if offers are available to enable MTMV interoperability. If not, modifications within the previous steps are needed. Afterward, a procurement procedure can be initiated.
Step 3 suggests how to come from a conceptual to a project-specific MTMV system design. Herein, the C&P development is of special interest, which will be verified by integration tests. The functional and dynamic performance will be demonstrated by offline, SIL, and HIL system testing.
The **final steps** towards an MTMV demonstrator contain aspects from the construction till the end of the life cycle. Especially during commissioning, sufficient training for operators is needed to become familiar with the amount of complexity within MT systems. A possible further point of consideration is expansions of the existing system with regards to (a) possible new functions and software upgrades, (b) novel technologies such as fault separation devices and DC-DC converters, and (c) the addition of further cubicles. Expandability needs to be considered already in the planning phase of the first MTMV demonstrator. Otherwise, commercially optimized solutions and further restrictions might result in locked-in solutions.

5.3. Beyond the First Demonstrator

To finally come to widespread MTMV HVDC grids, a roadmap towards rolling out future expandability would be beneficial. Three phases are seen as relevant.

Phase 1 is about gaining experience from the first MTMV HVDC demonstrator. This means that interoperability is proven. Also, necessary adjustments can be made to the existing requirements so future linking of hub projects is enabled.
Phase 2 is encompassing the development of an overall system design. Here, Figure 16 suggests three options.
Phase 3 finally leads to the standardization of modular sub-systems. Standardized technical and regulatory requirements are needed to ensure the modular expandability of the system. Moreover, the compatibility of converter stations and separate DC switchgear is of special relevance. The protection design is supposed to be modular and not restricted to certain system topologies. Finally, the overall goal is to achieve modular HVDC building blocks with compatible I/O interfaces, which include interoperability by design.

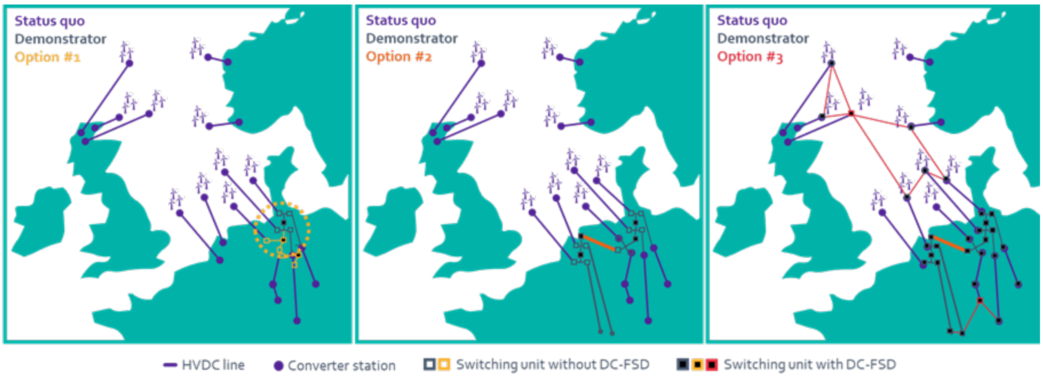


Figure 16. Options for the development of an overall system design [6].

To achieve these development phases, essential requirements can be divided according to Figure 17 in technical requirements, planning standards, roles of key actors, and further requirements. For each topic (e.g., System rating) within a group of requirements (e.g., Technical requirements), options and recommendations are provided [6].

Technical requirements:
- System rating
- Power flow control
- Dynamic stability
- Protections and Equipment
- Operational philosophy

Roles of key actors:
- Policy makers
- Energy regulators
- Standardization bodies
- Academy and research centres
- TSOs
- Vendors
- Consultants

Planning standards:
- Definition of technical terms and descriptions
- Strategy of potential interfaces for the exchange of signals and data
- Standardization of integration studies for future projects
- Standardized regulations for network connection
- ...

Further requirements:
- External threats
- Cyber security
- Cost/business case

Figure 17. Essential requirements to be considered for rolling out future expandability [6].

5.4. Summary

MTMV HVDC is considered an opportunity to introduce extended functionalities, compared to current point-to-point systems, which further enable large-scale wind integration from offshore and the interconnection between/within synchronous areas. To achieve this, the following aspects need to be considered:

1. To enable MTMV, it requires a common technically realizable vision across all relevant stakeholders. This vision requests a shared objective by TSOs and the support of HVDC vendors, consultants, and third parties to review the objectives. Overall, an effort to achieve strong collaboration across stakeholders to overcome technical hurdles is needed.
2. The core requirement to achieve MTMV is to demonstrate it. Several options exist for that. It is seen as necessary to take a step-by-step approach by (1) Setting up MT systems, (2) Gaining experience by operation, (3) Introducing MV.
3. MTMV is established by clear technical requirements, agreed planning standards, and responsibilities across stakeholders.

The results provided are intended to create and build a common understanding across all stakeholders that can then be applied to the next stage of the demonstration project. The technical hurdles are addressed. However, how they can be met on the contractual/legal side is still pending. The outcomes may be used in follow-up projects like InterOPERA as a starting point for discussions.

6. Long-Term View HVDC Technology

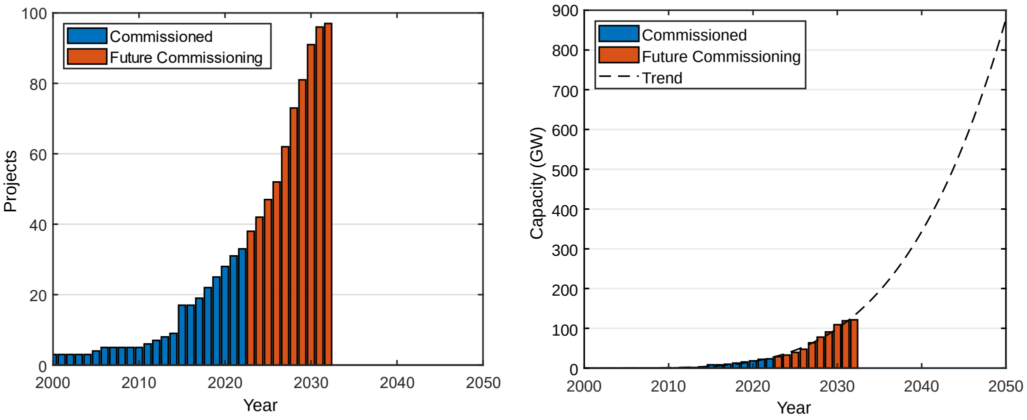
Developing and operating an MTMV HVDC grid requires not only technological solutions for simulation and interoperability but also a legal framework. Other factors also play a role. This section first assesses the increasing number of HVDC projects and, based on that, provides insight into unlocking investment for MTMV HVDC systems. Given the urgency and scale, an assessment of HVDC R&D priorities is provided. Looking further into the future, aspects regarding end-of-life and ownership models are discussed. Finally, staff scarcity is addressed, being a critical aspect of the massive deployment of offshore wind and (MTMV) HVDC systems. The content of this section is based on [11–13].

6.1. Increasing Number of HVDC Projects

Undoubtedly, a massive expansion of renewable energy sources (RES) generation capacity is required for the EU to reach carbon neutrality by 2050. Offshore wind power is expected to make up a significant share of the RES, especially in the North Sea countries [23]. While today, much offshore wind energy is brought to shore with AC connections, recently (with larger capacity and longer distances), offshore wind farms are increasingly connected using HVDC cables. For this reason, offshore wind development can serve as an indicator for the build-out of HVDC technology. Having access to an estimated potential of 380 GW of generation capacity in the northern European waters [24], the North Sea countries agreed on offshore wind targets of at least 120 GW by 2030 and 300 GW by 2050 in the 2023 Ostend Declaration [25]. By the end of 2022, 30 GW of offshore wind power installed capacity were operational in Europe (16 GW in the EU-27, 14 GW in the UK) [26]. Therefore, these targets require a 10-fold increase in installed capacity from today to 2050 and dictate the magnitude of offshore wind and HVDC development. The targets also show an accelerated rise in recent years, possibly ramping up further.

However, HVDC is not exclusively used for bringing offshore wind to shore but also has several additional purposes onshore and offshore. Many recently commissioned offshore HVDC projects are cross-country interconnections that enable energy trading. Interconnection projects include, for example, country-to-country connection onshore to onshore or hybrid projects that combine evacuation of offshore wind power with interconnection. Onshore HVDC is used for long-distance transmission using overhead lines or underground cables. Furthermore, like offshore, one purpose of onshore HVDC transmission is to facilitate cross-country interconnection to cope with European power system needs. In this context, the identified needs are grid reinforcement requirements to reach RES targets, keep security under control, and reduce the overall cost of electricity. Another use case of both offshore and onshore HVDC is replacing, to some degree, grid-stabilizing functionalities of existing AC assets, such as the inertia provided by synchronous generators. With all use cases combined and keeping the current HVDC growth rates, a projection of future HVDC deployment would lead to an approximately exponential growth of the total HVDC-based transmission capacity in Europe till 2050, as depicted in Figure 18b.

An incremental approach also seems to be the realistic way to integrate multi-terminal HVDC projects into the European grid and to realize meshed MTMV HVDC grids, rather than top-down planning of a large-scale HVDC grid, e.g., covering the North Sea area. A notable challenge for the existing European grid is that incorporating several HVDC projects into the AC grid likely leads to power flow constraints limiting the usable capacity of HVDC links. Therefore, significant AC transmission grid reinforcements will be necessary to distribute the power transmitted by HVDC projects [12]. Finally, TSOs and vendors may also face a tight project commissioning schedule, with many HVDC links expected to start operating almost simultaneously.



(**a**) Cumulative projects by year (**b**) Cumulative installed capacity

Figure 18. Deployment of European HVDC-VSC projects in past and future [12]. Data source: [27].

6.2. Unlocking Investment for MTMV HVDC Systems

Unlocking investments for MTMV HVDC systems is not obvious. For a first-of-a-kind (FOAK) MTMV HVDC demonstrator in Europe, the funding will not only depend on remuneration and on the reliability of being able to recoup investments but more heavily on long-term social and technology benefits. The project owner needs to be shielded from both the short-term risks of a project and marginal costs to lower project risk (e.g., additional equipment to provide redundancy, etc.) and longer-term risks of over-scaled or redundant infrastructure or equipment. In this respect, from a regulatory viewpoint, it would be useful to be able to make anticipatory investments [11]. The view in [11] is that raising capital for a FOAK demonstrator is less about technology and more about clear organization and processes. This view aligns with investor input. Still, technology de-risking must be included in the first MTMV project as a precondition for investments. This technology de-risking includes multi-vendor testing (see Section 3) and addressing liability questions Section 4. Fallback options could be a suitable approach to MTMV where a system is split into a ”core task” (e.g., wind energy to shore) and ”extra functions” (MT/MV), for example, using a DC-connection for parallel point-to-point HVDC links. If interoperability does not work in such a setup, the fallback options are separate single-vendor systems.

In the longer term, a huge number of HVDC systems are expected to be put into operation in Europe. In [11], a very simplified back-of-the-envelope style idea of the investment required in HVDC components and systems to achieve the integration of EU offshore wind generation targets, potentially consuming an unrealistically high portion of the yearly turnover of the primarily concerned North Sea transmission system operators—each year in the coming decades. Marginal costs of DC meshing offshore are anticipated to be limited compared to the total planned infrastructure investment. Depending on the distance between two offshore DC platforms, additional cable costs and appropriate protection are a very small part of the total costs when connecting two point-to-point HVDC connections offshore-offshore. Yet this interconnection offshore may bring significant benefits in grid performance and commercial benefits to both national and Europe-wide systems.

Given the anticipated total funding requirement and the complexity of meshing grids, we may also anticipate a potential shift in equity ownership from TSOs to new parties entering the offshore grid infrastructure market. These are both strategic and financial infrastructure investors. It may be in the form of partial or complete asset ownership. This may lead to new models for operation.

6.3. HVDC R&D Priorities

The research and development (R&D) priorities in an MTMV HVDC context must be approached with a strategic and comprehensive perspective. The surge in HVDC projects, driven by increased deployment goals, has led to financial, resource, and staff constraints. To efficiently achieve deployment, R&D efforts should prioritize modularization, component standardization/functional specifications, and interface assembly to enhance interoperability. Various reports, including those from the READY4DC community [13], projects like PROMOTioN [28] and OFGEM [29], and the HVDC SET Plan [30] highlight R&D priorities regarding, e.g., technology needs, upscaling HVDC manufacturing innovation, leveraging technical expertise, and addressing sustainability concerns. However, the growing demand for rapid deployment urges further R&D in managing interoperability, modular design, scalable manufacturing, and functional modeling in multi-vendor setups. In particular, functional modeling as part of the model-based systems engineering approach appears promising for the HVDC domain. This approach has been used successfully in other industries, such as cars and aircraft. Model-based systems engineering allows the collaboration of different stakeholders in one platform, the definition of model/data formats, the definition of functional requirements, the mapping of functional requirements into hardware devices, the effective definition of interfaces between assets, and the more effective re-use of elements for other projects [31]. Publication [32] details how model-based systems engineering could be applied in a multi-vendor HVDC setup.

The priority is establishing operational infrastructure, emphasizing two engineering R&D fields: interoperability across vendors and technical specifications and standards. This involves addressing challenges in multi-vendor control and protection integration, coordinated HVDC grid control, and resolving interactions between AC and DC systems. Additionally, R&D efforts must focus on efficiently expanding HVDC grids, considering complex dependencies in control and protection software and hardware. Circular economy aspects, such as recycling, ultimately also need attention, especially as offshore platforms and wind farms age. While higher power ratings and new functionalities are future considerations, the HVDC community stresses the importance of preventing innovation constraints amid R&D priorities [13].

6.4. End-of-Life and Ownership Models

In parallel, the long-term view of HVDC technology needs a careful examination of end-of-life considerations. End-of-life considerations for HVDC systems present multifaceted challenges for owners and utilities. Financially, regulated assets may involve revenue for life extension and end-of-life investments, while commercial assets might require remuneration, including an end-of-life reserve. A deferred liability on the balance sheet is essential to cover eventual expenses related to dismantling or removing infrastructure, tying up significant capital. Drawing lessons from the Oil and Gas (O&G) sector, where challenges in managing end-of-life assets were experienced (The O&G sector has faced challenges in effectively managing the end-of-life phase for offshore assets, such as platforms. Ownership of assets often changes over their lifetime, making it difficult to assess the final owner's capacity to fund disposal.), prompts questions about the European Commission's potential role in addressing this issue, especially concerning multinational assets spanning Exclusive Economic Zones.

In the realm of offshore wind infrastructure, the lifetime extension becomes a logical choice over removal, yet challenges arise due to the mismatch between cable and wind farm lifetimes. Regulatory considerations, especially regarding cable removal, vary across countries and involve factors like environmental impact and cable composition. The maintenance and lifespan of offshore HVDC grids, with substantial platforms engineered for 25 years but capable of lasting longer, pose further considerations. Innovations are needed to withstand challenges posed by harsh offshore environments, while regulatory aspects, market models, and government equity play pivotal roles in shaping a sustainable and efficient end-of-life strategy.

As the HVDC sector expands, strategic ownership models, such as phased ownership and state-owned infrastructure approaches, are emerging. Governments must carefully manage equity funding and potential credit rating downgrades, particularly amid the post-

COVID-19 financial recovery. The "golden share" mechanism, while providing government influence, requires thorough analysis within the EU framework. This comprehensive approach is crucial for ensuring a robust, sustainable, and innovative future for HVDC technology, addressing the complex challenges associated with its end-of-life phase. End-of-life considerations for HVDC systems present multifaceted challenges for owners and utilities. Financially, regulated assets may involve revenue for life extension and end-of-life investments, while commercial assets might require remuneration, including an end-of-life reserve. A deferred liability on the balance sheet is essential to cover eventual expenses related to dismantling or removing infrastructure, tying up significant capital. Drawing lessons from the O&G sector, where challenges in managing end-of-life assets are apparent, prompts questions about the European Commission's potential role in addressing this issue, especially concerning multinational assets spanning Exclusive Economic Zones.

6.5. Challenges with Non-Technical Capacity

Already today, the HVDC sector faces a scarcity of specialized HVDC engineers and skilled technicians [11]. This issue is expected to become more severe as the number of rolled-out projects increases. Similarly (and partially routed in the staff scarcity problem), another relevant is the need for ramping up the supply chain, for example, cable or transformer manufacturing [11]. The pressed staffing situation in the HVDC sector may delay developments. Notably, a poll of stakeholders in READY4DC indicated their high workload already in 2023 [11], as well as an overall need for more staff in the near future. The HVDC industry already today must put in an effort to find and hire suitable recruits—an effort that will need to be strengthened in the future. As short-term solutions, existing staff from other related domains could be retrained, and existing work processes could be reorganized, given at least some expected degree of similarity in many upcoming projects. Both would help deal efficiently with the upcoming workload. Ultimately, however, the more promising incentives discussed in the HVDC industry during the READY4DC project are, e.g., to enhance interaction between academia and industry in general and to design tailored education programs for the HVDC industry.

6.6. Summary and Recommendations

The massive deployment of (MTMV) HVDC systems will be a challenge. Towards this goal, the READY4DC project has resulted in several conclusions and recommendations (non-exhaustive) [11–13]:

- Financing a FOAK demonstrator is less about technology maturity and more about clear organization. This view aligns with investor interviews.
- Enormous investments needed in offshore and onshore HVDC infrastructure
- Regulated bodies need to be able to make anticipatory investments in HVDC infrastructure
- It is crucial to align research and R&D with efficient deployment. Priorities include expandability, standardization, interoperability, and efficient infrastructure operation.
- While deployment is key, fostering innovation remains an essential principle in this evolving field.
- The End-of-life phase of HVDC systems presents unique challenges. Strategies borrowed from sectors like O&G can provide valuable insights
- Earlier visions for the European HVDC supergrid may have resulted in the impression that a top-down planning and building approach for the complete infrastructure may be a way to move forward. Today, the HVDC community sees the first multi-terminal HVDC systems that appear to be extended piece-by-piece.
- In light of the staff scarcity in the HVDC sector, it must be ensured that HVDC is well-disseminated at universities and the general public to attract more technicians and engineers to the HVDC industry.

7. Conclusions

Advancements in multi-terminal HVDC systems present challenges and opportunities across various dimensions.

The READY4DC project addressed challenges in interaction studies, the legal framework, multi-vendor interoperability, and the long-term view and bigger picture for HVDC technology. The main outcomes are listed as follows:

- Special attention must be paid to the challenge of DC protection integration in multi-vendor setups.
- Increased harmonization and standardization are needed to ensure interoperability.
- A refined list of multi-infeed and interaction studies based on CIGRE B4.81 was presented.
- A flowchart of a multi-vendor interaction study process was proposed.
- The roles and responsibilities during different project stages from pre-project to operation are defined with different options depending on future multi-stakeholder setups.
- The advantages and disadvantages of several offline and online tools for interaction studies were compared, offering different trade-offs such that a user can make an informed decision.
- Different openness levels for converter models were discussed, leading to different levels of flexibility vs. complexity.
- The need for TSOs to take a prominent role in early multi-vendor HVDC project stages was underlined.
- From a legal perspective, the development of standards and other cooperation to reach interoperability should be open and transparent, for example, concerning the allocation of voting rights.
- IP in HVDC is typically protected with a combination of patents and trade secrets. To achieve interoperability, some confidential information may need to be shared. This can happen bilaterally or via a pool. Patents appear to be more easily shared via a pool-based system, whereas trade secrets appear to be more easily shared via bilateral non-disclosure agreements.
- To handle risk, connecting turn-key HVDC projects of different vendors—in a design with a fallback option into single-vendor systems—is suggested to limit the impact of failures.
- A clear allocation of roles and responsibilities is also needed such that liabilities are defined.
- Financing a FOAK demonstrator is less about technology maturity and more about clear organization. This view aligns with investor interviews.
- Enormous investments needed in offshore and onshore HVDC infrastructure.
- Regulated bodies need to be able to make anticipatory investments in HVDC infrastructure.
- The End-of-life phase of HVDC systems presents unique challenges. Strategies borrowed from sectors like O&G can provide valuable insights.
- In light of the staff scarcity in the HVDC sector, it must be ensured that HVDC is well-disseminated at universities and the general public to attract more technicians and engineers to the HVDC industry.

It is important to underline that the complexity of interaction studies increases in a multi-vendor environment, highlighting the need for collaborative efforts to maintain the robust operation of interconnected HVDC grids. Transparent communication among stakeholders involving TSOs, vendors, labs, and more is crucial to addressing interaction risks and scheduling studies at different project stages. Only transparent communication among stakeholders, study planning with clearly assigned roles and responsibilities, and routines for problem-solving will allow the HVDC community to avoid and solve interoperability risks.

MTMV HVDC presents opportunities for extended functionalities, requiring collaboration among stakeholders for a coherent approach. A realistic approach is recommended, focusing with urgency on technical requirements and mobilizing the infrastructure while not preventing innovation. Future research in HVDC should, therefore, reflect the sector's expected rapid growth rates. As a result—to mobilize the infrastructure—future research should focus on modular design, scalable manufacturing, and functional modeling/model-based systems engineering to facilitate interoperability processes. Furthermore, more research into multi-vendor control and protection integration, coordinated HVDC grid control, and resolving interactions between AC and DC systems is needed, reflecting different software and hardware constraints, as well as a need for HVDC grid expansion. In the long term, higher power ratings and circular economy aspects also need to be investigated.

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