READY4DC

Deliverable 1.2

MODELLING, SIMULATION FRAMEWORK AND DATA SHARING FOR MULTI-TERMINAL MULTI-VENDOR HVDC INTERACTION STUDIES

ABOUT READY4DC

The future electricity network envisioned by READY4DC will be characterized by a growing role of multi-terminal multi-vendor (MTMV) HVDC solutions within the current AC transmission networks both onshore and offshore. READY4DC is contributing to this synergistic process by enabling commonly agreed definitions of interoperable modelling tools, model sharing platforms, clear processes for ensuring interoperability, and an appropriate legal and political framework.

Disclaimer:

This project has received funding from the European Union's Horizon Europe Research and Innovation programme under grant agreement No. 101069656.

The views and opinions expressed in this article are those of the authors and the WG1 members, and do not necessarily reflect the official policy or position of specific project partners, nor that of the European Union.

Project

Duration: 1 April 2022 – 30 November 2023
Grant agreement: No. 101069656

READY4DC WG1 Whitepaper

Submission 2023-11-30

Everything from this report may be used under the condition of attribution to the authors in a correct reference: Leon Garcia, W.R.; Filliot, L., Deliverable 1.2: Modelling, simulation framework and data sharing for multi-terminal multi-vendor HVDC interaction studies (Ready4DC, 2023).

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

The emergence and development of HVDC (High Voltage Direct Current) grids offers exciting opportunities for power transmission across regions. However, the intricacies of managing interactions, especially in Multi-Terminal Multi-Vendor (MTMV) environments, can be challenging. This whitepaper presents an analysis of interaction studies in the MTMV HVDC system, emphasizing the need for comprehensive understanding and strategic approaches. This whitepaper also recognizes the achievements of current network codes and T&D Europe guidelines in interaction studies and suggests expanding upon these foundations.

Chapter 1, "Description of Interaction Phenomena", highlights the importance of understanding interaction phenomena in hybrid AC/DC grids for optimal design and operation. A list of interaction phenomena is provided at different time constants, justifying the choice of Electromagnetic Transient (EMT) simulation tools for interactions analysis due to its capability to cover a wide frequency spectrum. While current network codes offer a foundational understanding, they may not encompass all scenarios, such as future interactions through DC meshed grids.

Chapter 2, "Workflow for Interaction Studies", introduces a rigorous workflow for conducting interaction studies in MTMV HVDC projects. At its core, interaction tests validate system interoperability. This chapter emphasizes collaboration among stakeholders to ensure effective model integration, meticulous testing and insightful analysis enabling the diagnostics of interoperability issues.

Chapter 3, "Roles Assessment in Interaction Studies", evaluates the roles and responsibilities of stakeholders in interaction studies. As MTMV HVDC systems bring in new stakeholders, the chapter categorizes them into three primary groups: vendors, integrators (HVDC system operators, AC TSOs), and supporting third parties. A flexible approach to role engagement, depending on the project phase, is recommended.

Chapter 4, "Effect of Converter Openness on Interaction Study Roles", explores scenarios with different openness levels of converter C&P functions. Emphasizing the need to specify functional outlines, the chapter details how varying levels of openness influence methodological considerations, stakeholder responsibilities and IP risks. A clear balance is sought to ease the execution of interaction studies and facilitate the analysis and resolution of issues by meaningful and engaged stakeholders.

Chapter 5, "Analysis of EMT Simulation Tools for Multi-Vendor Interaction Studies", analyzes distinctions between offline and real-time simulations, and their significance in interaction studies for MTMV HVDC. This chapter evaluates various parameters, including procedures for model sharing, performance and accuracy. The overarching message is for stakeholders to choose the most fitting simulation tool according to their role in interaction studies.

In conclusion, this whitepaper offers a panoramic view of strategical and technical aspects of interaction studies within MTMV HVDC systems. The dynamic nature of HVDC systems requires studies that are precise and timely. By grasping the nuances of interactions, defining efficient workflows, facilitating stakeholder collaboration, and understanding the intricacies of converter openness and simulation tool capabilities, resilient and secure MTMV HVDC systems can be developed with a smooth integration among vendors.

INTRODUCTION

The increasing number of HVDC projects has brought about new challenges and questions, particularly when multiple vendors are involved in the same project. While single-vendor turnkey solutions have been the norm until today, with one vendor responsible for providing all the equipment, engineering, and commissioning services, the trend is now shifting towards multi-terminal solutions. This shift has introduced new challenges in terms of coordination, interoperability, and ownership, highlighting the need for a more comprehensive approach to system integration.

In the context of multi-terminal HVDC systems, the possibility of a multi-vendor environment arises, where different vendors provide different components or subsystems of the HVDC system. The European vision of future super grid systems, depicted in Figure 1, is one simplified representation of how future MTMV HVDC would interconnect the European power system to share clean renewable power. However, designing and operating MTMV HVDC systems is a complex task, given the heavy reliance on switching valves and the critical role of control systems in ensuring reliable and robust DC system operation. This is complicated further by the potential differences between each DC converter of different vendors, which can affect coordination and interoperability.

Figure 1. Vision for a European Super Grid (Corbett, 2010).

Ensuring coordination and seeking the same overall system performance is beneficial for the TSO and the end-user, even in scenarios where different vendors are connected to the same HVDC grid. Adverse converter interactions that degrade the performance of the HVDC system could be originated by vendor-specific implementations, including differences in modeling, control tuning, and parameterization. In this scenario, interaction studies play a crucial role in ensuring the design of reliable and robust MTMV HVDC systems, which motivated the partners of this project to propose this whitepaper. Some of the questions this document aims to address are illustrated in Figure 2 and matched to the sections where they will be discussed (in Table 1).

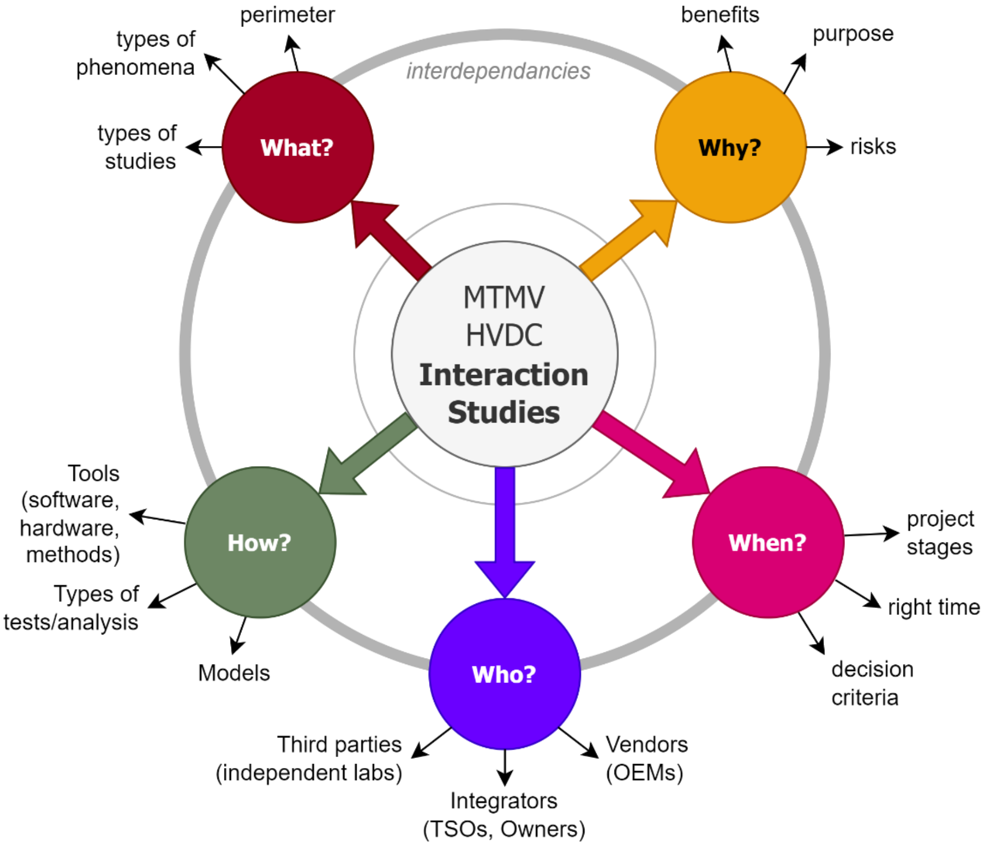


Figure 2. Questioning on interaction studies in a MTMV HVDC context motivating this whitepaper.

Table 1. Whitepaper sections mapped against main questions on interaction studies.

Question	**Whitepaper Section**
Why are these studies so important?	Intro
What are the different types of interaction studies needed in MTMV systems?	1
How are these studies performed ?	1, 2, 3
By whom?	2, 3
When is the right time to perform such studies?	3
What factors are to be considered when performing such studies ?	4
What are the available techniques, tools and models?	5

MTMV HVDC grids involve a complex network of stakeholders, including TSOs, developers, owners, vendors or even third parties such as real-time simulation laboratories. All these stakeholders could play a role in the specification, design, manufacture, operation and maintenance of HVDC assets. TSOs are responsible for overseeing the transmission and distribution of electricity and can be single or multiple entities operating the grid on behalf of one or multiple system owners. This is why TSOs together with owners in the role of an integrator will be evoked in this whitepaper.

The integrators' role should ensure a safe and efficient operation of the HVDC assets in these multi-vendor solutions. It would be responsible for coordinating and integrating the various components of the system provided by different vendors. A stakeholder in the role of integrator could be responsible for conducting interaction studies and must identify any potential issues or conflicts that may arise with other components of the power network. However, since these interactions are much originated from the control of the converters, highly tight to vendors IP, the vendors must be fully committed as well, for instance, in providing expertise, models and capabilities in line with the project's requirements. Especially when there is a need for multi-terminal HVDC grids for which the range of interactions and application of the approach have largely not yet been assessed.

There is indeed the possibility of new interactions between more than two converters (provided by different vendors) on the DC side of the system. With the involvement of multiple vendors, the roles and responsibilities of each stakeholder must be re-defined clearly to ensure a successful outcome. The complexity of ownership and responsibility in a MTMV meshed context can also make it challenging to identify and assign liability in the event of problems or failures caused by interactions. This makes it even more important to conduct thorough interaction studies, following clear guidelines, workflows, roles and methods that help identifying and mitigating any potential issues in a coordinated manner.

In conclusion, this WG1 whitepaper aims to provide guidance on interaction studies in a MTMV HVDC context, addressing challenges and questions that arise when multiple vendors are involved in a project. This has been possible thanks to the participation of partners representatives from the main stakeholders mentioned previously. It is capital for all stakeholders to work together and have clear communication and coordination to ensure the safe and efficient operation of the HVDC assets and the transmission of electricity. Therefore, it is important to establish when and what is to be delivered by TSOs for interaction studies, as well as the timing and scope of the vendors' deliverables for the same purpose.

We hope that the information presented in this document will be helpful to all stakeholders involved in the InterOPERA project and beyond. We wish you success in your efforts to design, operate, and maintain reliable and robust MTMV HVDC systems.

STAKEHOLDERS' DEFINITIONS

The different options for the organization and responsibility framework of HVDC system owners, operators and vendors are not detailed here, but owning and operation of meshed HVDC grids were widely discussed in EU 2020 PROMOTioN Project, well documented in (Seitz *et al.*, 2019).

HVDC System Owner

The HVDC system owner is the entity that holds ownership of the HVDC system and is responsible for its development, construction, and operation. The HVDC system owner could be:

- a Transmission System Operator (TSO),
- an Independent Transmission Operator (ITO),
- an association of TSOs, ITOs,
- a developer responsible for the HVDC system: a public or private company, a utility company or an independent power producer (IPP),
- Offshore transmission owners (OFTOs like in UK)
- an association of developers.

In a large MTMV HVDC system, the impact of different HVDC system owners can be complex. It is possible that there may be multiple HVDC system owners in the same system, each with their own interests and goals. Coordination and cooperation between the different owners are essential to ensure that the system operates efficiently and effectively. The HVDC system owner is responsible for the overall performance and maintenance of the system, including ensuring interoperability between different vendors' equipment. When owners take the role of HVDC system integrators, this responsibility is fully assumed.

HVDC System Operator

The HVDC system operator is the entity that is responsible for the day-to-day operation and maintenance of the system. HVDC system operators ensure that the system is operated within the limits set by the system owner and the regulatory authorities.

In a large MT MV HVDC system, it is possible that there is a single operator responsible for the entire system, or that each HVDC system owner has its own operator responsible for a specific portion of the system. It depends on the design of the system and the agreements between the different stakeholders. In any case, the operator(s) must ensure that the different portions of the system are operated in a coordinated and safe manner. They could be:

- a Transmission System Operator (TSO),
- an Independent System Operator (ISO),
- an Independent Transmission Operator (ITO),
- an association of TSOs, ITOs, ISOs.

Full Ownership Unbundling (FOU)

Full ownership unbundling is a regulatory model that aims at separating the ownership of the transmission system from the generation and supply of electricity. This is done to ensure that the transmission system is operated and maintained in an independent, unbiased, and non-discriminatory manner. The main goal of full ownership unbundling is to promote competition in the wholesale electricity markets and to ensure that the transmission system is operated and maintained in a safe and efficient manner.

Independent Transmission Operator (ITO)

In the context of full ownership unbundling, an Independent Transmission Operator (ITO) is an organization that is fully separated from the generation and supply of electricity and is responsible for the ownership, operation, and maintenance of the transmission system. This means that the ITO is responsible for the construction, operation, and maintenance of the transmission system, and the management of the transmission tariffs. This is done to ensure that the transmission system is operated and maintained in a safe, efficient, and non-discriminatory manner and to promote competition in the wholesale electricity markets.

Independent System Operator (ISO)

In full ownership unbundling, the ISO does not own or maintain the transmission assets and its role is limited to the utilization and coordination of the transmission system. The ISO is responsible for operating the transmission system but does not own it. The ISO is responsible for ensuring that the transmission system is utilized in a safe, efficient, and non-discriminatory manner. This means that the ISO is responsible for dispatching generators, maintaining system security, and ensuring that transmission is used efficiently. The ISO also coordinates the movement of wholesale electricity in a specific region.

Offshore Transmission Owner (OFTO)

An Offshore Transmission Owner (OFTO) is a company that is responsible for the ownership and operation of offshore transmission assets, such as transmission lines and substations, that connect offshore wind farms to the onshore grid. The main role of an OFTO is to manage the transmission of electricity generated by offshore wind farms to the onshore grid, and to ensure that the offshore transmission system is operated and maintained in a safe and efficient manner. The OFTO is also responsible for ensuring that the offshore transmission system is highly available and transmission tariffs are fair.

Independent real-time simulation laboratory

An independent real-time simulation laboratory refers to a facility or organization that is separate from the main product development teams and stakeholders. Its purpose is to perform testing and validation of different components and subsystems before they are integrated into the final product. Independent real-time simulation laboratories may assist HVDC system owners and/or operators with the HVDC system integration and testing, including interaction studies before and after tendering.

The independence of the lab allows for objective and unbiased testing, as well as the ability to identify and address any issues or discrepancies before they become major problems. Independent real-time simulation laboratories typically have a wide range of testing equipment and expertise to ensure that the final product meets the necessary safety, performance, and functional requirements. They are also responsible for creating and maintaining test plans, procedures, and protocols to ensure that all testing is done in a consistent and controlled manner.

HVDC system integrator

The task of an HVDC system integrator involves bringing together all components and subsystems of an HVDC system and ensuring they work together seamlessly. This role involves coordination with vendors, designing control systems, and overseeing testing and commissioning. The HVDC system integrator has expertise in multiple domains and can work with a range of technologies and suppliers. This role can be performed by HVDC system owners, operators, vendors, or developers, and the specific entity behind this role may be specified as needed. The term "HVDC system integrator" is used in this whitepaper to refer to this role without specifying the legal entity behind it.

Wind Developers

The Wind Developer is the owner of wind generation sources. They are responsible for the construction, operation, and maintenance of the wind farm, and may also be involved in the HVDC system integration and testing process especially in countries where the offshore wind farm developer is also responsible for the installation and commissioning of the grid connection system before the handover to an OFTO.

HVDC project developers

An HVDC project developer is an entity or individual who plans, designs, and implements HVDC projects, including the development of the HVDC infrastructure and related assets. HVDC projects can be point-to-point or multi-terminal HVDC connections, multi-purpose HVDC grids, among others (e.g., the North Sea Wind Power Hub (NSWPH).

Vendors

Vendors are suppliers or manufacturers of the AC/DC converter station, other PEID/IBR (Power Electronic-Interfaced Device/Inverter-Based Resource) or the coordinated DC Grid Controller; the DC Grid Controller supplier is considered as a vendor as its role within the interaction studies would be like that of a station manufacturer. Vendors may also be assisted by a third-party real-time simulation laboratory, especially for HIL (Hardware-in-the-Loop) studies. Vendors may be involved in the design, manufacturing, and testing of the HVDC system components, and may also be involved in the HVDC system integration and testing process.

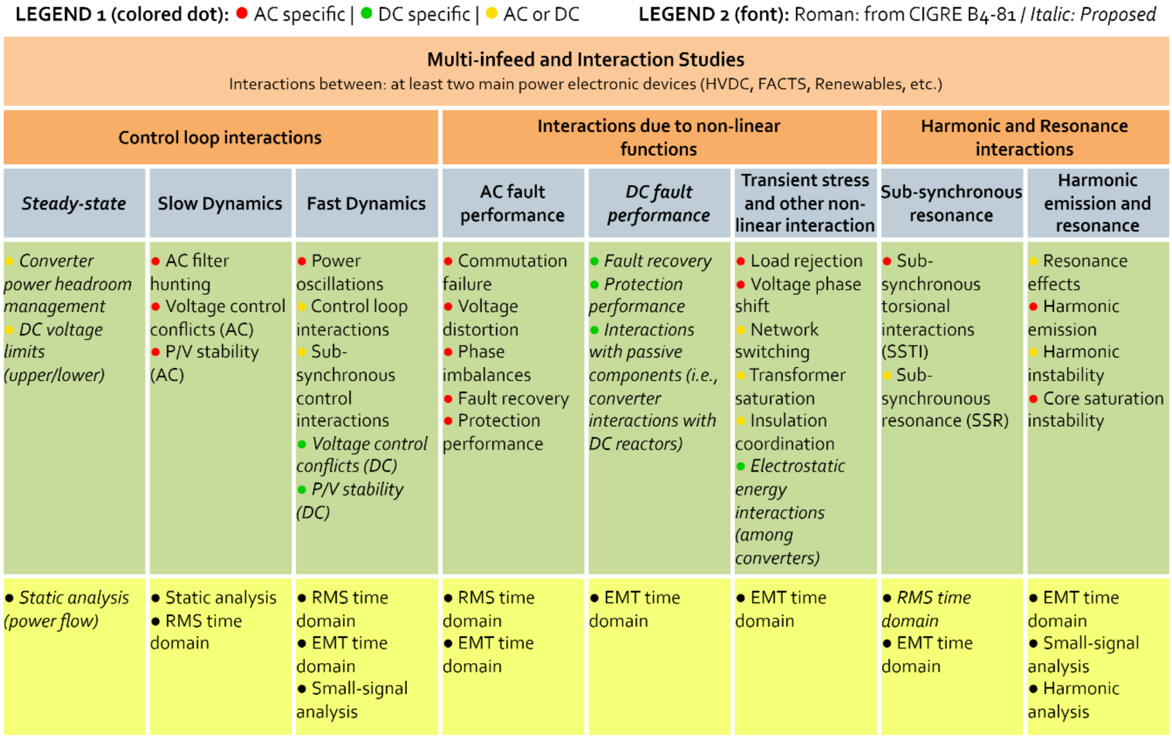
1 DESCRIPTION OF INTERACTION PHENOMENA

According to recent publications (Ming Cai et al., 2021) (T&D Europe, 2022) interaction studies in MTMV HVDC systems focus on the potential effects that different HVDC converters may have on one another, as well as their interactions with network passive components and conventional power plants. These interactions can have both positive and negative effects on network stability. Positive interactions can lead to improved stability, while negative interactions (or negatively damped interactions) can lead to deterioration of system performance. HVDC converters can cause unexpected negative interactions on the grid due to their fast controls and ability to inject harmonic voltages and currents into the grid. Proper tuning is important to prevent local instabilities that could disrupt global frequency stability. These interactions are important to consider in the specification, design and operation of multi-terminal HVDC systems.

Completed and ongoing interaction studies in HVDC systems from different angles have been identified and are listed as follows:

- CIGRE Brochure 119 (WG 14.05): Interaction between HVDC convertors and nearby synchronous machines, (G. Andersson et al., 1997)
- CIGRE B4 – 38: 563 Modelling and simulation studies to be performed during the lifecycle of HVDC systems, (J. A. Jardini et al., 2013)
- ENTSO-E guidance document for national implementation for network codes on grid connection: Interactions between HVDC systems and other connections, (ENTSO-E, 2018)
- ENTSO-E Workstream for the development of multi-vendor HVDC systems and other power electronics interfaced devices, (ENTSO-E, 2021)
- CIGRE B4 – 70: 832 Guide for electromagnetic transients studies involving VSC converters, (S. Dennetière et al., 2021)
- CIGRE B4 – 74: 864 Guide to develop real-time simulation models for HVDC operational studies, (Q. Guo et al., 2022)
- T&D Europe White paper : Studies for Interaction of Power Electronics from Multiple Vendors in Power Systems, (T&D Europe, 2022)
- [Ongoing] CIGRE B4-81: Interaction between nearby VSC-HVDC converters, FACTs devices, HV power electronic devices and conventional, Expected report date: August 2022
- [Ongoing] CIGRE B4.82: Guidelines for Use of Real-Code in EMT Models for HVDC, FACTS and Inverter based generators in Power Systems Analysis, Expected report date: April 2023
- [Ongoing] CIGRE B4-85: Interoperability in HVDC systems based on partially open-source software, Expected report date: July 2023
- [Recent] CIGRE C4/B4-52: TB 909 - Guidelines for Subsynchronous Oscillation Studies in Power Electronics Dominated Power Systems, June 2023
- [Recent] GB ESO: Guidance Notes for Model Exchange for Converter Based Plant Interaction Studies, January 2023

Notably, the T&D Europe white paper makes reference to classification of interaction studies, which has been taken as reference and amended in Figure 3 according to new phenomena expected to appear in a MTMV HVDC environment.



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 3. Categories of interaction studies proposed in CIGRE B4-81, sub-categories and phenomena amended.

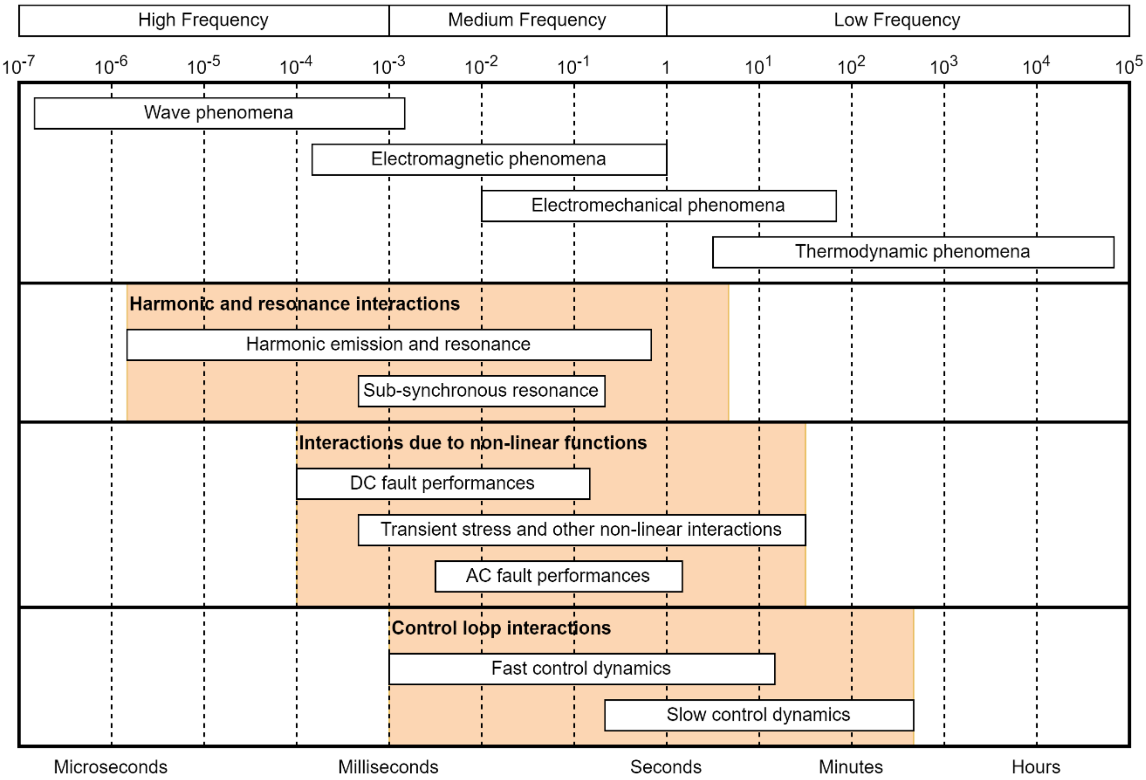


Figure 4. Categories of interaction studies placed in time.

The list in Figure 1 is quite exhaustive, however, the following points are highlighted:

- For multi-vendor studies, it will be important to prioritize interaction studies. Indeed, with the increase of MTMV HVDC systems size, the complexity of such studies increases as well. There is need for fitting them in time and at the right stages of a specific project, whether the system is new or built from interconnection of existing ones.
- One way of prioritizing could be identifying expected outcomes of each study and defining when in the project such outcomes are mandatory or critical. Project stages are specification, design, validation and operation (running system) stages.
- New rules for identifying potential interaction risks as it has been proposed for AC side interactions may be useful to develop also for DC side interactions, so that the system modelling can be reduced to smaller zones.
- A wide range of studies can be covered through EMT time-domain simulations.

Interactions on the DC side of HVDC grids refer to various phenomena that occur when multiple HVDC systems are connected together and are also connected to an AC grid. Some phenomena are specific of the DC side, some of the AC side, but they may also be interlinked on both sides. Next sections are proposed as a brief introduction on some of the interactions mentioned in Figure 3.

Recent case studies (T&D Europe, 2022) conducted in the UK (the National HVDC Centre) and France (RTE International Lab) are mainly focused on interaction studies conducted through EMT simulations such as offline and HIL validation and demonstration tests. On the one hand, offline simulation studies use typically generic models conceived by experts from TSOs, academia, labs or vendors, and benefit from a widespread use due to less resources and expertise required to develop and setup such tests. On the other hand, hardware-in-the-loop (HIL) tests, extensively used by vendors to validate their systems, is becoming more accessible to other actors such as TSOs themselves, laboratories and other third parties to perform not only interaction tests, but train experts on HVDC operations and maintenance. Another type of testing is the SIL, which implies having industrial software inside the simulation or test, either offline or in a real-time simulation.

Since EMT time-domain simulations benefit from a large acceptance among the main stakeholders and seem to be able to represent many of the existing interaction phenomena, this whitepaper will mainly focus on this type of tool. Evidently, the added value of an interaction test, whether it is offline, SIL or HIL, must be assessed according to the different stages of an MTMV HVDC project and will be analyzed here.

1.1 DC Side interactions

Multi-terminal DC grids connected through cables or overhead lines in radial or meshed configurations are subjected to much faster dynamics and transients than AC grids, which makes DC side interactions more complex to study. The illustration in Figure 5 denotes the zone for these interactions to occur.

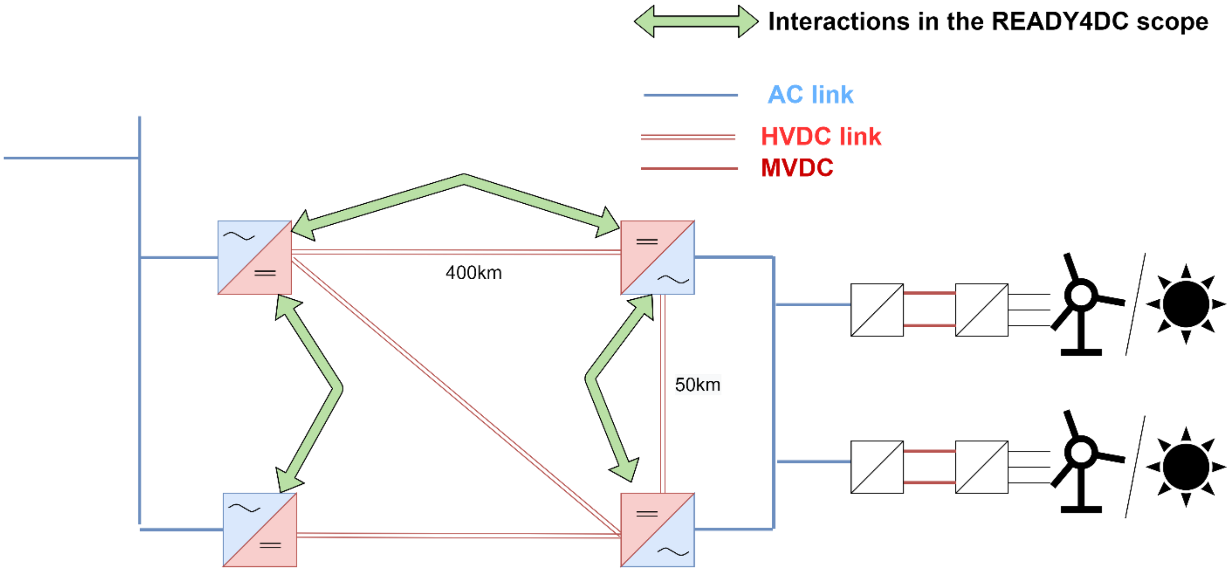


Figure 5. Illustration of DCside interactions use-case.

Some of the interactions that could be listed as DC interactions are:

- **Energy "interactions" among converters for DC voltage stability:** energy in DC grids is mainly of electromagnetic and capacitive nature. Transmission cables and lines will passively contribute to the energy flows in the system. On the contrary, AC/DC converters, depending on their type, can actively contribute to an energy interaction in the system. Even though large MTDC systems may include some of the older technologies (LCC, VSC 2-level), they are expected to be dominated by sophisticated converter-type converters. These converters have a significant amount of capacitive energy stored inside the converter in encapsulated sub-modules. The capacitive energy stored in these sub-modules can negatively or positively affect the surrounding systems stability. For this reason, it is expected that energy "interactions" in converter-type dominated MTMV HVDC systems become an important matter of study at some point of the project.
- **"Interaction" of converter power headrooms and droop parameters allocated for DC voltage stability:** this may or may not be considered as an interaction, since it is more related to the optimization of MTMV systems operations mainly at a pre-design or design stage. The MTMV system must be able to primarily deliver a required active power, from a renewable source or from an AC grid A to B, or C, etc. A certain amount of active power needs to be reserved for system stability functions that may be considered necessary or critical by TSOs. The power headroom allocated to these functions needs to be coordinated among converters in an optimal manner, taking into account specific constraints to the location where each converter is installed. Indeed, each AC grid may impose different constraint levels. This is an interaction that could be classified as a steady-state one.

- **Interaction with DC protection (e.g., DC reactors):** MTMV grids will require a protection system to be secure and reliable. The most performant protection scenario being a fully-selective one is expected to require DC reactors needed to limit the rate of rise of fault currents, but it also supports non-unit protection algorithms to avoid communication for selectivity. The inclusion of several DC reactors and DC Circuit Breaker (DCCB) components may introduce new kinds of interactions to the MTMV system, since the converter control is sensible to the equivalent inductance value of the system. The multi-vendor context would only make the assessment of DC reactor impact on the system transient stability more complex.
- **High frequency studies:** interactions between DC components can produce harmonic distortion in the DC network, which can affect the performance of other electrical equipment connected to the system. Harmonic distortion can also cause heating and other non-linear effects in the DC network, which can impact the overall system efficiency. Also, switching transients can occur when the MTMV system switches between different operating modes, such as during fault clearing or system reconfiguration. These transients can cause voltage and current spikes in the DC network, which can affect the performance of the system and potentially damage the equipment. Finally, resonances can occur when the network has a natural frequency that is close to the frequency of a harmonic component of the AC voltage. These resonances can cause large voltage and current swings in the DC network, which can lead to instability and potentially damage the equipment.
- **DC-PCC conformity studies (e.g., DC under voltage ride though):** at the DC point of common coupling (PCC) the HVDC system connects to the DC grid. The DC under voltage ride through (UVRT) capability refers to the ability of the HVDC system to maintain DC voltage within acceptable limits during DC grid faults or disturbances. During a fault or disturbance in the DC grid, the DC voltage at the PCC can drop. If the DC voltage drops below a certain level, it can cause the HVDC system to trip and shut down. Therefore, it is important to ensure that the HVDC system has the appropriate DC UVRT capability to maintain DC voltage within acceptable limits during DC grid faults.

1.2 AC side interactions

AC side interactions in HVDC systems refer to the interactions that occur between the HVDC system and the AC grid to which it is connected. There are two types of AC side interactions: interactions between power electronic devices in the AC grid and the converter station, and interactions between adjacent power converters connected via the AC side. Interactions between power electronic devices in the AC grid and the converter station are not specific to multi-terminal DC systems and are typically studied by each TSO. These interactions may include interactions between generators, series compensation capacitors, and other power electronic devices in the AC grid. Interactions between adjacent power converters connected via the AC side are specific to multi-terminal DC systems and may include interactions between different converter stations or different windfarm power converters connected to the same AC energy hub or through a short AC link. These interactions can be studied by the vendor on a single-vendor system case, but for multi-vendor scenarios, the interaction studies need to integrate models from several vendors.

The scheme in Figure 6 illustrates the different possible interactions in the AC side and the ones that READY4DC needs to detail and pave the way for future projects. The two adjacent converters connected closely into the same AC grids are from a same MTDC network.

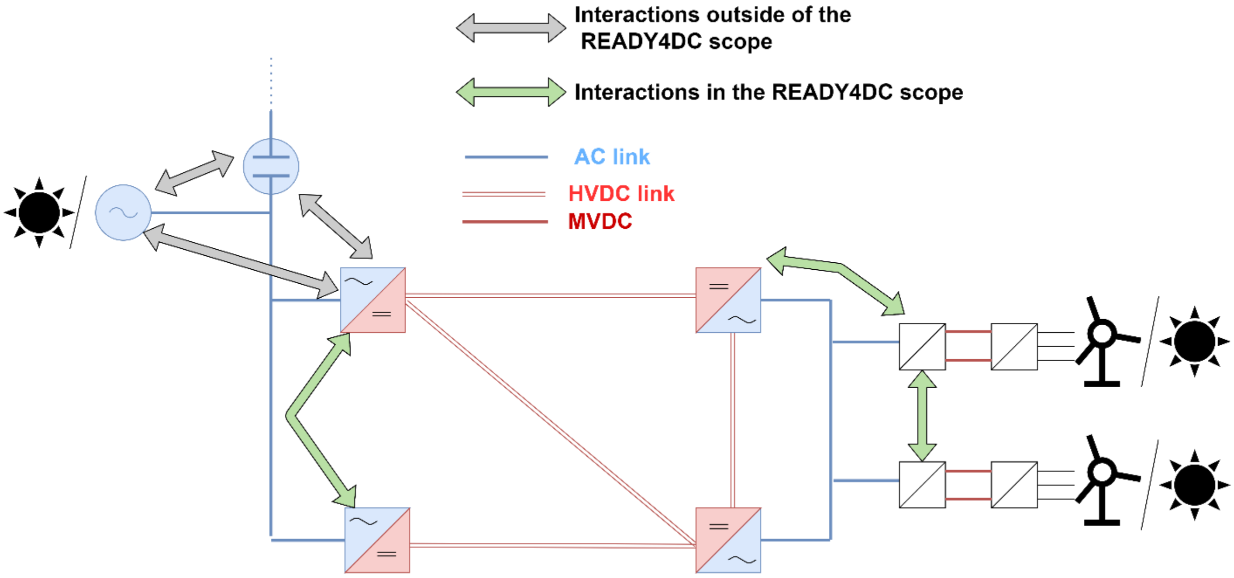


Figure 6. Interactions scope in READY4DC. The renewable energy sources can be offshore wind farms as well as solar PV plants. A recent paper (Wang et al., 2022) confirms the interaction of Solar DC sources and AC system.

A similar situation would occur on the case of "hybrid systems" (Figure 7): two HVDC links in parallel connected to a same AC network (like the double circuit between France and Spain). Studies would be similar in that case but is not specific to multi-terminal case, so they are not part of our current scope.

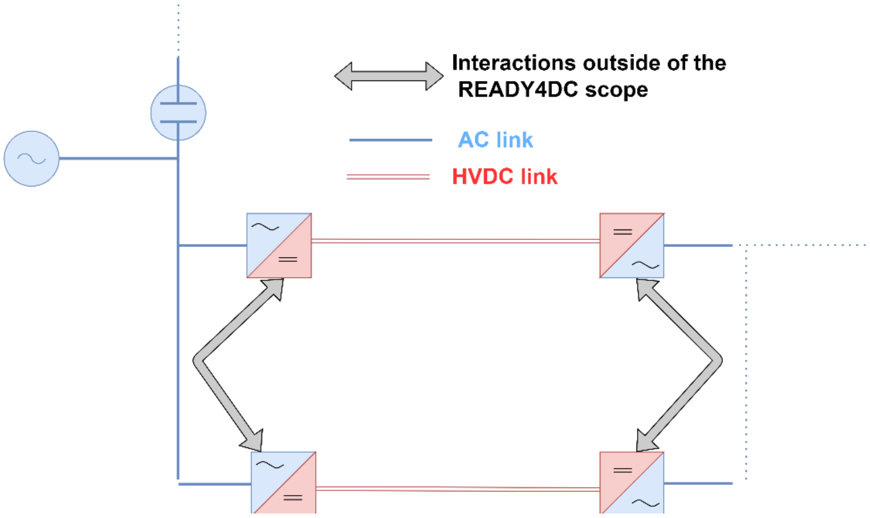


Figure 7. Multi-terminal scheme that is not under READY4DC scope since the DC side is not linked.

Some of the interactions that could be listed as AC interactions are:

- **High Frequency harmonics:** HF harmonics can be generated in the AC grid by the switching actions of the power electronic devices in the HVDC system, which can cause harmonic distortion and potentially interfere with other electrical equipment connected to the same grid. The HF harmonics can be mitigated by filtering and other control techniques, but their impact needs to be carefully analyzed to ensure that the system operates reliably.
- **Sub-synchronous control instability (SSCI)**: Sub-synchronous control instability can occur when the control systems of the HVDC system interact with the mechanical system of the AC grid, causing instability and potentially damaging the equipment. This interaction can occur through torsional oscillations or other mechanical effects, and it needs to be carefully analyzed and controlled to ensure stable operation of the system.
- **Sub-synchronous resonance (SSR)**: Sub-synchronous resonance can occur when the natural frequency of the AC grid is close to a harmonic frequency of the HVDC system, causing large amplitude oscillations and potentially damaging the equipment. This interaction can be mitigated through careful modeling and control techniques, such as damping control and frequency response analysis.
- **Sub-synchronous torsional interaction (SSTI)**: Sub-synchronous torsional interaction can occur when the torsional oscillations of the AC grid interact with the HVDC system, causing instability and potentially damaging the equipment.
- **Sideband oscillations in fundamental frequency and switching frequency range**: Sideband oscillations can occur in the AC grid when the HVDC system interacts with the grid through the modulation of the switching frequency of the power electronic devices. These oscillations can cause instability and potentially damage the equipment, and they need to be carefully analyzed and controlled through appropriate filtering and control techniques.

Interactions of HVDC systems on the AC side is a widely studied topic nowadays. The main complexity comes from the multi-vendor scenario, which neither is new. The following Table 1 illustrates the focus that should be made in READY4DC in order to propose novelty to the subject:

Table 2. Scope of the interaction studies considered in WP1.

	MMC converter	**Windfarm /Solar Power Electronics**	**DC grid elements (DC reactors, breakers, PFCs, DCDC converters…)**	**AC grid elements (Generator, Series Compensation Capacitors…)**
MMC converter	Yes	Yes	Yes	Out of scope
Windfarm Power Electronics	Yes	Yes	Out of scope	Out of scope
DC grid elements (DC reactors, breakers, PFCs, DCDC converters…)	Yes	Out of scope	Yes	Out of scope
AC grid elements (Generator, Series Compensation Capacitors…)	Out of scope	Out of scope	Out of scope	Out of scope

1.3 Identification of interactions requiring studies

In a large multi-terminal HVDC system, it may not be feasible to study all possible interactions between different stations due to the exponential increase in the number of combinations as the grid expands. Therefore, it is important to identify which interactions require studies and when to perform them.

To decide which interactions to study and which to neglect, various criteria can be used. For AC side interactions, the Multi Infeed Interaction Factor (MIIF) can be used as a criterion. The MIIF is based on angle deviation, voltage deviation, and is weighted with reactive or active power. The unit interaction factor, which considers the interaction between generators or machines, can also be used as a criterion.

For DC side interactions, distance between stations can be a factor in deciding which interactions require studies. Stations that are close to each other are more likely to have important interactions, but this is not the only criterion. CIGRE C4.49 provides guidance on when to consider interactions between stations that are far away. In addition, efforts and assessment by CIGRE B4.82 have identified the need to consider frequency ranges and the requirement for components to be passive above a certain frequency range.

Although some interactions may be neglected, it is important to note that neglecting interactions could theoretically pose a risk of unexpected behavior that was not raised during simulations. However, this risk is considered limited, and with more experience and understanding of the system, specific requirements can be set, and a limited number of interaction studies can be conducted to ensure safe and reliable operation of the system.

2 WORKFLOW FOR INTERACTION STUDIES

Interaction studies are an essential part of designing and operating a MTMV HVDC grid. These studies involve simulating the performance of the HVDC grid under different scenarios and conditions to identify potential issues and evaluate its performance. Types of interaction studies were discussed in section 1. In this section, we analyze the interaction studies workflow and assess the roles and responsibilities of different stakeholders within it.

Unfortunately, this is not a straightforward task, and it is mostly likely that roles and responsibilities in interaction studies depend on system specificities. For instance, the existing network code for interaction studies applies when a risk of interaction is estimated through the AC grid between power electronic converters at close vicinity (see Figure 9). The current code is thus based in the case where HVDC systems are mainly point-to-point single-vendor turnkey solutions. In such cases, interactions may occur between different vendors only at the AC point of coupling (PoC).

We can expect that this will also be the case when DC PoC between different vendors becomes an increasingly common scenario in future multi-terminal HVDC grids. Not to mention that AC interactions can still interfere with the multi-terminal system. In such new context, two scenarios are possible, the **green field** scenario where the multi-terminal HVDC system is designed from scratch, or the **brown field** scenario where the multi-terminal HVDC system is built upon expanding an existing link or interconnecting existing links. In each case, the system can either remain a single vendor or become a multi-vendor system.

As illustrated in Figure 8, this chapter will present the evolution of the interaction studies workflow from the basis set by the network code in a context point-to-point turnkey HVDC solutions into a workflow that must involve the increasing complexity of multi-vendor and multi-terminal HVDC scenarios.

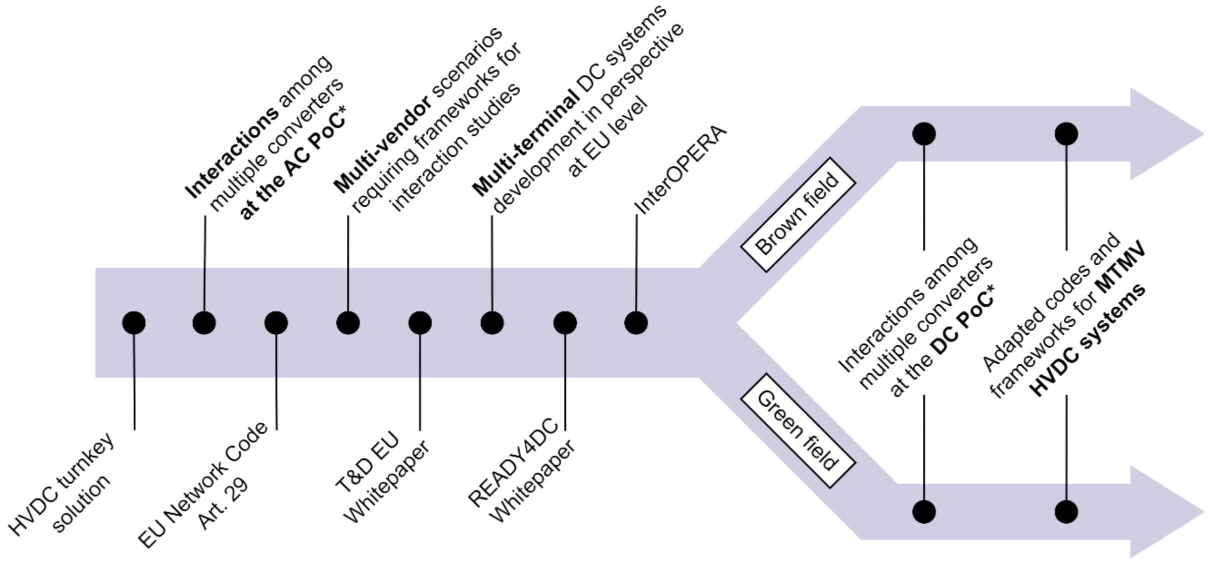


Figure 8. Rationale of the interaction study workflow analysis.

2.1 Network code: European rules for interaction studies

The Commission Regulation (EU) 2016/1447 of 26 August 2016 established a network code on requirements for grid connection of HVDC and direct current-connected power park modules. The regulation is intended to provide a clear legal framework for grid connections and to facilitate union-wide trade in electricity, ensure system security, integrate renewable electricity sources, increase competition, and allow more efficient use of the network and resources for the benefit of consumers. This code is described in document 32016R1447 (European Commission, 2016) and specifies a first methodology for interaction studies at the AC connection point as depicted in Title II, General Requirements for HVDC Connections, Chapter 4, Requirements for control, and specifically in Article 29, "Interaction between HVDC systems or other plants and equipment". Article 29 can be a base for defining roles and responsibilities in the workflow proposed for MTMV HVDC grids. Here are given the rules specified by article 29:

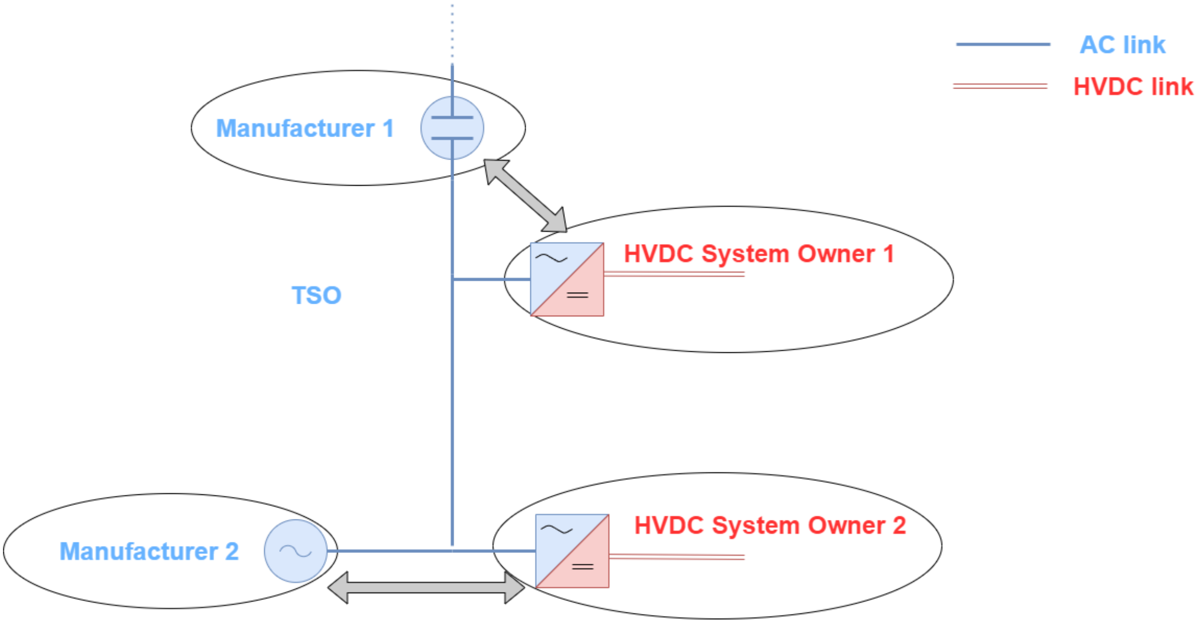


Figure 9. Perimeter of the interaction studies covered in Article 29 of the CR (EU) 2016/1447 of 26 August 2016.

Interaction between HVDC systems or other plants and equipment:

1. When several HVDC converter stations or other plants and equipment are within close electrical proximity, the relevant TSO may specify that a study is required, and the scope and extent of that study, to demonstrate that no adverse interaction will occur. If adverse interaction is identified, the studies shall identify possible mitigating actions to be implemented to ensure compliance with the requirements of this Regulation.
2. The studies shall be carried out by the connecting HVDC system owner with the participation of all other parties identified by the TSOs as relevant to each connection point. Member States may provide that the responsibility for undertaking the studies in accordance with this Article lies with the TSO. All parties shall be informed of the results of the studies.
3. All parties identified by the relevant TSO as relevant to each connection point, including the relevant TSO, shall contribute to the studies and shall provide all relevant data and models as reasonably required to meet the purposes of the studies. The relevant TSO shall collect this input

and, where applicable, pass it on to the party responsible for the studies in accordance with Article 10.

4. The relevant TSO shall assess the result of the studies based on their scope and extent as specified in accordance with paragraph 1. If necessary for the assessment, the relevant TSO may request the HVDC system owner to perform further studies in line with the scope and extent specified in accordance with paragraph 1.
5. The relevant TSO may review or replicate some or all the studies. The HVDC system owner shall provide all relevant data and models to the relevant TSO to allow such a study to be performed.
6. Any necessary mitigating actions identified by the studies carried out in accordance with paragraphs 2 to 5 and reviewed by the relevant TSO shall be undertaken by the HVDC system owner as part of the connection of the new HVDC converter station.
7. The relevant TSO may specify transient levels of performance associated with events for the individual HVDC system or collectively across commonly impacted HVDC systems. This specification may be provided to protect the integrity of both TSO equipment and that of grid users in a manner consistent with its national code.

In summary, it is stated that when several HVDC converter stations or other plants and equipment are within close electrical proximity, the relevant TSO may specify that a study is required, outlining the scope and extent of that study, to demonstrate that no adverse interaction will occur. If adverse interaction is identified, the studies shall identify possible mitigating actions to be implemented to ensure compliance with the requirements of this Regulation. The studies shall be carried out by the connecting HVDC system owner with the participation of all other parties identified by the TSOs as relevant to each connection point.

An adaptation to DC interaction studies is needed. Indeed, the present EU network code does not specifically address the issue of interaction studies for the connection of multiple HVDC systems or other plants and equipment at a single DC point of connection. Figure 10 illustrates the different interactions and stakeholders involved in MTMV HVDC networks:

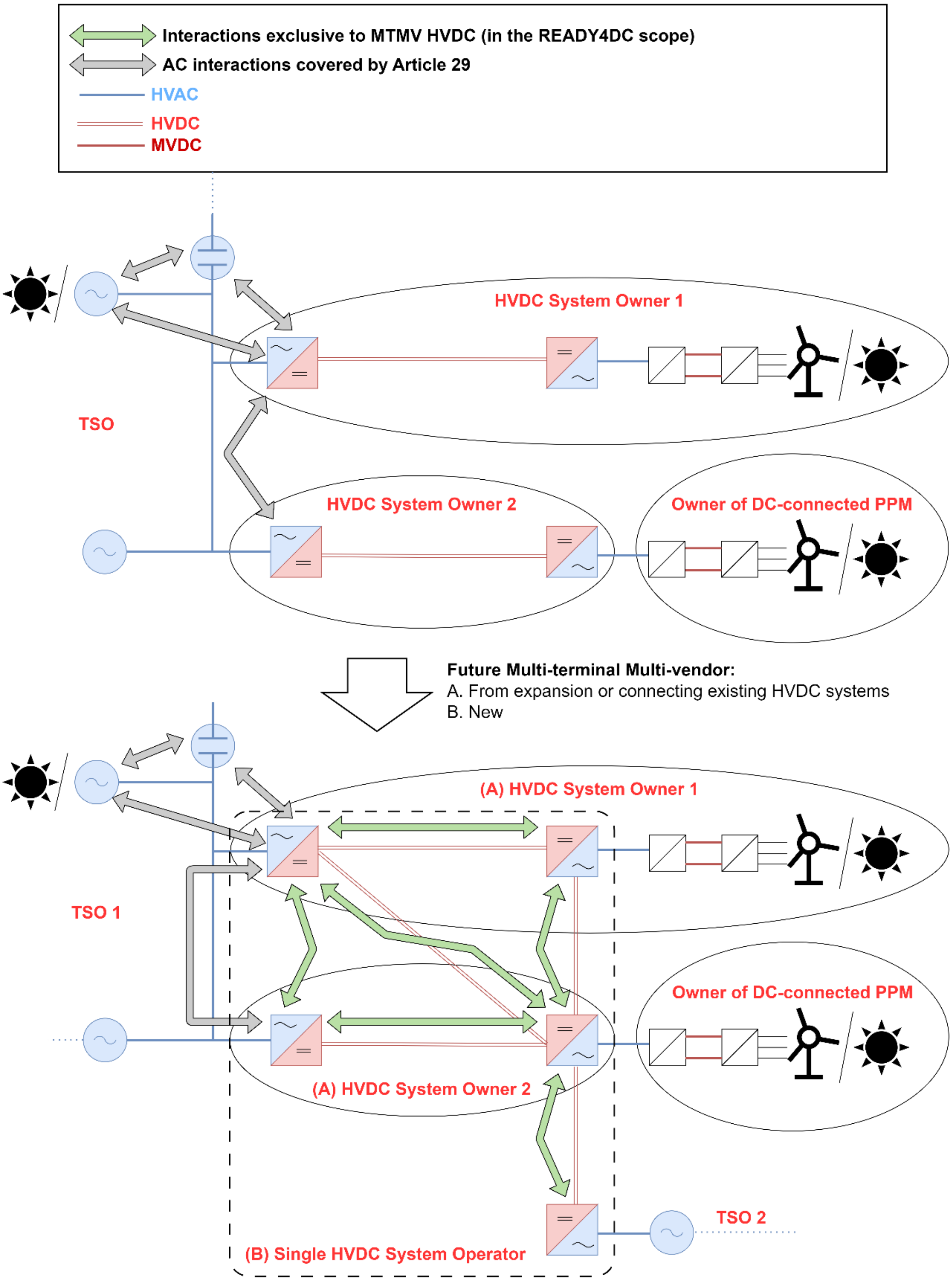


Figure 10.Illustrative scheme for interaction studies considered in CR (EU) 2016/1447 and identified gaps for MTDC grids.

2.2 T&D Europe base case

The multi-vendor interaction study involves vendors sharing required information directly through TSOs or HVDC system owners. The exchange of information requires a signed agreement which defines the purpose, scope, format, and timing of the information exchange, as well as the process for meetings to discuss any potential issues. The T&D Europe whitepaper (T&D Europe, 2022) is already placed in the scenario where multiple vendors are performing interaction studies, but not necessarily in a multi-terminal HVDC system. Despite of this, it describes and illustrates in a concise and simple way the application of the network code in three stages as follows in Figure 11:

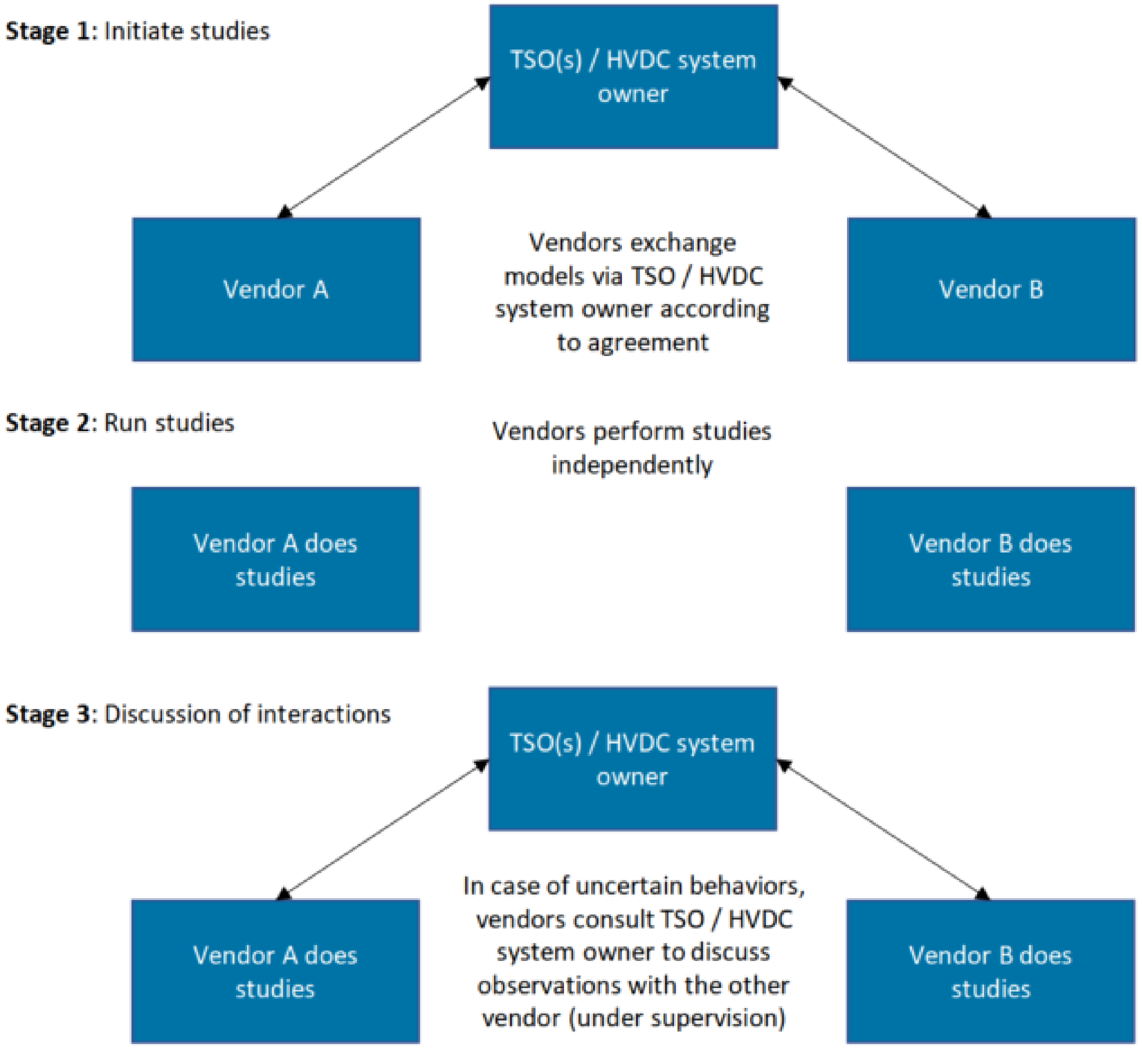


Figure 11. Integrator, here represented by TSOs and/or HVDC system owners, delegate interaction studies to vendors, who due to IP protection prefer to perform interaction studies independently, exchanging respective, black-boxed models.

- **Stage 1** involves exchanging the minimum required models and performing a benchmark.
- **Stage 2** involves each vendor performing studies using their own model and the model(s) provided in stage 1.
- In case of interactions or observations, **Stage 3** involves either vendor contacting the other parties for discussion under the supervision of the TSOs or HVDC system owners (forming the integrator as proposed in this white paper).

The T&D Europe report (T&D Europe, 2022) provides a concise explanation of a workflow, but it does not address the applicability of this approach to more complex scenarios or larger MTMV HVDC systems. Furthermore, it does not specify the stage at which the interaction studies mentioned are conducted. However, it can be inferred that these studies are part of the design stage, conducted prior to the installation of new equipment that may interact with existing PEIDs. Due to these considerations, there is a motivation to delve deeper into the analysis, which is one of the driving factors behind the proposal of READY4DC and will continue further in the so-named InterOPERA project.

2.3 A viable generic workflow

The current network code (European Commission, 2016) and T&D Europe (T&D Europe, 2022) outlines interaction studies reflect somehow a consensus achieved among various stakeholders. The approach presented in this whitepaper aims to build upon these initial approaches by proposing a generic workflow that can be extrapolated to the new MTMV HVDC context. This generic methodology to perform interaction studies aims to be tool-agnostic and not dependent on specific models or types of interaction studies. Figure 12 illustrates the overall workflow, showcasing the progression through different phases.

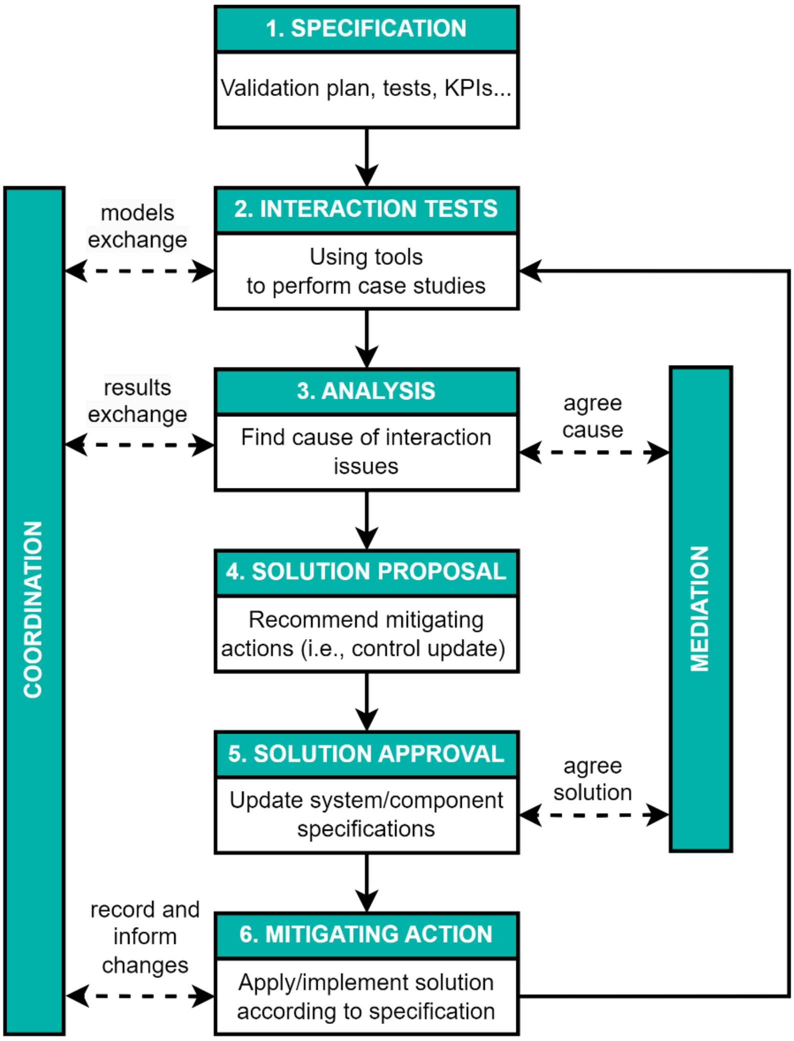


Figure 12. Flowchart of the multi-vendor interaction studies process.

2.3.1 Coordination and mediation

The **coordination** involves discussions between different relevant stakeholders to establish system and component model requirements. It also includes defining the level of detail included in the models and establishing rules regarding information sharing. The goal is to ensure that the models meet the established requirements. Model sharing may occur not only between vendors but also with other stakeholders such as HVDC operators, TSOs, wind developers and other relevant third parties involved in interaction studies.

One possible approach for model sharing is the establishment of a model "bank" facilitated by the system operator, which provides stakeholders with specific access rights to retrieve the required models. This ensures controlled access and availability of the necessary models while maintaining data security and integrity. Additionally, the system operator may prepare online black-box models, representing the resulting grid that covers multiple converter stations. These black-box models enable vendors to assess the integration of their systems within the broader grid context.

It will be essential to maintain a technology-neutral perspective in the model requirements, for instance, avoiding dependencies on specific compiler versions, as the goal is to establish a solution that is not tied to a particular technology. Model requirements must ensure compatibility, interoperability, and seamless integration among different systems and tools employed in the multi-terminal multi-vendor HVDC interaction studies.

Additionally, it is important to note that the **coordination** role in step 1 is ongoing throughout the process. This role involves ensuring that all stakeholders, including vendors, are on the same page and that communication is clear and effective. This is particularly important in step 4, where mediation is necessary to resolve disagreements.

If there is a disagreement among stakeholders involved (including vendors, HVDC operators, TSOs, wind developers, wind vendors...) a **mediation** process is necessary to facilitate reaching a mutually agreed-upon solution. During the mediation process, it is important to foster open communication and collaboration among the different types of stakeholders. By including all relevant stakeholders in the mediation process, a more comprehensive and well-rounded solution can be reached in the next step, considering the different perspectives and expertise of each party.

2.3.2 Step 1: Specification

The HVDC system operator(s) is responsible for writing and providing a validation plan for the interaction studies. This validation plan should include the following:

- Identification of the interaction studies required, and which ones can be neglected.
- A full list of all case studies that will be tested.
- Acceptance criteria that have been agreed upon in advance.
- Key performance indicators (KPIs) to be measured during interaction studies.

It is worth noting that an accurate validation plan defined in step 0 is crucial for the success of the interaction tests to be done in step 2. It is important to note that while the TSO holds the responsibility for these tests, collaboration and flexibility with other relevant stakeholders is essential. For instance, vendors may need to modify certain aspects of their system based on the analysis conducted during the interaction studies. The aim is to ensure that the system meets the required specifications and performance targets, and vendors play a crucial role in achieving these requirements. Therefore, a close partnership among relevant stakeholders is necessary throughout the workflow to address any necessary modifications and ensure the successful implementation of the validation plan during a specific stage of the MTMV HVDC project.

2.3.3 Step 2: Interaction tests (off-line, SIL or HIL)

This phase is where the actual interaction studies take place, following the validation plan established in step 0. This step involves integrating models from different entities, preparing simulation models, and applying various test case scenarios. If any interoperability issues arise, they are then analyzed and troubleshot as described in subsequent steps. Finally, it is important to ensure that the results of the interaction studies are thoroughly documented and reported, including any issues that were identified. This documentation can be used to inform future studies and to ensure that the HVDC grid is operating at optimal performance.

2.3.4 Step 3: Analysis

This step focuses on identifying the root cause of any interoperability issues that were identified in the simulation step. The analysis process involves a comprehensive review of simulation results and conducting further testing if needed, taking into consideration the varying accessibility of data among different stakeholders. The analysis should be conducted in a thorough and well-documented manner to facilitate effective explanation and communication with the main stakeholders involved. It is important to note that an interaction involves different equipment and systems working together to meet the overall customer requirements. Pinpointing the exact cause of an issue to a single specific equipment can be challenging.

Furthermore, in a multi-vendor context, interaction issues between components provided by different vendors can arise. In such a situation, it is possible that two entities may attempt to solve the problem in parallel, resulting in new interoperability issues. Therefore, it is important to have a coordinated approach to address interaction issues caused by multiple vendors. This could involve a joint team or committee consisting of representatives from all relevant entities, including vendors, the system operator, and the system integrator. The team can work together to identify the root cause of the interaction issue and develop an appropriate solution that considers the impact on the entire system.

During the analysis phase, stakeholders with different roles and responsibilities may have varying levels of access to the simulation results and data. It is important to acknowledge that data accessibility may differ depending on the specific stakeholder's involvement in the project.

2.3.5 Step 4: Solution proposal

During this step, the stakeholders collectively consider the findings from the analysis conducted in step 3 and bring forward potential solutions. The solution proposal process should encourage collaboration and input from various stakeholders, including vendors, operators, and other relevant parties. The proposed solutions should be well thought out, considering the impact on the entire system and the feasibility of implementation.

2.3.6 Step 5: Solution approval

The proposed solution undergoes a comprehensive review and approval process involving all stakeholders. It is important to note that while some solutions may not require full documentation, there may be cases where vendors can update controls or make modifications without providing extensive details on the specific changes. A balance between the need for thorough documentation and the flexibility to make necessary updates or modifications needs to be found. While detailed documentation is important for comprehensive understanding and traceability, it is also recognized that certain modifications, especially related to controls, may require a level of flexibility in the documentation process. This allows vendors to implement updates efficiently while still maintaining the overall integrity and performance of the system.

The approval process should prioritize effective communication, ensuring that all stakeholders are informed of any changes made, even if not fully documented, while still maintaining appropriate levels of transparency and accountability. The approval process should consider the specific project phase in which the interaction study was performed, whether it is before or after the bidding stage. Depending on the phase, the approval may involve modifications to functional specifications, technical specifications, system design or operational settings.

2.3.7 Step 6: Mitigating action

Based on the solution validated in step 6, updates may be made to the controls, protection systems, or other relevant components of the HVDC grid. Mitigating actions may go beyond control updates and encompass broader aspects of the system's functionality, including protective measures and equipment modifications or replacements. The implementation of mitigating actions should be closely monitored to ensure their effectiveness. This monitoring process includes evaluating the performance of the updated equipment in standalone operation. The vendor responsible for the specific equipment involved in the mitigating actions holds the responsibility for conducting the necessary tests to ensure that the updated equipment operates as expected and meets the required performance criteria.

3 ROLES ASSESSMENT IN INTERACTION STUDIES

In this section, we discuss the list and definition of roles to be taken by different stakeholders across the generic workflow for interaction studies presented in Figure 12, in alignment with the process described in Article 29 of the network code (European Commission, 2016) and T&D EU (T&D Europe, 2022). First, there is a need to define new stakeholders in the MTMV HVDC grid context.

3.1 Definition of stakeholders

The HVDC Grid Operator, in the case of a newly planned MTDC network, or HVDC System Owners, in the case of expansion or interconnection from existing HVDC systems, are responsible for coordinating interaction studies. They shall do this in conjunction with all relevant parties, including TSOs from different countries or zones and vendors of the converters. In the foreseen MTMV HVDC context, more stakeholders may be involved in the interaction study process than those considered until now. Table 3 makes the parallel between the current situation and the expected future one.

Table 3. Extrapolating stakeholders featured in the network code for interaction studies to a new MTMV HVDC grid context.

	AC/DC interaction studies today	HVDC MTMV context
Grid Operator	AC TSOs	**HVDC System Operator & AC TSOs:** one or several TSOs, mainly the ones operating previous links, or those operating AC networks at the AC point of connection.
Party willing to connect to that grid	**HVDC System Owner:** (owner of the point-to-point link or HVDC equipment, e.g., BESS, STATCOM) willing to connect to the same AC network where a HVDC system exist within a certain minimum electrical proximity on the AC side causing a risk of interaction.	- **Multiple HVDC System Owners:** (owner of a point-to-point link) willing to connect with another HVDC System Owner to a DC point of connection. - **Single HVDC System Owner or multiple owners:** willing to create several AC points of connection with at least three AC/DC converters that are also linked on the DC side.
System integrator role	**HVDC (MV) system integrator:** AC TSOs and wind farm developers carrying out interaction studies as described in Article 29 from network code.	**HVDC MTMV system integrator:** the association of owners or operators or independent companies with the role of designing an MTDC network that fulfills operators' requirements for reliable and safe operation of the MTDC system in harmony with surrounding AC networks. Since it is a role, can be attributed to different kinds of stakeholders, i.e., vendors, TSOs, independent third parties, developers, or a consortium regrouping some of them.

Building on the workflow presented in the previous section, we propose a role assessment of key stakeholders involved in interaction studies, seeking to complement previous works. Three main categories of stakeholders will be distinguished for the rest of this section:

- **Vendors or (OEMs)**: responsible for providing the technology that forms the basis of the interactions, including control and protection devices.
- **System Integrators**: body regrouping HVDC system operators, owners, one or multiple TSOs.
- **Supporting Third Parties:** expert third parties that can contribute to interaction studies by bringing tools, methods and knowledge to support and optimize the process or solve issues (i.e., R&D companies and laboratories, consultants, universities, hardware and software suppliers…).

3.2 Definition of roles in interaction studies

To assess which roles are to be performed by stakeholders, those roles must be defined. Roles have already been mentioned in the network code. A parallel between the proposed workflow and the network code process for interaction studies is made in Table 4, with the aim of identifying such roles. It also illustrates the entities that are stated to be participating in each part of this process, according to the network code and it is extrapolated to the new stakeholders' definition.

Table 4. Extrapolation and matching of Article 29 from network code and the proposed interaction studies workflow.

Workflow step	**Role** within **interaction studies** according to network code **(Art. 29)**	Potentially responsible entity	
		From existing network code	**MTMV HVDC grid context**
(1) Specification	(1) **Identify** the need of a study and its **scope/extent**	TSO	HVDC System Operator(s)
	(2) **Identify** relevant **parties** taking part in the study	TSO	HVDC System Operator(s)
	(3) **Define responsibility** (liability?) for studies (it may lie with the TSO)	Member States (approval from national regulator entity under TSO recommendation)	Member States (approval from European regulator under HVDC System Operator(s) recommendation[1])
	(4) **Specify** transient levels of performance for individual HVDC system or collectively across commonly impacted HVDC systems	TSO	HVDC System Operator(s)
	(5) **Collect** contributions and **models/data**, and pass it to study makers where applicable	TSO	HVDC System Operator(s)
	(6) **Provide** relevant **data/models** for some/all studies replication	HVDC System Owner	All parties
(2) Interaction Tests	(7) **Undertake** the **studies** and **inform results** to all parties	Connecting HVDC System Owner or TSO if decided otherwise by a Member State	HVDC System Owners or Integrators, or HVDC System Operator(s) if decided otherwise by a European regulator
	(8) **Contribute** to the studies and provide relevant data/models	All parties identified by entity listed in 4	All parties identified by entity listed in 4
	(9) **Perform further studies** by TSO request	HVDC System Owner	HVDC System Owners or Integrators (supported by vendors)
(3) Analysis	(10) **Assess** the **results** and request further studies	TSO	HVDC System Operator(s) or HVDC System Integrator
(4) Solution Proposal	(11) **Identify** possible **mitigating actions**	All parties	All parties
(5) Solution Approval	(12) **Review** or **replicate** some/all **studies** and **mitigating actions**	TSO	HVDC System Operator(s)
(6) Mitigating Action	(13) **Apply** any necessary **mitigating actions**	HVDC System Owner	HVDC System Owners (supported by vendors)

According to what is defined by the current network code, the HVDC system operator is pivotal, it is accountable for interaction studies and must analyze the results. Consequently, there is a need for effective coordination between different vendors to ensure that models meet the requirements for interaction studies. The vendors, such as AC/DC converter station suppliers and DC grid control manufacturers, also play an essential role. The HVDC system operator(s) must ensure that the coordination process is effective.

The HVDC System Operator(s) are expected to select the entity responsible for conducting studies, such as specific vendors or an HVDC system integrator. Recommendations from these studies would need approval from a public entity (Member States), in a similar way to how a TSO's recommendation is approved by a national regulatory entity for AC interaction studies. The HVDC system integrator will likely need to collaborate with any relevant parties to conduct interaction studies. In some cases, reviewing or replicating interaction studies can be feasible. As the number of terminals in MTMV HVDC systems grows, however, these tasks become increasingly complicated and costly. Researchers are exploring alternative solutions, like using specialized labs capable of reconfiguring replicas and conducting simulations in a dispersed fashion.

Roles and responsibilities of the HVDC system integrator and vendors must be clearly defined as they are the primary stakeholders interested in resolving interaction issues. To simplify the roles assessment in interaction studies, these roles are simplified into a single word each, categorized and listed as follows:

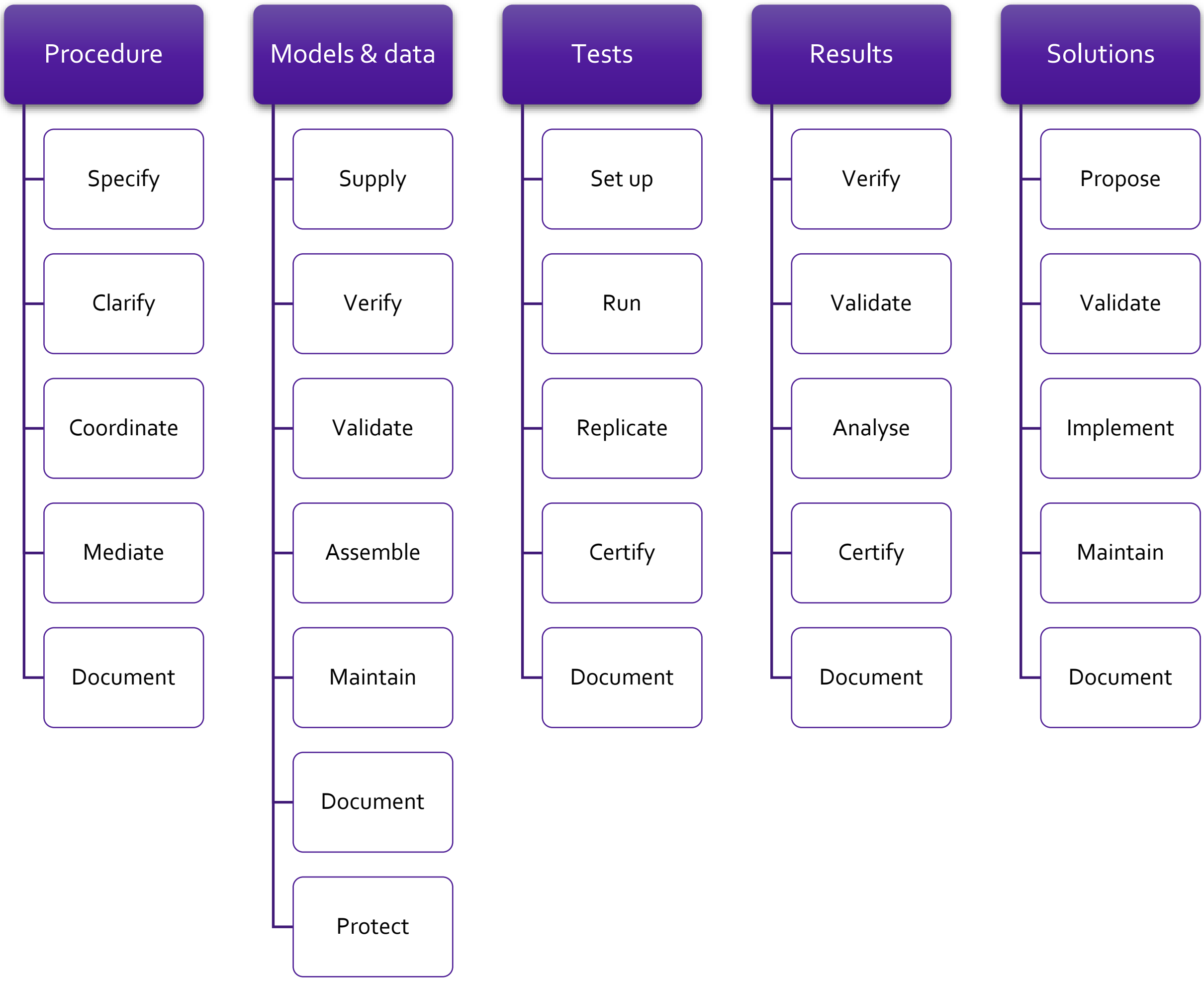


Figure 13. List of roles grouped in five categories defined for interaction studies in a MTMV HVDC grid development context.

3.3 Stakeholders’ roles assessment

A critical concern is determining the most appropriate time to commence interaction studies during a MTMV HVDC project. As illustrated in Figure 14, such a project progresses through several stages, including specification and pre-design, design, validation, and operation (running system). The first two are in preparation of the bidding procedure, the last two after the project have been awarded to vendors for design and commissioning.

Interaction studies could potentially occur at any of these stages using different tools and methods available, with each providing varying levels of system knowledge and data availability. However, upon the awarding of contracts, vendors and TSOs routinely engage in interaction studies, spanning both the design and operational stages. They serve to validate the system design further and facilitate a more precise evaluation of technological implementations and interoperability of actual control and protection systems via HIL studies.

In the next sub-sections, the topic starts with a role assessment for the usual interaction studies done after a contract is awarded in an MTMV HVDC project. Then, it moves on to insights about studies that might be done in earlier phases.

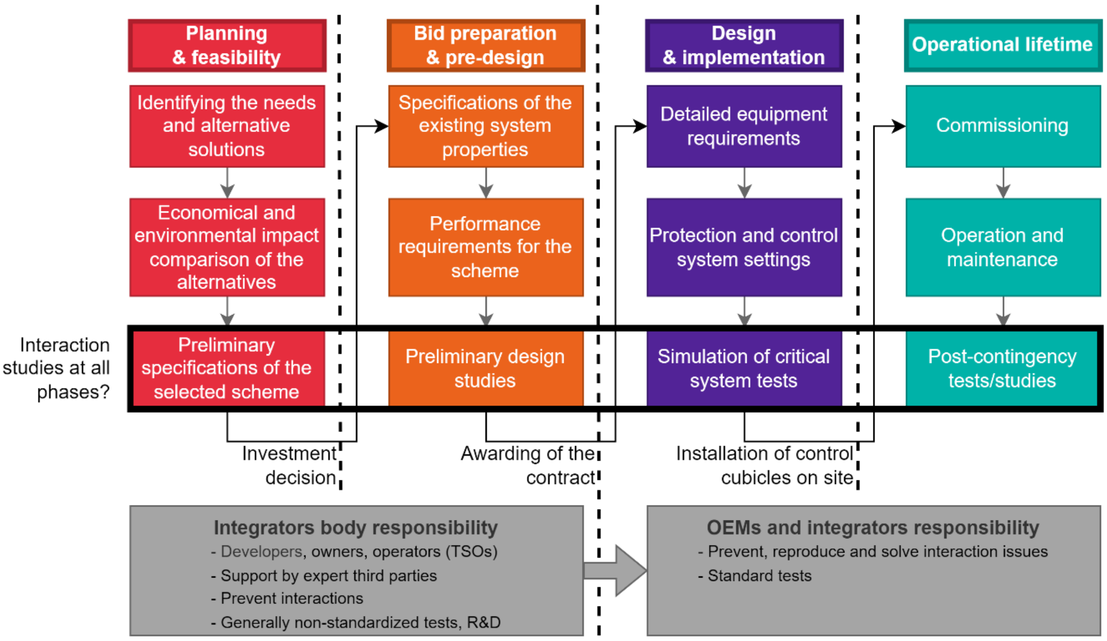


Figure 14. Phases of a MTMV HVDC project and the possibility of interaction studies across them.

3.3.1 Roles after contract award

3.3.1.1 From the generic workflow perspective

In Figure 13, we provided a list of roles to be performed in interaction studies. Here, these are mapped against the three main stakeholders in interaction studies, as suggested in Table 5.

Table 5. Potential roles of stakeholders in interaction studies ***after*** *contract award.* ***M denotes "Must", C is for "Could"****.*

MTMV HVDC project phase / Stakeholder

		Design			**Operation**		
		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

This mapping leads to a potential level of involvement in interaction studies that will need to be assessed for a particular project context. Some must participate, particularly vendors, and some could possibly contribute to a particular scenario. The aim of this whitepaper is to provide the full span for this level of involvement considering the three main stakeholders that may play a role in interaction studies. An illustration for this span is provided in Figure 15.

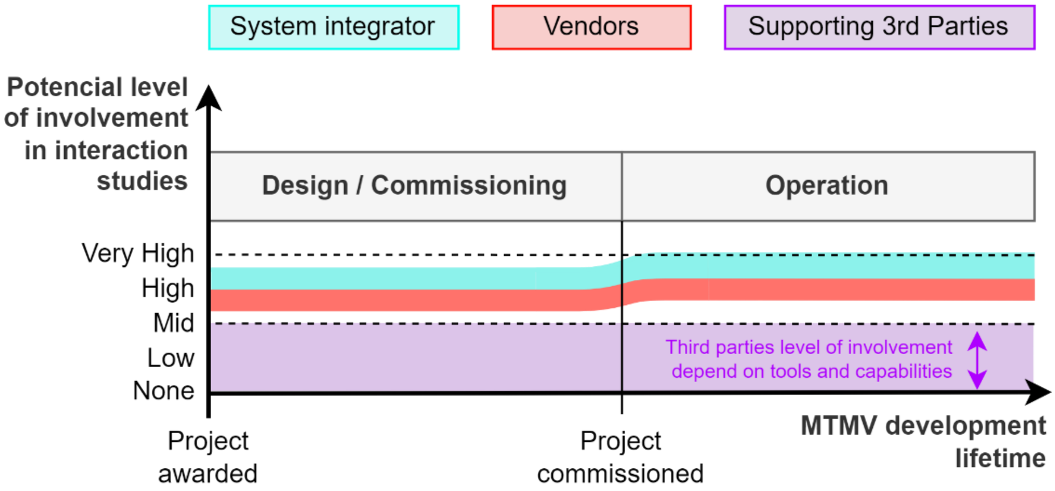


Figure 15. Potential level of involvement of main stakeholders in interaction studies after contract award.

This figure suggests a span for the involvement of the integrator (TSO, HVDC Operators and/or owners) to remain high, while the vendor is slightly lower, not having to coordinate interaction studies. The final level will depend on the capacity of the integrator to perform some of the roles independently from the vendor. In addition, the role of a third party, as the previous mapping suggests, is more focused on testing modelling, analyzing and proposing solutions, which gives it a span of involvement ranging from none to mid-level.

For the sake of simplification and exemplification, two possible scenarios are provided on the degree of involvement of the main stakeholders (see Figure 16) applied to the generic workflow presented before:

- **Scenario 1: the current trend** for a post award instance suggests a strong collaboration among vendors and TSOs or integrators of future MTMV HVDC systems.
- **Scenario 2: a prospective scenario** where the involvement of more stakeholders is observed, which might bring more value to interaction studies but also might increase procedural complexities.

3.3.1.1.1 Procedural roles: coordination, supervision and mediation.

In **both scenarios**, the HVDC system integrator assumes the vital role of coordination. They set the acceptance criteria, validation plans, and act as an intermediary in the exchange of models under defined circumstances. They are also responsible for appointing an external mediator if an unresolved issue arises, thereby ensuring smooth interaction between vendors.

Another important consideration is determining the responsibility of vendors for any issues that may arise after the engineering phase, such as several years after commissioning, when conducting post-failure analyses. The integrator may worry that vendors will not accept responsibility for an issue after verifying and comparing the behavior of their own system with the functional specifications, or that they may try to shift the blame to another vendor. Although, this is highly unlikely, as vendors have a vested interest in delivering high-performance converter stations to maintain a competitive edge. Any issues that do arise can be resolved through mediation by the integrator and through multilateral maintenance and support contracts between vendors and the integrator body (consisting of HVDC owners and operators).

3.3.1.1.2 Testing roles and required models and data sharing.

After the contract is awarded, vendors play a crucial role in conducting interaction studies and resolving interoperability issues. This is particularly important in **Scenario 1**, step 2, testing, where they are particularly involved in testing. This setup does not prevent the integrator from independently verifying or validating study outcomes, it is thus expected that TSOs replicate some or all of the tests.

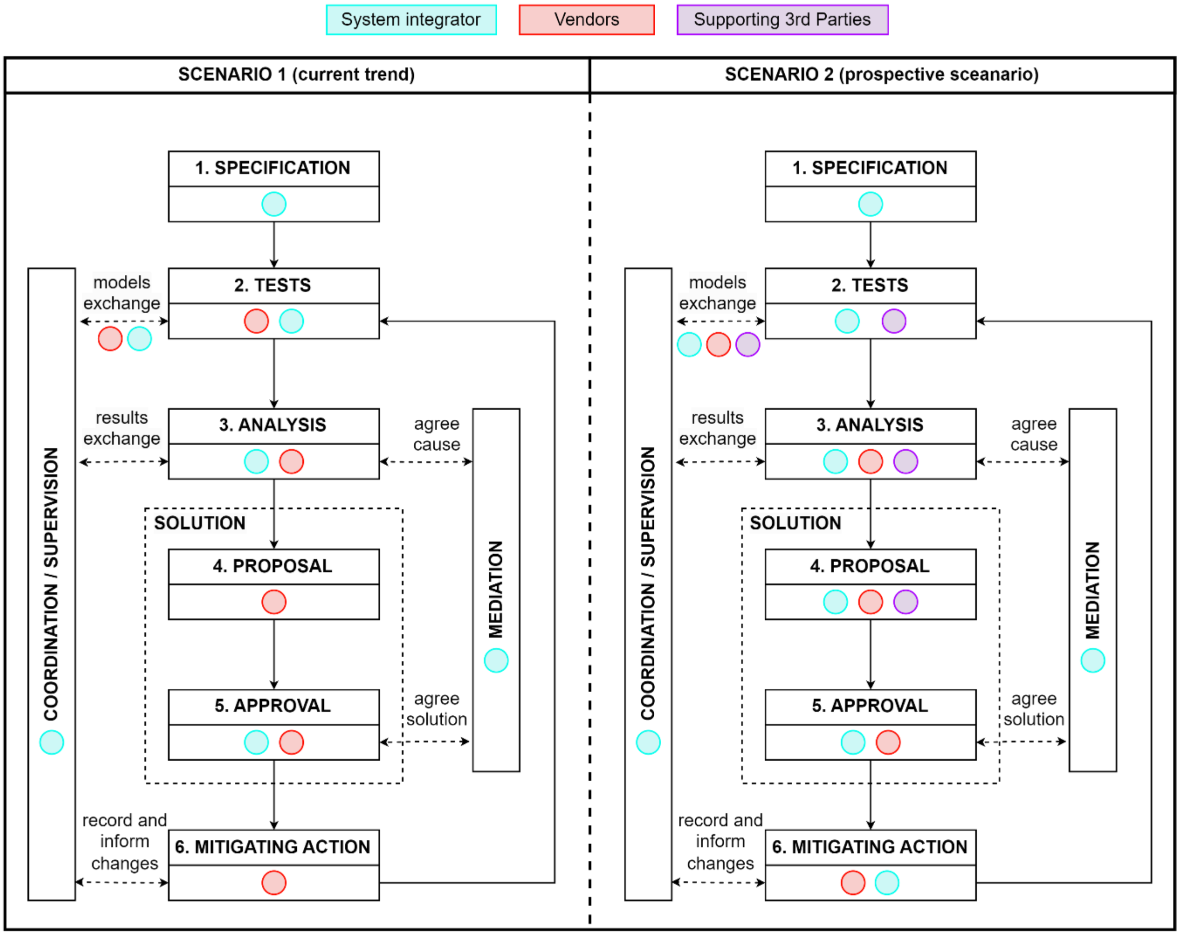


Figure 16. Current trend and prospective scenario for roles in interaction studies after contract awarding.

For **each scenario**, model sharing could potentially lead to legal issues, and therefore, contracts must specify how detailed the models should be to ensure model protection. Models may be exchanged under clear and defined circumstances, via the coordinating integrator. The process of model exchange must adhere to clearly defined conditions, ensuring Intellectual Property (IP) protection through pre-established agreements. In this matter, **scenario 2** involves an additional stakeholder profile, which may require more complex approaches for IP protection.

3.3.1.1.3 Roles in results analysis and solving interaction issues.

In **both scenarios**, while non-vendor stakeholders may conduct studies in parallel, the primary responsibility for approving and implementing lies with the vendors who design, provide, and implement the system's main components. Moreover, documentation is vital to keep system information updated. **Scenario 2** suggests an interesting situation for the integrator which is being able to perform tests with higher autonomy. At operational stages, this might facilitate following-up on upgrades, planning maintenance actions and future upgrades. Indeed, some TSOs have decided to support the creation of third-party laboratories hosting HIL replicas of strategical HVDC systems. Strong vendor support is still expected.

In **both scenarios**, vendors always guarantee the ability to tune their own control systems, assuming responsibility for their controls and models. Technical difficulties may arise when one vendor updates its control, requiring the others to retrieve these new releases. Multi-lateral maintenance contracts need to be in place to mitigate such risks. To address post-failure analyses, responsibility determination, and potential blame-shifting, mediation by the integrator and the establishment of multi-lateral maintenance contracts between vendors and the integrator body (comprising HVDC owners and operators) are essential. In **scenario 2**, the integrator can also perform interaction-mitigating actions on their own, which could simplify the implementation process, however, it may still need to be endorsed by vendors.

3.3.1.2 Tool-driven perspective

Tools and methods to perform interaction studies may not be the same for the different stakeholders due to their capabilities and diverse restrictions (i.e., technology maturity, security, legal). However, it is an important aspect to consider when analyzing scenarios of role repartition in interaction studies in post award conditions. Since EMT time domain simulations benefit from a large acceptance among the main stakeholders and seem to be able to represent many of the existing interaction phenomena, this whitepaper will mainly be focused on this specific tool for interaction studies. Moreover, there has been lots of efforts from experts working groups on modelling and EMT setup characteristics and types of interaction testing, particularly by CIGRE, as depicted at the beginning of section 1.

Recent case studies (T&D Europe, 2022) conducted in the UK (the National HVDC Centre) and France (RTE International Lab) are mainly focused on interaction studies conducted through EMT simulations such as offline and HIL tests. On the one hand, offline simulation studies can use generic or real vendor models conceived by TSOs, academia, labs or vendors. This type of testing benefits from widespread user experience due to the relatively low resources and expertise required to develop and set up. On the other hand, hardware-in-the-loop (HIL) tests, which also benefit from extensive experience by vendors that have been using them to validate their HVDC systems, is becoming more accessible to other actors such as TSOs themselves, laboratories and other third parties to perform not only interaction tests, but also to train experts on HVDC operations and maintenance procedures. Another type of testing is the SIL, which can be placed midway between the offline and HIL worlds and could sometimes be a necessary step in the development of an HIL setup. However, the focus will be given to offline and HIL testing types in this analysis, since together they represent the largest share of test setups nowadays.

Evidently, depending on the type of tool to be used for a particular interaction test, the scenario of role repartition may be impacted because different stakeholders will have access to different kinds of tools and models. For instance, one could expect different tools to be available between the green field and the brown field development scenarios for the MTMV HVDC system.

3.3.1.2.1 Offline tests with realistic vendor models

After contracts are awarded, vendors are chosen and can make use of their offline HVDC system models. These vendor models are often the closest representation of the actual system. Consequently, the success of offline testing in identifying potential interaction issues heavily relies on the accuracy and reliability of these models.

In multi-vendor settings, whether for brown field or green field MTMV HVDC developments, sharing models amongst vendors –either in a unified or distributed offline test setup– can enhance the design of systems with reduced risk of interaction issues. The integrator's main role is to oversee this model exchange, ensuring IP protection for vendors. Using black-box models can safeguard this IP, albeit increasing the complexity of test setups and making interaction analysis more challenging. Currently, this approach –which corresponds to **Scenario 1–** is more prevalent for offline testing in MTMV contexts.

The prospective **Scenario 2** might see integrators or third-party entities with access to vendor models for interaction testing during the design and operation phases. This is currently less realistic as vendors prefer maintaining oversight of their deliverables, especially for the design phase. Yet, if generic models mirroring vendor model behavior are discovered by the integrator – i.e., if an interaction appears in the live system and the integrator manages to emulate it offline using generic models – the integrator might validate these for offline interactions testing in the future. The primary goal wouldn't be influencing designs but assisting in pinpointing interactions between different vendor designs through specifications. This also aids the integrator in observing how vendor designs impact the overall system – a broader perspective better understood by the integrator.

It may be worth noticing that the green field vs brown field situations may affect the choice of role repartition scenario. Indeed, while the former offers more liberty, the latter have pre-conditions that may impact the availability, ownership and location of offline models and test setups.

3.3.1.2.2 HIL tests using vendor replicas

HIL tests, long favored by vendors, are common in hardware development. They consist of a device under test (DUT) and a "plant," a simulated environment where the device operates under realistic conditions. Their interconnection can either be test-specific or mimic industrial interfaces. In MTMV HVDC systems interaction tests, the DUT is the hardware embedding the HVDC converter's control and protection, and the plant represents the electrical environment of the converter's installation – transmission lines, cables, transformers, converter valves (detailed or equivalent models) among other electrical equipment.

Scenario 1, where replicas are vendor-managed, even when hosted by a third party like HVDC Centre or RTE international, this appears to be a standard approach. Vendors have access to their control cubicles to troubleshoot interoperability issues or test an updated version of the control. To do so, it is possible to provide vendors with remote access to different workstations in the lab. The cubicles from different vendors can be placed in different rooms and the vendor only has access (remote or physically) to one of the rooms. Usually, vendors test their equipment on their own side. The second host for replicas can use them for further analysis and handle any post-commissioning studies. Vendors send their engineers to tune the controllers, since vendors are still sole able to manipulate the controllers.

However, challenges emerge in multi-vendor contexts, especially in deciding the physical location for the HIL setup. Vendors may need to share or put replicas together themselves in a single location to study interactions with the system that is going to be installed in the field. In addition, the possibility of vast interconnected multi-terminal HVDC systems complicates the task of designing a representative plant for testing, as it should encompass surrounding AC and DC networks.

These complexities underpin prospective **Scenario 2**: centralizing HIL test setups with an integrator, possibly aided by a third party. The HVDC system integrator provides the location for the replicas of different vendors to be placed and perform interaction studies. Vendors can provide the integrator with the necessary support to handle those replicas, the level of support depending on the level of autonomy of the integrator to perform the studies, from basic tuning to advanced re-configuration.

However, for expansive EMT systems spanning multiple nations, there's uncertainty about the relevance of individual replicas for each scenario. Alternate solutions might involve hybrid HIL/offline setups: cloudsimulated large network plants paired with vendor or integrator hardware for interaction testing ? A key concern is the feasibility of such setups. Since the electrical grid is where interactions manifest and spread, the cloud-based system must manage minute time-steps and ensure no interaction issues are hidden.

3.3.1.2.3 Hybrid HIL with real-time vendor or generic models (SIL)

Once more, the brown field (from expansion) and green field scenarios can impact the role repartition in interaction studies performed using HIL tools. In the case of MTMV developed from expansion, compatibility between old and new replicas may become an issue; possibly a limitation to the use of real hardware motivating the research for innovative interaction testing approaches. For instance, mixing vendor replicas with vendor or generic models representing the existing equipment. In such a case, the existing equipment is part of the plant, while the vendor replicas representing the new equipment are the DUTs.

3.3.2 Before contract award

3.3.2.1 From the generic workflow perspective

While interaction studies in the post-bidding stages are commonplace, there is less discussion about their execution in pre-bidding phases. For instance, interaction studies at R&D, pre-design and specification phases could be relevant if adequate tools and methods are available and they allow to decrease the risk of interactions from system pre-design and specification.

Although these preliminary studies might lack detailed industrial models and instead rely on generic or academic ones, their results can guide system requirements development, refined during later design stages. If interaction studies are determined beneficial prior to a contract award, a role assessment might be valuable. The proposed approach can be found in Table 6.

Interaction studies can be conducted in two primary contexts: collaborative industrial R&D and pre-design studies. For MTMV HVDC systems, the former is particularly relevant. Pre-design studies, on the other hand, serve primarily to aid TSOs or system owners in crafting technical specifications for bid solicitations. In both scenarios, the TSO can minimally assume a role autonomously. Nevertheless, while collaborative

Table 6. Potential roles of stakeholders in interaction studies ***before*** *contract award.* ***M denotes "Must", C is for "Could"****.*

		MTMV HVDC project phase / Stakeholder					
		Pre-project / R&D			Pre-bidding / Pre-design		
		System integrator*	Vendors	Supporting 3rd parties	System integrator*	Vendors	Supporting 3rd parties
Procedure	Specify	M	/	/	M	/	/
	Clarify	/	/	/	/	/	/
	Coordinate	C	C	C	M	/	/
	Mediate	/	/	/	/	/	/
	Document	M	M	M	M	/	/
Models & data	Supply	C	C	C	M	C	C
	Verify	C	C	C	M	C	C
	Validate	M	C	/	M	C	/
	Assemble	C	C	C	C	/	C
	Maintain	/	/	/	/	/	/
	Document	M	M	M	M	M	M
	Protect	M	M	M	M	M	M
Tests	Set up	C	C	C	C	/	C
	Run	C	C	C	C	/	C
	Replicate	/	/	/	C	/	/
	Certify	/	/	/	/	/	/
	Document	M	M	M	M	/	M
Results	Verify	C	C	C	M	/	C
	Validate	M	C	/	M	/	/
	Analyze	C	C	C	M	/	C
	Certify	/	/	/	/	/	/
	Document	M	M	M	M	/	M
Solutions	Propose	C	C	C	C	/	C
	Validate	M	C	/	M	/	/
	Implement	/	/	/	/	/	/
	Maintain	/	/	/	/	/	/
	Document	M	M	M	M	/	M

*TSOs, HVDC operators and owners

R&D often incorporates vendors and other stakeholders throughout the study, the pre-design phase—being integral to a formal project workflow—might limit vendor participation due to potential disqualification risks. Hence, vendor roles in interaction studies during the pre-design phase should be limited.

This role analysis indicates the scope of stakeholder involvement in interaction studies, as illustrated in Figure 17. Collaborative R&D offers flexibility and openness, encompassing coordination, testing, and addressing interactions using generic and academic models. Conversely, during the pre-bidding or pre-design phases, the system integrator primarily oversees coordination. Vendors might have limited participation, perhaps sharing models, while third parties can offer support in any phase, contingent upon their expertise and tool availability.

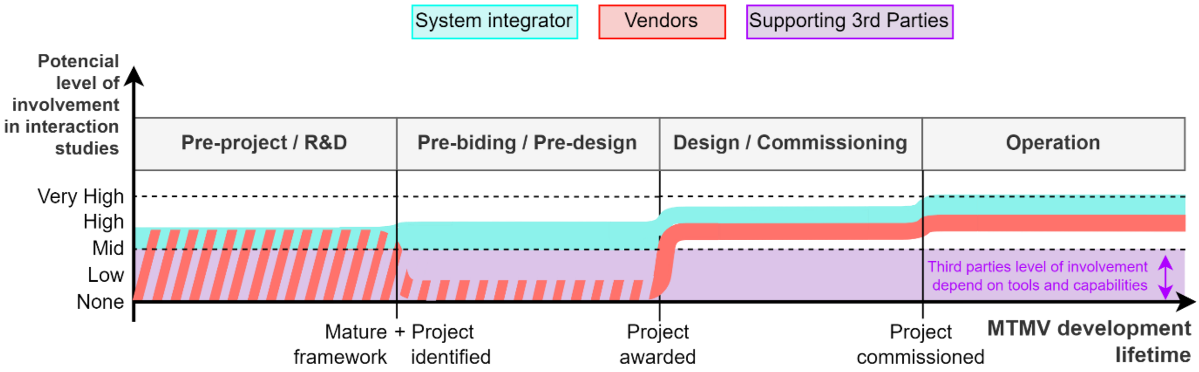


Figure 17. Potential level of involvement of main stakeholders in interaction studies before contract award.

Both contexts set the stage for interaction studies with role repartition scenarios expected to be somewhere within the span presented in Figure 17. These additional prospective scenarios are illustrated in Figure 18 and are briefly described as:

- **Scenario 3: prospective scenario** with potential involvement of the three types of stakeholders and with a different finality that the original generic workflow.
- **Scenario 4: prospective scenario** with main involvement of the integrator with supporting third parties, vendors minimized due to disqualification risk.

In **Scenario 3**, which is about collaborative R&D, these studies can be used to cross-validate models for interaction studies. This is because the system integrator could compare results against real project data, which could improve the model validation process overall. This setting might also help in creating standards, frameworks or guidelines, and new tools for interaction studies, possibly with input from vendors and other outside parties.

In **Scenario 4**, interaction studies can help refine the early design and specification stages. This might make things more complicated for TSOs since it requires a detailed or deep technical specification. But given the expected rise of power electronics in future electric grids, this shouldn't be overlooked. Depending on the tools at hand – with minimum vendor involvement –, and the nature of the project (like if it's a new project or building on an existing one), the main system planner might lean on outside experts to set these requirements. The goal might be to guide vendors towards creating a system that has fewer interactions.

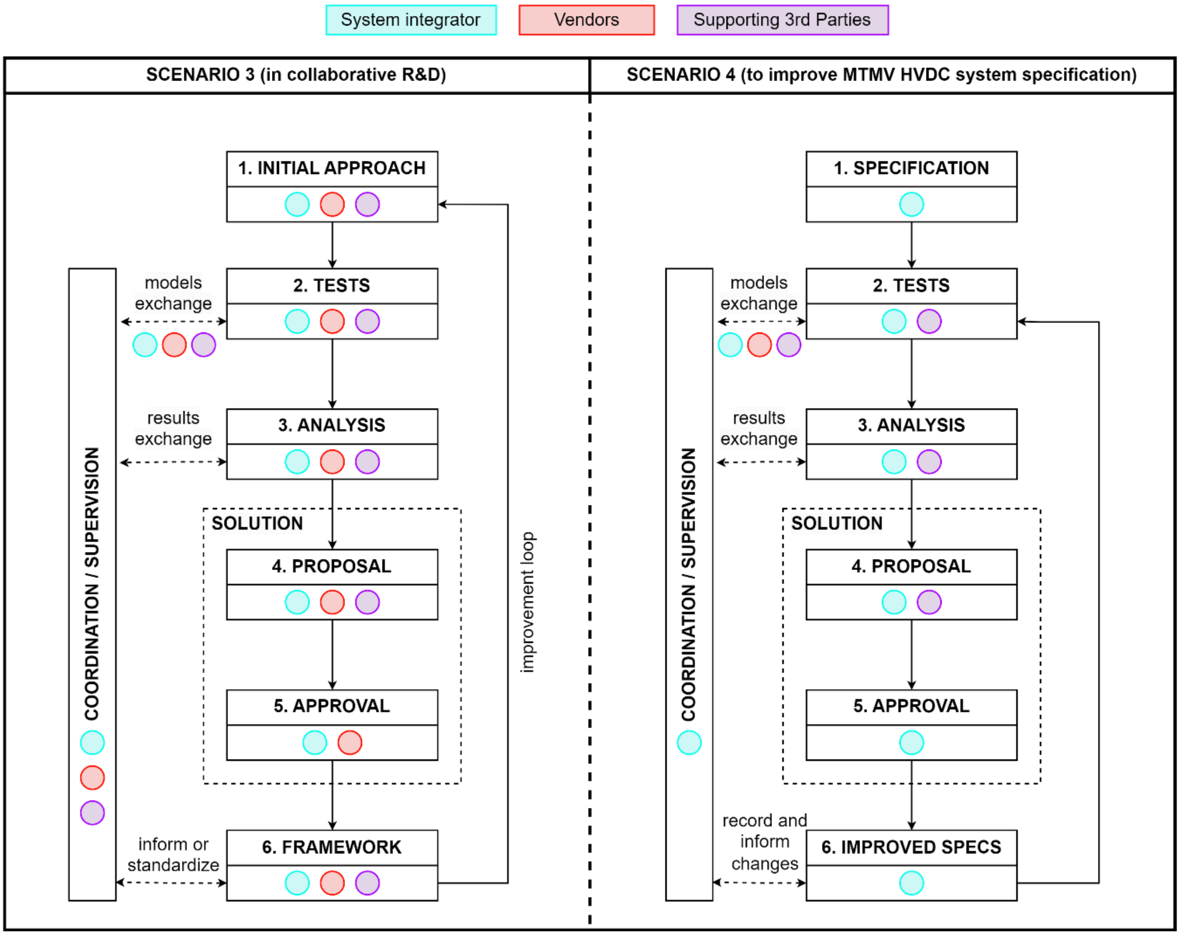


Figure 18 Prospective scenarios for role repartition in interaction studies before contract award.

3.3.2.2 Tool-driven perspective

Models and EMT simulation tools play a vital role in today's interaction studies. However, before a project is awarded, these tools and models are often restricted to what vendors can provide without exposing sensitive intellectual property. Yet, there's potential in using interaction studies during R&D and pre-design phases to enhance both modeling, tool and test procedure development. They could involve using generic hardware and software models with advanced configurable parametric test setups for sensitivity analysis. Indeed, sensitivity analysis could offer insights on the typical causes for interactions. This information could be valuable to specify robust requirements in terms of interactions or even help problem-solving in post award project stages.

3.3.2.2.1 Offline tests using generic or real vendor models

In a **greenfield** MTMV HVDC system development context, one possible way to perform interaction tests in both **Scenarios 3 and 4** is to use generic models developed by control experts within offline simulation setups. Data obtained through these simulations could help to understand interactions between different kinds of well-known control structures. While generic models may not provide an accurate representation of the real system and the proprietary models from vendors are desirable, the use of generic models will allow operators and owners to gain experience in understanding different types of interactions in MTMV HVDC systems. Additionally, the use of a variety of models in sensitivity analysis will enable operators and owners to understand interactions for different combinations of model types within the same grid. As the massification of MTMV HVDC systems occurs over time, it could be possible that offline generic models are improved or even are associated to a certain vendor model behavior, much like happened with the models of every component in the AC system. Another possibility for future integrators such as HVDC operators and owners, is to consult vendors to provide real offline models (with or without real-time running ability) for pre-qualification during specification stages (Scenario 4 in Figure 18), an approach the Great Britain is promoting recently through novel regulations. Overall, while the use of offline SIL with generic models may have some limitations, it can still provide valuable insights for R&D or during the specification phase of a MTMV HVDC project.

Especially for **Scenario 4** and in the context of **brownfield** MTMV HVDC system development, both generic and vendor-specific models can be integrated into a single offline testing environment. Typically, models for current equipment are readily available, either from vendors or integrators. Before selecting a vendor for a project, new equipment models might not exist yet. However, generic models can still be used in offline interaction tests in combination with models of the existing equipment.

3.3.2.2.2 HIL tests with generic hardware or vendor replicas

For both prospective **Scenarios 3 and 4**, it is assumed that HVDC system operators or owners acting as integrators or vendors could use vendor replicas to perform interaction studies in a pre-award stage to anticipate multi-vendor interoperability issues. Again, as mentioned previously, this requires that the integrator has the necessary number of replicas and is allowed to use them for this purpose. This approach may exclude vendors for which the integrator does not have hardware replicas in their inventory and may also limit opportunities for innovation as hardware replicas may be outdated versions with older functionalities. HIL for interaction studies may be different based on the context of a project: whether it's a greenfield (new development) or a brownfield (modifying/upgrading existing infrastructure).

In **greenfield** scenarios before a contract award, HIL tests could be seen as having limited additional value, since vendor replicas are usually not yet available. Indeed, HIL studies are mainly conceived to test hardware, so relevance is higher when hardware is real and supplied by its vendor. However, even in the absence of a committed vendor, generic hardware could help set generic performance benchmarks or identify potential challenges in HIL interaction testing procedures.

3.3.2.2.3 Hybrid HIL tests with generic hardware/vendor replicas and real-time generic/vendor models

In the context of **brownfield** MTMV HVDC system development, hybrid HIL tests present a fitting strategy for both **Scenarios 3 and 4**. Such tests combine the use of vendor hardware or replicas from existing systems with software models, creating a hybrid HIL/SIL testing environment. This blended setup offers a realistic testing platform by integrating both generic and actual models. An alternative approach to consider involves leveraging high-powered computation units to run multiple offline simulations concurrently. These simulations would use DLLs containing digital twins of the vendor's control. Several factors demand consideration. Firstly, it's essential to assess the value of conducting these tests before finalizing vendor selection. One should also examine the feasibility of executing black box libraries in real-time and, if viable, ensuring cross-validation with offline and/or real models. The division of responsibilities among stakeholders may also affect this setup. Integrators overseeing this configuration should have the flexibility to modify both the HIL setup and the associated models. During R&D stages, vendors could manage collaboration in this regard. However, in the pre-design phase, their involvement might be compromised by potential disqualification risks, as previously noted.

3.4 Summary and recommendations

MTMV HVDC projects involve complex dynamics beyond just technical considerations. Analyzing these projects through both procedural and tool-driven perspectives offers valuable insights into their stages, both before and after contract awards. **Scenario 1** represents current industry practices, whereas **Scenario 2** points to a shift towards greater involvement by integrators and third-party contributors. **Scenarios 3 and 4**, though speculative, hint at emerging trends: **Scenario 3**, reminiscent of projects like InterOPERA, indicates a push towards collaborative R&D to establish interoperability standards for MTMV HVDC systems. **Scenario 4** underscores the urgency in multi-terminal designs pushing vendors to be proactive in early project phases. Navigating this field requires addressing multiple concerns. Technical safeguards might offer an initial barrier against IP risks during model and data sharing, emphasizing the importance of navigating the legal landscape. The redundancy in interaction studies enriches our comprehension of system dynamics. Moreover, maintaining models post-commissioning is crucial for system adaptability and addressing unexpected interactions. Interaction studies are central to these projects. Equipped with tools like data, models, and replicas, both vendors and integrators play critical roles. A balanced environment (see Figure 19), where tools and expertise intertwine, would promote protected data exchange. Such a setting allows integrators to identify interactions, while vendors can validate systems through specific tests, possibly guided by integrators.

As we await results from initiatives such as InterOPERA, there's hope for a comprehensive framework. This framework should merge the aims of both vendors and integrators, bringing together tools, knowledge, and objectives. Achieving this synergy will position the industry to better tackle MTMV HVDC project challenges, setting a path where collaborative innovation becomes the norm.

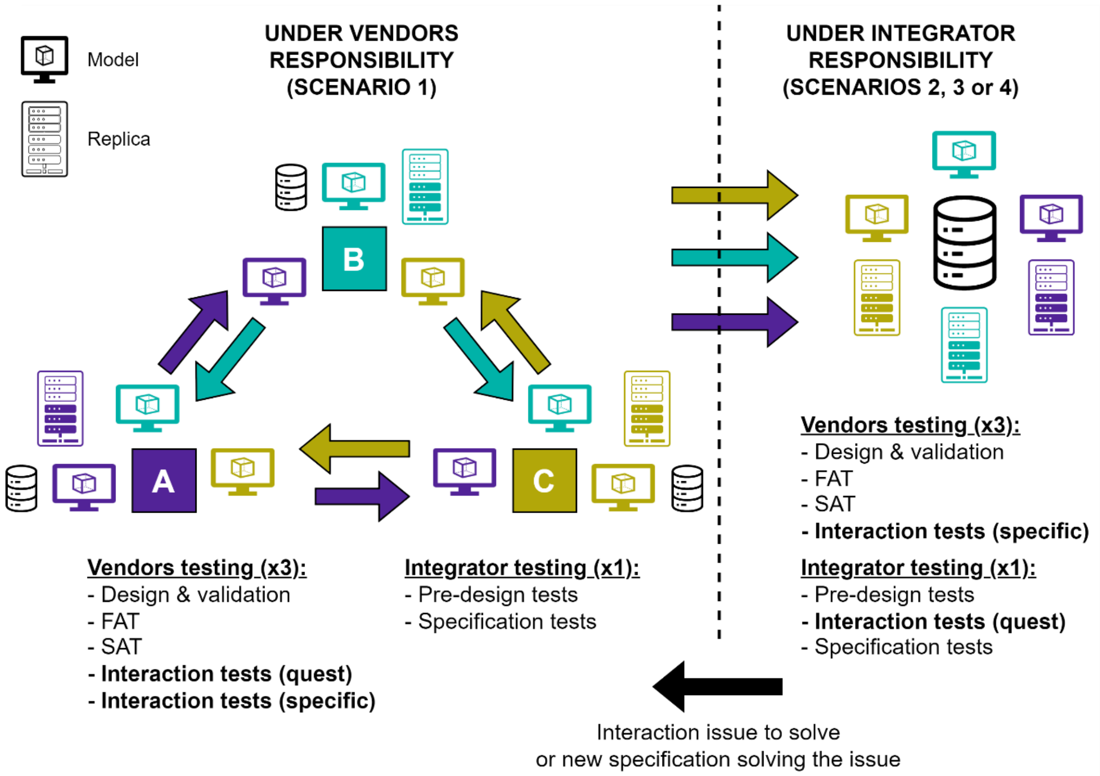


Figure 19. Data, models and replica environment among vendors and integrators for interaction studies.

4 IMPACT OF CONVERTER C&P FUNCTIONAL OPENNES ON INTERACTION STUDIES

Multi-level Modular Converters (converter) are essential elements for the stability of MTMV HVDC systems, with vendors playing a pivotal role in their control development. Understanding the distribution and accessibility options concerning converter control and protection (C&P) functions is important to identify hot spots in the interaction study workflow. The balance between intellectual property (IP) protection and control system accessibility would affect the capacity of different stakeholders to perform a role within the interaction study process. Here, we explore how varying degrees of converter functions accessibility impact methodological scenarios for interaction studies, specifically scenarios 1 through 4.

converter functions can be categorized by their proximity to the converter hardware. Low-level functions, being closer, directly influence the MMC converter's integrity and longevity. In contrast, high-level functions primarily dictate HVDC system behavior. Such distinctions are highlighted in sources like Jahn et al. (2022) and resonate with the objectives of CIGRE Working Group B4.85. The clear delineation of functional specifications enhances system robustness. By setting precise guidelines, system interoperability is assured, allowing functions' accessibility to remain at a higher, less detailed level, thereby fortifying the system against potential vulnerabilities.

Our discussion points to which parts of the converter control and protection models are supplied by the converter station manufacturer, which are sourced externally, and the accessibility levels within these functions.

4.1 Reminders on main converter functions

The converter C&P system is responsible for managing the power flow and voltage levels of the HVDC system, as well as recovering the system after faults and disturbances. converter functions are organized in a hierarchical structure, divided into two levels: the high-level or outer loops and the low-level or inner loops. The high-level functions are responsible for the overall operation and management of the HVDC system, including the DC node voltage control, active power control, and reactive power control. This functional level also manages the global energy management of the system. The low-level control, on the other hand, is responsible for the internal converter controls and the fast current control loop. This level of control includes the phase-locked loop (PLL) and the current regulation, as well as the phase/arm energy balancing. The inner low-level control includes valve switching and submodule balancing, modulation, and hardware protection.

Another important feature of converter C&P is its flexibility and adaptability. The converter C&P system can be customized and configured to meet functional specifications of the HVDC system. The function parameters and settings can be adjusted to optimize the performance of the system, depending on the operating conditions and the type of power being transmitted. Finally, the converter C&P system must enable integration and communication with other systems and components. This is especially important in systems that involve multiple vendors and different types of C&P equipment. Clear and well-defined vendor model interfaces are necessary to ensure compatibility and proper operation of the system. In the following table, a list of functions typically found at high and low levels is recalled.

Table 7. Main levels of functional in an converter and associated C&P functions.

Functional level	Main C&P Functions
High-level C&P functions (outer)	DC Node Voltage Control
	Converter Protection, Supervision, Management
	Active Power Control (P, Vdc)
	Reactive Power Control (Q, Vac)
	Global Energy Management
	Grid forming controls
	Grid Synchronization
	Advanced Protection (grid)
	Advanced Communication (grid)
Low-level C&P functions (inner) Inner High	Internal Converter Controls and Protection
	Fast Current Control Loop
	PLL
	Current Regulation
	Phase/Arm Energy Balancing
Inner Low	Valve Switching
	Submodule Balancing, Modulation
	Hardware Protection

4.2 On the degree of openness for converter C&P functions

To facilitate understanding, we begin by defining the degrees of accessibility for converter functions:

- **Low-degree Accessibility:** all control levels of the converter station are treated as a 'black box' by the vendor. Interaction studies only access interfaces vital for DC grid coordination and control.
    - **Accessibility:** black-boxed with no accessible variables.
    - **Configuration:** exclusively by the vendor.
    - **Responsibility:** the vendor is accountable for understanding, developing, and providing all converter control layers. If interaction issues arise, only the vendor, with its unique access to the C&P structure, can propose and execute the necessary modifications.
- **Medium-degree Accessibility:** the vendor offers limited access, allowing parameterization of the functions by another party.
    - **Accessibility:** black-boxed, but with a range of variables accessible by the integrator.
    - **Configuration:** primarily by the vendor, with some flexibility for integrators.
    - **Responsibility:** vendors create functions, interfaces, and documentation to empower an integrator to adjust the converter functions' configuration and parameters, facilitating system customization and optimization.
- **High-degree Accessibility:** functional layers of the converter undergo a split. The criteria for this division are under research, with sources like (Jahn et al., 2022) offering insights. A potential split separates functions into those relevant to hardware and those relevant to the system.
    - **Accessibility:** some C&P functions are externalized with compatible interfaces.
    - **Configuration:** hardware-relevant functions are managed by the vendor. System-relevant functions, however, can be configured either by another vendor or the integrator.
    - **Responsibility:** hardware-focused functions remain under the purview of the vendor. System-focused functions are transparent, granting integrators the capability to co-design and propose algorithms to mitigate interaction challenges.

For a clearer visualization, Figure 20 illustrate the three degrees of openness, and Table 8 delineates the responsibilities of stakeholders for each degree of converter functions accessibility, and the extent to which controllers can be provided by various entities, including station manufacturers or integrators.

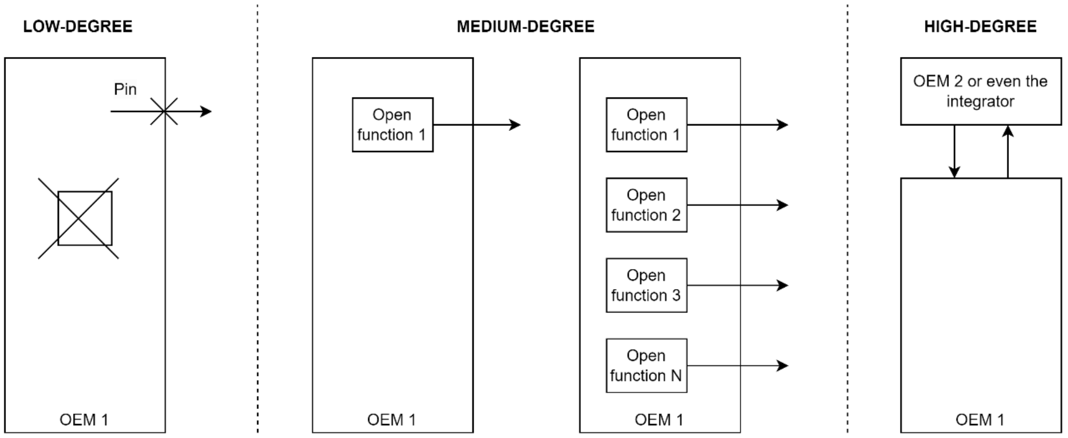


Figure 20. Converter functional openness illustrated.

Table 8. Options for repartition of system relevant functions (outer loops) in a MTMV HVDC.

Degree of accessibility of converter C&P functions	Hardware relevant functions (in inner -low and -high levels)	System relevant functions (outer level and inner-high)
Low-degree: Full station manufacturer approach	Provided by station manufacturer as black boxed functions	Provided by station manufacturer as black boxed functions
Medium-degree: Full station manufacturer with accessible parameters and documentation	Provided by station manufacturer as black boxed functions	Provided by station manufacturer, some functions reconfigurable and accessible to integrators
High-degree: High-level converter functions can be co-designed/modified by an integrator.	Provided by station manufacturer as black boxed functions	Provided transparently (white-box) by manufacturer, some functions can be modified by integrators

4.2.1 Low-degree: full-vendor approach

In In a low-degree accessibility approach, the converter station manufacturer entirely manages the converter C&P functions. These functions are black-boxed and external entities can't access them. Interaction studies, therefore, rely on the vendor for any function's modifications.

While a DC grid controller (potentially from another vendor) might offer certain parameters, this might not suffice for every interoperability challenge. Thus, actual functions modification might be necessary.

The integrator, an intermediary entity, is pivotal in coordinating various HVDC project vendors and ensures proper system integration. While they can influence the DC Grid controller parameters and initial schedules, they can't modify the actual C&P functions in a low-degree scenario. The HVDC owner oversees data sharing and legal frameworks but might have minimal involvement in the functions update process.

In the simulation step of interaction studies, both the integrator and vendors can perform all case studies independently from the converter C&P functions openness. When analyzing simulation results in case of interoperability issues, the integrator's scope of analysis is limited, while vendors have more flexibility. To recommend functions updates, the integrator's scope is very limited, while vendors have more flexibility as well. To perform functions updates the integrator must rely on vendors to do so.

- **Low-degree openness level advantages:**
    - An efficient software/hardware interface between converter C&P functions and the system.
    - Vendors possess optimum converter functions expertise.
    - IP protection and optimized internal functions delays.
- **Low-degree openness level drawbacks:**
    - Black-boxed C&P functions complicate stable C&P strategies, especially for multiple vendors.
    - Integrators find it challenging to pinpoint and address interoperability issues.
    - Iterative communication is needed for vendor functions updates.
    - Clear communication and data sharing protocols are essential but might be burdensome.

In interaction studies, both the integrator and vendors can perform simulations. However, while vendors can more freely analyze results and recommend updates, the integrator's capability in these areas is constrained. Table 9 showcases the limitations of stakeholders in interaction studies for a low-degree functions accessibility.

Table 9. Limitations for stakeholders participating in interaction studies in case of low-degree functions accessibility.

ID	Workflow activity	Vendor	HVDC System integrator
2	**Interaction tests:** Simulating all case studies	Possible	Possible
3	**Analysis:** Find cause of interaction issues	Possible	Possible
4	**Solution:** Recommending mitigating actions	Possible	Very Limited
6	**Implementation:** Apply solution to interaction	Possible	Impossible without vendor

4.2.2 Medium-degree: accessible functional parameters

In this approach, the converter station vendor retains control of the converter, but a selection of its functions and parameters becomes available for supervised testing. This provides the integrator with the ability to delve into a portion of the analysis and troubleshooting, giving them a hands-on role in adjusting some C&P functions settings. However, the ultimate authority for fine-tuning remains with the vendors. Recommendations can come from the integrator, but the application of major updates is still vendor driven. Selection of these accessible features is based on:

- Debugging and troubleshooting level of difficulty.
- The parameter's role in resolving interaction challenges.
- The potential risk of revealing intellectual property (IP).

Some general advantages and disadvantages on this level of openness are:

- **Medium-degree openness level advantages:** the traditional approach (low-degree) places solution responsibility solely on vendors. Medium degree, however, empowers integrators to actively participate in simulation analysis and attempt to rectify interaction challenges. Both methodologies have shared benefits:
  - They maintain vendors' comprehensive control over C&P layers, aligning with their expertise on turnkey solutions for HVDC-links.
  - Vendors, being experts in converter C&P functions, ensure optimal adjustments to software and hardware interfaces.
  - The medium degree offers enhanced access to C&P functions for the integrator, which can speed up studies. This can sometimes eliminate the need for model regeneration by vendors, allowing direct parameter adjustments.

    - An integrator's involvement, especially in MTMV projects, centralizes and streamlines communication among all parties, simplifying the overall project development process traditionally held between TSOs and vendors.
- **Medium-degree openness level drawbacks:** relying on vendor-driven C&P functions in integration presents certain challenges:
    - Restricted access may limit an integrator's understanding and ability to rectify interaction issues.
    - Vendors might provide limited parameter information, especially for sensitive ones, making it hard for integrators.
    - Determining whether a problem originates from vendor settings or integrator adjustments can be ambiguous.
    - Limited converter C&P expertise can hinder integrators from independently addressing or improving interactions.
    - Intellectual property (IP) exposure remains a concern, with possible legal repercussions for perceived IP violations. Though the T&D Europe white paper helps mitigate this risk, it's essential to use it as a foundational guide to avoid potential IP challenges.
    - Vendors might find the maintenance of accessible interfaces burdensome, especially if they're required to provide a dedicated user interface.

The table below clarifies the roles of the integrator and vendor during MTMV interaction studies under this approach.

Table 10. Limitations for each stakeholder participating in the interaction study workflow in case of Medium-degree.

ID	Workflow activity	Vendor	HVDC System integrator
2	**Interaction tests:** Simulating all case studies	Possible, but with higher risk of IP disclosure to other vendors	Possible
3	**Analysis:** Find cause of interaction issues	Possible	Possible
4	**Solution:** Recommending mitigating actions	Possible	Possible but limited based accessible parameters and level of reconfigurability
6	**Implementation:** Apply solution to interaction	Possible	Possible but limited based accessible parameters and level of reconfigurability

In sum, the medium-degree approach offers integrators a more involved role in simulation analysis and issue rectification. However, while they gain greater insight and control, there are clear limitations, especially when accessing and adjusting certain functions and parameters still under vendor control.

4.2.3 High-degree: part of the converter C&P functions designed and implemented by an integrator.

In this approach, a third-party integrator crafts and deploys the upper-level converter C&P functions. This integrator, aware of the distinct C&P hardware capabilities of vendors such as bandwidth and delays, tailors the grid C&P across different levels (including the DC grid control level). Meanwhile, the task of the converter station manufacturer is narrowed down to just the lower-level functions.

Figure 21 depicts an ideal versus a practical scenario. Ideally, upper-level functions should exclusively manage system-relevant functions, and hardware-focused functions should be limited to low-level functions. There's a mix, with some low-level functions impacting the system and some upper-level functions affecting the hardware. To guarantee smooth system operation, it's crucial to assign system-centric functions mainly to the upper functions and hardware-centric ones to the lower functions. Recent research (Jahn *et al.*, 2022) has presented graph theory methods for this optimal division. However, minimizing the physical connection between both functional levels also matters. While the graph theory technique excels at optimizing functional divisions, it might not reduce physical interfaces. Moreover, the feasibility of this method is questionable given the proprietary nature of converter C&P functions.

Manual partitioning is another route, but it's intricate. Definitions of what's 'upper' and 'lower' level can vary, complicating universal agreement across vendors. Three proposed manual partitioning models are:

- The integrator primarily handles converter high-level C&P functions development.
- A combined team of TSOs, vendors, and academics oversees converter high-level C&P functions.
- A single DC Grid controller manufacturer supervises the high-level functions across all stations.

In the latter two models, the integrator can tweak certain converter high-level C&P parameters, introducing a new hardware interface. In the first model, embedding the functions into the vendor's hardware could prompt technical and liability concerns, making a separate hardware system for functions by the integrator more appealing. A quick glance at stakeholder participation in high-degree interaction studies is presented in Table 11.

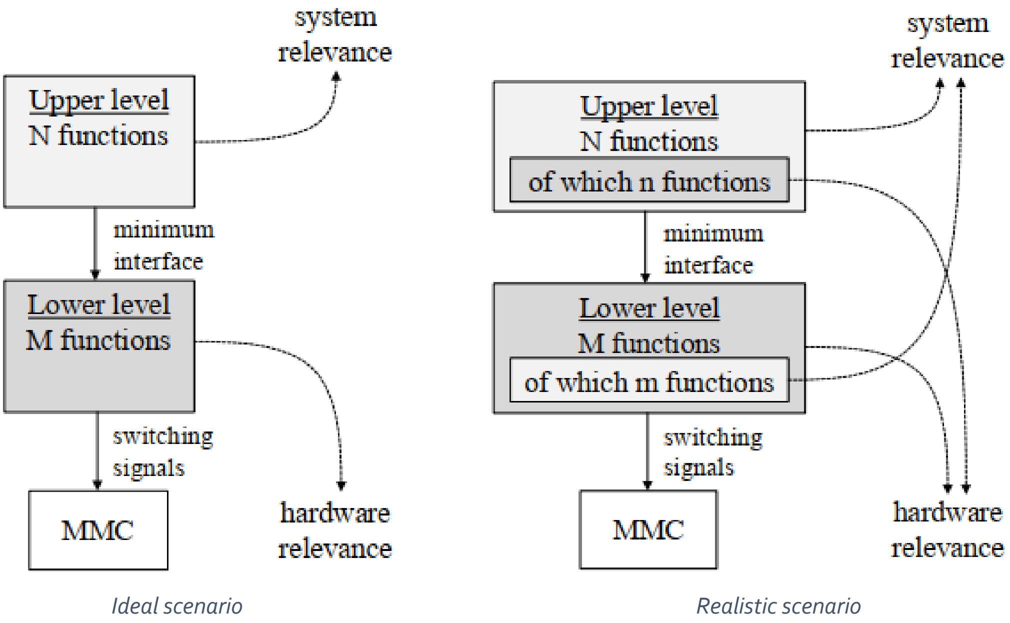


Figure 21. High-level idea of converter functional partitioning (Jahn et al., 2022).

Table 11. Limitations for each stakeholder participating in the interaction study workflow in case of High degree.

ID	Workflow activity	Vendor	HVDC System integrator
2	**Interaction tests:** Simulating all case studies	Possible, but with higher risk of IP disclosure to other vendors	Possible
3	**Analysis:** Find cause of interaction issues	Possible	Possible
4	**Solution:** Recommending mitigating actions	Possible	Possible and limited to the accessible C&P functions
6	**Implementation:** Apply solution to interaction	Possible	Possible and limited to the accessible C&P functions

A few advantages and disadvantages of this openness level are:

- **High-level openness degree advantages:**
    - Anticipatory design: by having a centralized authority on system-related functions, interoperability issues can be detected and rectified during the initial stages.
    - Efficiency boost: standardized guidance can lead to a more streamlined design process across vendors.
    - Transparency and collaboration: open-source solutions become feasible, mitigating IP conflicts and fostering a cooperative environment for C&P system development.
- **High-level openness degree drawbacks:**
    - Integration complexity: this model represents a stark deviation from traditional converter systems, potentially complicating integration into pre-existing setups.
    - Experience gap: there might be a lack of expertise or familiarity on the integrator's part in crafting converter C&P designs.
    - Technical challenges: unless they deliver the hardware, integrators' software-only solutions might spawn technical and liability challenges.
    - Potential innovation stagnation: limiting the role of station vendors might stifle innovation in converter C&P.
    - Liability discrepancies: disparities in responsibilities between integrators and equipment vendors could lead to substantial risks, especially in the event of system or equipment failures.

4.3 Summary and recommendations

After evaluating the various degrees of converter control accessibility for interaction studies in the context of MTMV with an integrator's involvement, it's evident that each option has its strengths and drawbacks.

- **Low-degree accessibility**, which maintains the interface between converter control and the overall system via vendors, prioritizes the safeguarding of vendor IP and leverages their converter control expertise. However, it restricts the integrator's ability to delve deep into interaction studies using obfuscated models or replicas.
- **High-degree accessibility** offers total access to control functionalities, simplifying troubleshooting and decentralizing interactions. However, it demands the integrator to be profoundly adept in converter control and prompts questions about accountability.
- **Medium-degree accessibility** seems to offer a middle ground, granting greater but still limited control access, balancing troubleshooting ease, and centralizing interactions. Nevertheless, this approach requires intense collaboration between the integrator and vendors due to constraints on how much the converter control can be adjusted.

The optimal choice varies depending on the project's specifics, the number of involved vendors, and the MTMV HVDC grid's development direction. Table 12 offers tentative evaluation criteria to assess each accessibility degree, highlighting some comments on advantages and disadvantages.

Table 12. Example of evaluation criteria commented for the level of accessibility of converter controls.

Evaluation criteria	Comments
Incentives technological innovation	No comments yet.
Incentives market competitiveness	No comments yet.
Optimized software/hardware interface between converter control and system	With low-level control accessibility this can be easily ensured by vendors. The more accessible the control becomes, more parties can develop parts of the same controller, which may have an impact on the quality and efficiency of the software/hardware.
Use of vendors expertise on converter control	This is something to incentive in either control accessibility option.
Protection of vendor IP	Full, black-boxed models ensure the best protection for vendor IP. Model responses can be interpreted, and reverse engineered. More accessibility to control functions and more interfaces could increase the risk of IP leaks.
Optimized control delays in power electronics control	No comments yet.
Integrator's autonomy to analyze outcomes and solve problems, and dependence on vendors	From low to high level of accessibility, the autonomy goes from poor to best. In the low-level scenario only, vendors can analyze and problem solving. However, integrators who are not vendors must become control experts as well for all systems involved in a project. The higher the level of accessibility to certain control functions, the less dependency on vendors.
Burden on vendors to maintain and test interfaces	Responsibility lies purely with vendors when accessibility is at the lowest. It should be shared among vendor or non-vendor integrators when accessibility is higher.

When exploring potential methods to adjust converter control parameters, three conceptual avenues stand out (see Table 13):

- **Configuration tool:** this tool, specifically designed for integrators, would come equipped with detailed guides, reset functions, and computations for auxiliary parameters.
- **Simple mask:** envisaged as an intuitive interface, it facilitates direct parameter alterations.
- **Raw input pins:** despite being a prevalent method in real-world projects, this approach is often seen as cumbersome due to extensive documentation and expertise requirements.

Table 13. Pros and Cons of Options to Edit converter Control Parameters.

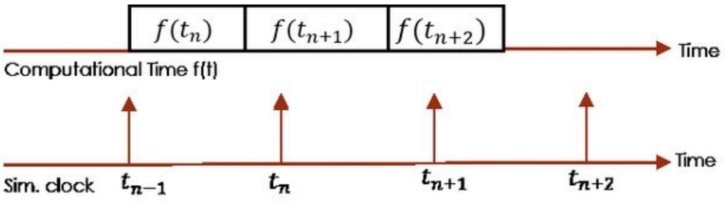
Criteria / Options	Configuration tool	Simple Mask	Input pins
Difficulty of maintenance for vendor	High	Medium	Low
Usability/readability	Good	Good	Bad
IP secure	No	Ok	Ok
Help in troubleshooting and understanding of the system	High	Medium*	None
			*Depends on parameters description in the mask.

Considering the future trajectory, comprehending converter controls stands as a pivotal development pathway to ensure robust and trustworthy MTDC systems. The extent of converter control accessibility's impact on the proposed methodological scenarios for interaction studies warrants thorough exploration. Each methodology described in Scenarios 1 to 4 aligns differently with the converter control accessibility degrees. Thus, stakeholders should collaboratively assess these options at a project's onset. By prioritizing specific advantages, stakeholders can make an informed decision that aligns with their interests and ensures the effective delivery of their contributions.

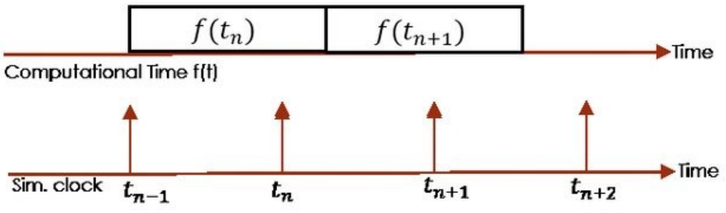
5 ANALYSIS OF EMT SIMULATION TOOLS FOR MULTI-VENDOR INTERACTION STUDIES

This chapter provides a thorough analysis of available Electromagnetic Transient (EMT) simulation tools for conducting multi-vendor interaction studies. The focus is on two simulation types: offline and real-time simulations. Real-time simulations are essential for hardware-in-the-loop (HIL) test benches. Defining offline and real-time simulation types is crucial.

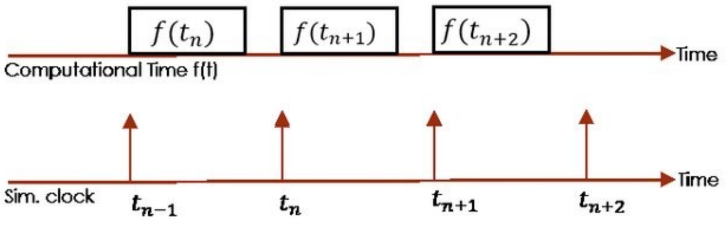
- **Offline simulations** calculate EMT equations, solving all variables without adhering to a constant real-time clock. Processors might solve equations faster or slower than real time.
- **Real-time simulations** always solve EMT equations faster than a set time step to synchronize with the real-time clock. See Figure 22 for illustration.



a. Offline Simulation: Faster than Real Time



b. Offline Simulation: Slower than Real Time



c. Real Time Simulation: Synchronized

Figure 22. Offline and real-time simulation illustrative meaning from (Noureen et al.*, 2017).*

Multi-terminal HVDC systems are dominated by electromagnetic transient phenomena, especially on the DC side. Normal operation and fault transients occur in the range of 100ns – 1μs (see Figure 23). These systems rely on power electronic converters and DC breakers, nonlinear components that complicate mathematical representation. The Nyquist rule dictates that simulation time-step should be at least twice as fast as the studied phenomenon. This applies to both offline and real-time simulations. For instance, if the electromagnetic phenomenon has a 20μs time constant, the simulation time step must be 10μs to accurately replicate it.

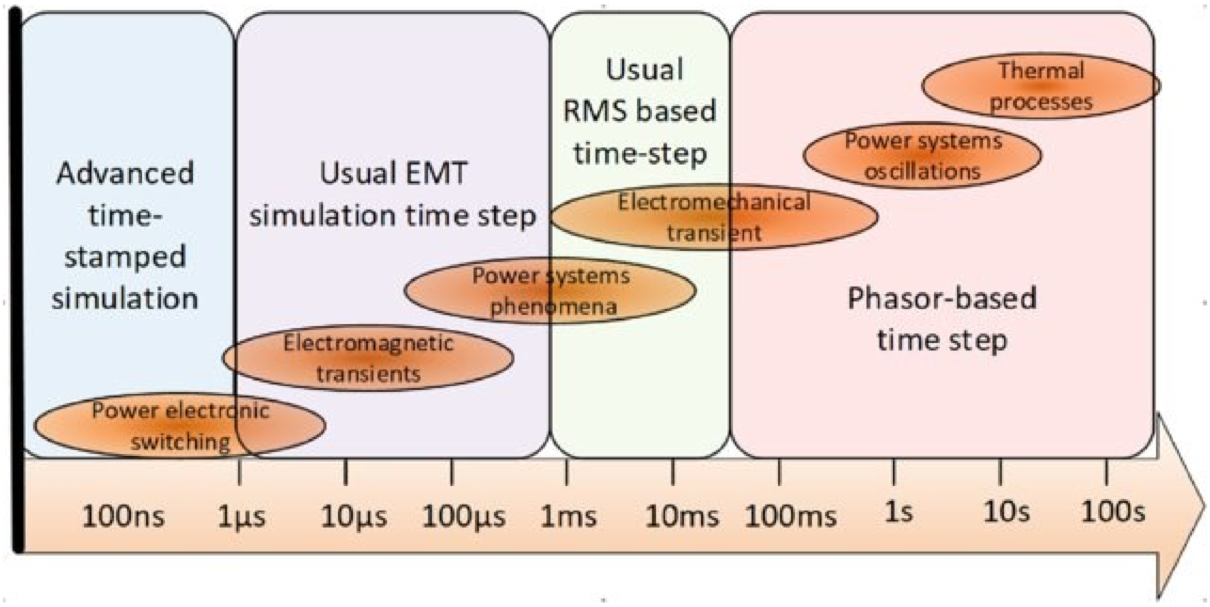


Figure 23. Time step values for different power system studies from (Campos-Gaona and Anaya-Lara, 2019).

- In **offline simulations**, a 10µs time step integrates into differential equations, but results aren't constrained to this rate. Real time isn't a factor. Phenomena lasting 1 second in reality won't be simulated in exactly 1 second; it can be faster or slower, depending on CPU computation time.
- In **real-time simulations**, a 10µs time step requires solving equations faster than 10µs to match real-life speed. A 1-second phenomenon is simulated in 1 second. Results halt and are delivered when 10µs have passed according to the real-time clock. Overruns occur if solving takes more than 10µs, compromising accuracy.

Offline simulations are less resource-intensive and cheaper than real-time ones. Choosing the right simulation type depends on study needs. Sections 5.1 and 5.2 in this chapter will describe the two type of tools that make use of offline and real-time simulations to run interaction tets: software-in-the-loop (**SIL**) and hardware-in-the-loop (**HIL**) tests. Section 5.3 discusses integrating converter control and protection models for SIL and HIL studies. Section 5.4 compares software models and hardware replicas for suitability. Section 5.5 summarizes findings and recommendations, aiding future decisions on EMT simulation tool usage.

5.1 Software-in-the-loop (SIL) tests using off-line or real-time simulations

5.1.1 Description

Software-in-the-Loop (SIL) simulations are computer simulations used to test control and protection software behavior in a simulated MTDC system environment. SIL simulations can be conducted in either offline or real-time modes, depending on the scope of the interaction study. The choice between the two modes depends on the specific goals, yielding the most meaningful results. Various variations of offline and SIL tests are possible. In **offline SIL** studies, simulations typically run on a single station without parallelization. Electrical plant, control, and protection models operate on the same CPU. This configuration represents the functions and logic of future software. In cases with parallelization, multiple

CPUs can solve system equations concurrently. Interaction studies might involve extensive power system zones due to MTDC's long-distance interconnections. Detailed modeling requires significant computational resources, depending on the phenomena being observed. Some advantages of **offline** simulations are:

- Lower cost due to less demanding simulator requirements.
- Potential for greater physical model accuracy, as no fixed time step constraint exists, allowing for detailed calculations.
- Easier setup with minimal training for less complex systems.
- Compatible with manufacturer-provided black-box models, which might have small resolution time-steps.
- Cost-effective software licenses per computer with lower maintenance requirements.

Real-time SIL studies must adhere to the real-time clock, necessitating parallelization. Parallel computing becomes crucial in real-time SIL. Using multiple CPUs on a simulator, calculations must fit within a fixed time step, synchronized with real-time. Larger systems require more control and protection functions and processing units to meet real-time constraints. A real-time test bench, connected to a Device Under Test (DUT), exchanges data like measured variables and control commands. Connecting an industrial DUT prototype results in Hardware-in-the-Loop (HIL), discussed in the next section. Alternatively, SIL prepares interfaces with industrial hardware, testing protocols and communication interfaces. Control and protection software algorithms still run on simulation hardware. Some advantages of performing **real-time** SIL tests are:

- Modular transition to HIL setup by replacing processors with real control hardware.
- Faster simulation speeds with a powerful simulator (without parallelization).
- Proven solution for de-risking complex systems due to intelligent electronic devices, such as power electronics, in large power systems.

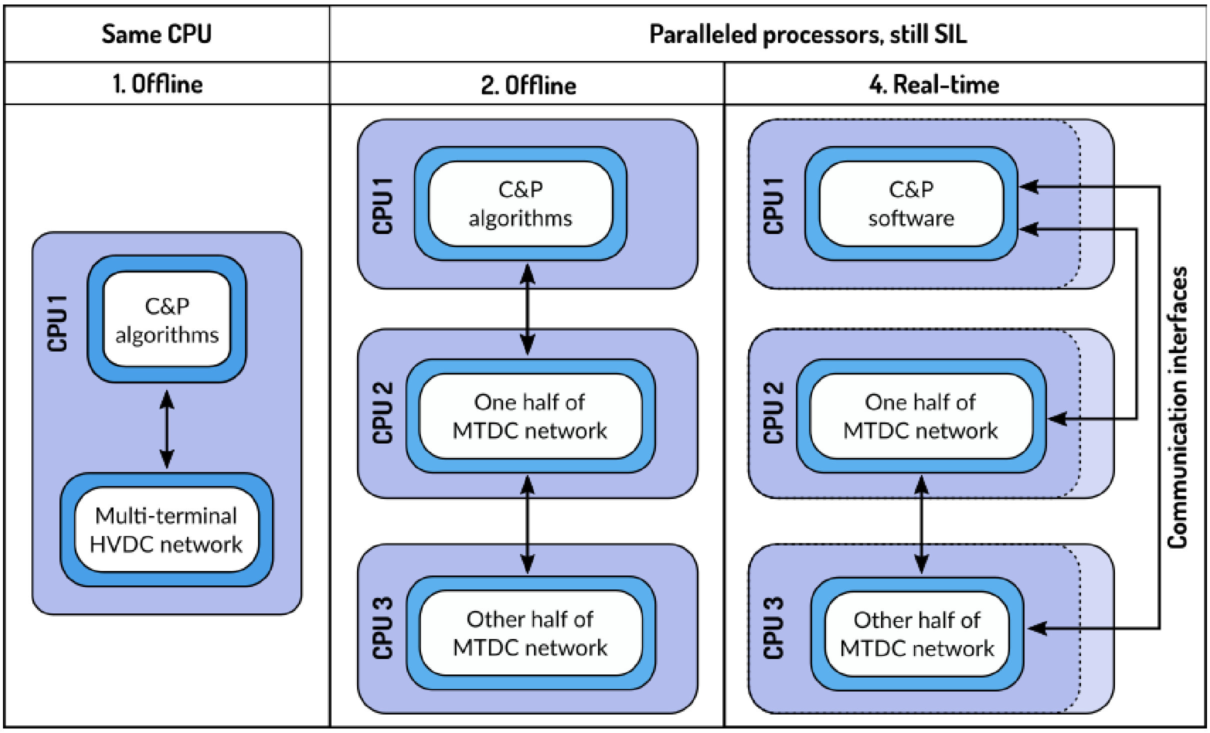


Figure 24. Different possible arrangements for SIL interaction studies with either offline or real-time simulations.

Offline simulation tools running on simulators offer a balance between accuracy and computational speed. While real-time simulators benefit from specialized operating systems enabling efficient parallelization and even "faster than real-time" simulations, they are prone to overruns, which must be carefully surveilled to avoid decreasing accuracy of results. Choosing between real-time and offline simulation depends on goals, model complexity, and resources available. Advancements in offline simulation technology, including parallel computing and high-performance computing, are improving speeds. Offline simulation tools are becoming faster through such advancements. Currently, suppliers don't provide custom simulators as turnkey solutions, but this could change based on their strategies.

Table 14. Comparison of different types of SIL simulation tools for interaction studies.

Simulation Type	Cost	Computation speed	Risk on Accuracy	Complexity of setup †	HIL compatibility
Offline SIL W/O parallelization	Low	Slow*	Low	Low	No
Offline SIL With parallelization	Medium	Medium	Low	Medium	No
SIL Real-time W real interfaces	High	Fast	High	High	Yes

*Can be faster with parallel computing.
† With the right level of expertise, SIL and Offline can both be set up in reasonable and comparable times.

5.1.2 Offline and real-time models validation process

In software-in-the-loop (SIL) simulations, the term "model" refers to either a component or control model provided by a vendor. The "standalone" validation of the model is a crucial step in ensuring the accuracy and reliability of the model before it is used for interaction studies. This process involves checking the technical code expectations, comparing data between different simulation tools, and aligning the model with actual in-service results. Figure 25 shows the flowchart of the validation process of a model by vendor and how it is linked to the interaction studies.

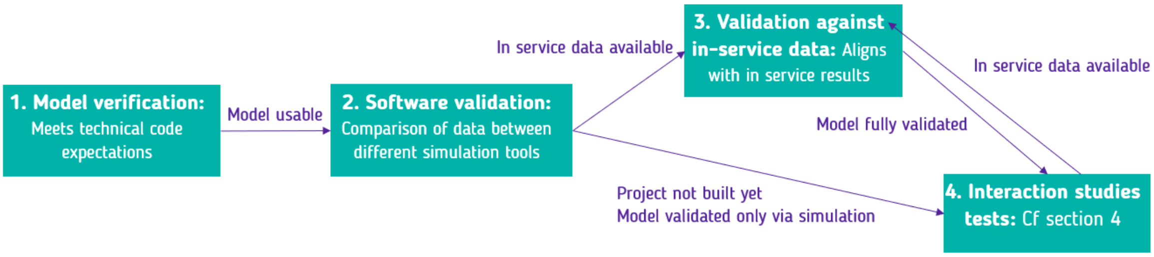


Figure 25. Standalone model validation process.

The validation process of a model starts with the Model Verification step, which involves checking that the model meets the technical code expectations. If the model passes this step, it is considered usable and moves on to the next step, the Software Validation. In this step, the comparison of data between different simulation tools is conducted to ensure the accuracy of the model. If the project has already been built, the validation process continues to the Validation against In-Service Data step, where the model is aligned with the actual in-service results. If the project has not yet been built, the model is considered validated only through simulation and is ready to move on to the Interaction Studies Tests (cf. section 1).

5.1.2.1 Model verification

The primary objective of model verification is to establish the model's suitability for simulation, adhering to technical requirements and expectations essential for further validation and interaction studies. Vendors must undertake several evaluations to verify the model's validity.

- **Compatibility and Integration:** Confirm that the model can be compiled for the intended software environment and smoothly integrated into the desired simulation tool. Compatibility ensures the model's practicality within the simulation environment.
- **Physics and Technology Representation:** Assess if the model accurately represents valid physics and technology. Adequate sensitivity for subsequent validation and interaction studies is ensured. Verify the model against technical code expectations, including computational power, necessary for meaningful simulations.
- **Fit for Purpose:** Ensure the model's suitability for a range of required simulations. Additionally, ascertain that all pertinent functions are incorporated and unmodelled functions are clearly addressed in terms of when and how they should be considered and represented.

5.1.2.2 Software validation

During the development of HVDC systems, verifying model accuracy is an essential step. Prior to system construction, two validation approaches can be adopted. One involves comparing simulation outcomes with in-service data from a similar HVDC system. The other focuses on software validation of the model itself. The latter option is generally favored, as discrepancies between simulation tools tend to be smaller compared to disparities between distinct electrical systems.

It's worth noting that software validation could provide additional benefits. It can instill confidence in the correctness of contractors' control functions. When considering consistent grid codes across projects in the same or different countries, early-stage validation offers valuable insights. While perfection might not be achieved, leveraging insights from validated models in past projects can significantly guide development and verification processes.

Software validation of the model follows model verification. The vendor's model should be validated solely through software studies. Various possibilities exist for software validation, including:

- Validating a new control model within an existing, proven system using a single simulation tool.
- Comparing simulation results of the model between two different simulation tools or environments.
- Utilizing statistical analysis of simulated data to validate model accuracy.

Examples in the HVDC industry encompass validating a new control model through comparison with real-life data from similar systems. Another approach involves comparing results from different simulation environments, such as offline SIL studies and HIL studies, for real-world conditions. Furthermore, model validation using statistical analysis compares simulation outcomes against expected performance data, reinforcing model accuracy.

5.1.2.3 Validation against in-service data

This validation approach is applicable once the project is commissioned or when certain devices are prepared for Factory Acceptance Tests (FAT). Validation against in-service data ensures the model's alignment with actual performance and monitors relevant changes.

Two types of in-service data validation tests exist:

- **Planning in-service test scenarios:** replicating previously tested software-based simulation scenarios in the actual electrical system and comparing results.
- **Using in-service data from unplanned events:** recreating unexpected operational events through simulation and comparing outcomes to validate the model.

The second approach is relatively easier, requiring no on-site testing. In contrast, planning in-service scenarios demands more effort and raises questions about its necessity in validation. In-service data validation is crucial as equipment ages, requiring model updates for consistent performance representation. Typically performed every five years, this validation focuses on events such as start-up and ramp-up, excluding DC faults (Grid, 2022).

Challenges arise in sharing real system data among stakeholders. Once commissioned, manufacturers no longer own the data; TSOs take over. Sharing TSO data, especially from unexpected events, can be sensitive due to potential economic implications. To share such data, TSOs must provide explanations alongside the data, and confidentiality clauses must be established on a case-by-case basis. The legal framework covers field data, including Transient Fault Recorder (TFR) data. While TSOs are open to sharing data with project-specific agreement signatories, sharing with others is restricted.

5.1.2.4 Existing codes: the GC0141 in Great Britain

In the context of GB grid code provisions, GC0141 available in (ESO, 2023), introduced on January 5th, 2023, underscores the necessity to support interaction studies. It mandates the exchange of black-boxed models for EMT simulations, both in real-time and offline settings. Specific clauses, such as PC.A.9.4 and 9.5, detail data exchange requirements. Compliance with these provisions ensures accurate and reliable interaction study outcomes, fostering confidence in the modeling and simulation processes. These grid code provisions offer guidelines for model verification and software validation, aiming to establish model suitability, physics representation, and accurate simulations. The validation process of models is a key facet in securing robust and meaningful interaction study results, paving the way for effective decision-making in MTDC system design and operation.

5.2 Hardware-in-the-loop (HIL) tests

HIL simulations are an important part of the development and testing process for HVDC projects. This technique involves using control cubicle replicas to manage and safeguard real-time simulations of MTDC power systems, as illustrated in Figure 26. It's important to emphasize that each hardware control replica is specifically designed for a particular project and converter station. The focus is primarily on converter control interactions, but hardware replicas can also originate from manufacturers of Intelligent Electronic Devices (IEDs) that offer an additional layer of control and protection for MTDC systems.

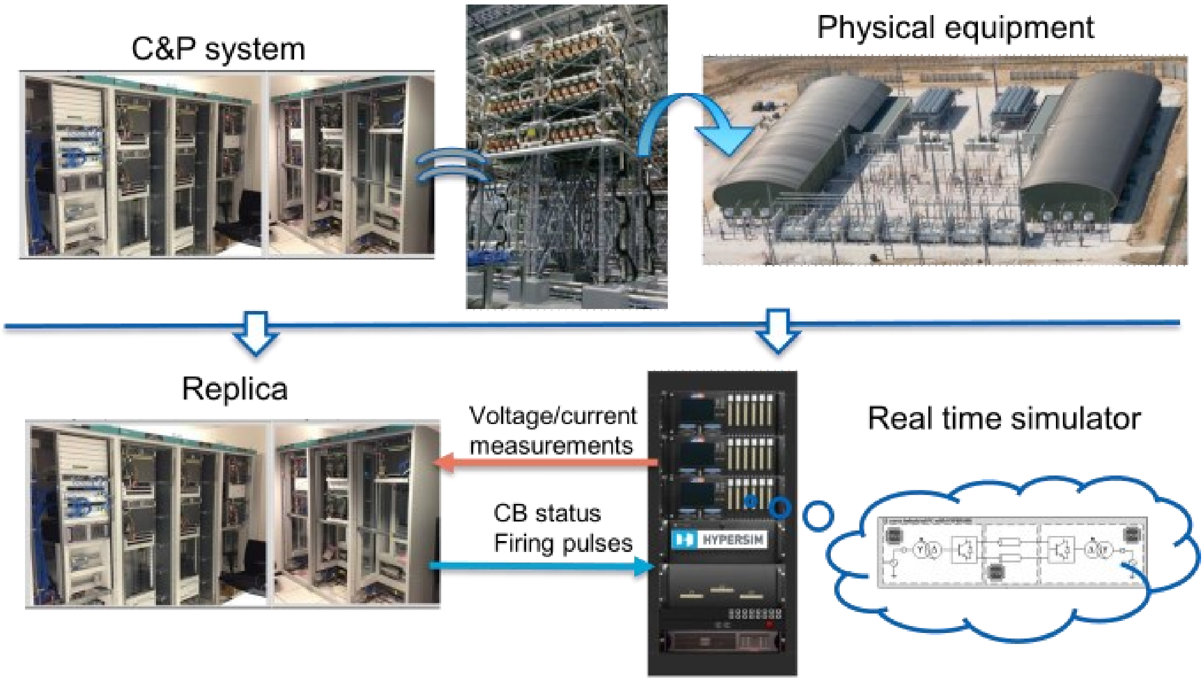


Figure 26. Overview of an HIL setup of a real HVDC link using replicas (Pisani et al.*, 2019).*

In a HIL setup, the objective is usually to test the hardware itself and validate its proper integration in the system that it controls or protects. There are three main notions to keep in mind, the plant, the device under test (DUT) and the interface between them. In this case, the plan is the electrical grid environment, such as the AC and DC grids in a detailed or simplified model including cables, lines, breakers, capacitors, inductors, transformers, generators, loads or even converters. The DUT for interaction studies would usually be the controllers of the converters, the protection IEDs and other types of C&P equipment. No power equipment is used in HIL, this is called Power HIL (PHIL). Interfaces between DUT and the plant can be expected to be:

- **Non-industrial/generic interfaces** when the sole purpose is to test the C&P functions alone. It could be the case for standalone C&P systems for master control and supervision, protection IEDs, running in generic hardware. It could be the case with algorithms running in FPGA or micro-computers (raspberry pi) with the purpose of developing new prototypes for C&P.
- **Industrial interfaces or communication protocols** which are integral part of an industrial converter controller or protection IED.

As MTMV HVDC systems grow, the HIL system can become complex due to the increasing number of replicas needed to control the entire system. In such scenarios, a hybrid approach of HIL and SIL (Software-in-the-Loop) can be advantageous. This approach involves using HIL replicas to represent specific sections of the system or functions, while employing software models for real-time simulation of other parts, as illustrated in Figure 27.

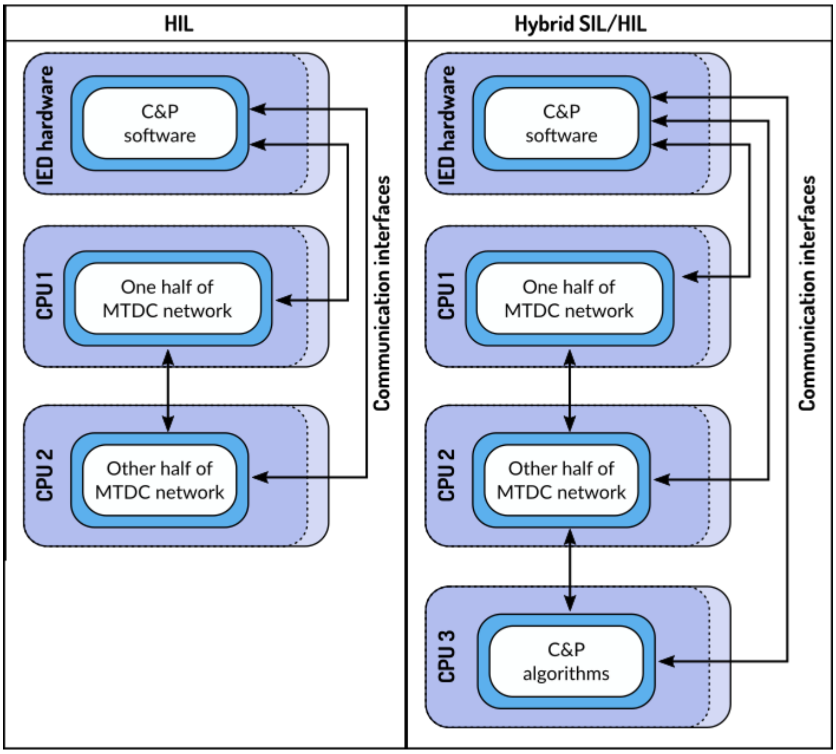


Figure 27. HIL and hybrid SIL/HIL illustrated.

5.2.1 HIL Interaction Studies in Common Labs

In multi-terminal multi-vendor (MTMV) HVDC projects, each vendor often possesses its own laboratory or simulation facility for conducting HIL studies on their equipment. However, when simulating interactions between diverse vendors' equipment, coordination and cooperation become essential. To address this, some initiatives, like the National HVDC Centre in the UK or RTE International labs in France, have established shared labs or simulation centers where equipment from different vendors can be collectively tested and validated.

For effective HIL interaction studies, integrators collaborate with vendors to facilitate cubicle provision, as vendors are well-versed in controlling their replicas. Integrators conduct these studies with vendor support, enabling collaborative troubleshooting and solution recommendations. Given that vendors are experts in their own hardware, they are best suited to supervise or drive tests using their replicas in other labs. These labs provide a common space for cubicles from diverse vendors, ensuring stringent security measures to protect the confidentiality of vendors' equipment and software.

5.2.2 Characteristics of centers for HIL studies

Creating a HIL simulation center requires careful consideration of its attributes. This specialized facility should allow various vendors to integrate and test their control systems in a dynamic and realistic environment. Potential entities responsible for such centers include private organizations or TSOs themselves.

Centers such as the **National HVDC Centre** and **RTE International** have adopted a methodology allowing vendors to conduct studies within their TSO simulation facility. This center offers a commonly hosted network analysis environment where confidential TSO network models, developed in real-time RTDS studies, can be combined with vendor-specific models or replica hardware for existing or new projects. Real-time study environments serve as I/O interfaces, enabling vendors to run their own models/hardware within a broader study environment while observing specific model behavior in detail. The center ensures physical segregation to protect vendors' IP and confidentiality. These measures involve agreements with major vendors, controlled access, data management, cyber and physical security, and co-signatory status in the System Technical Code for data exchange across TSOs.

5.2.3 HIL simulations of several connected HVDC systems

When considering the connection of two DC grids in the future, a unique challenge arises: how to conduct HIL studies for the connected system if the DC systems are simulated in separate centers? Using co-simulation via cloud-based real-time simulation is unsuitable for HIL tests due to communication delays. Therefore, local simulators are necessary. Three options might be proposed for addressing this challenge:

- **European-level center**: establishing a single European-level center hosting all DC projects seems ideal, though implementation may be complex. This center could be publicly funded by the EU, with non-EU members like the UK and Norway seeking bilateral agreements for participation.
- **Integration of labs**: when connecting HVDC systems simulated in different labs, moving cubicles to a single lab for the new connected system could be an option. This might evolve into the first option with time, postponing the solution until the need arises.
- **Hybrid simulation setups**: This approach involves keeping hardware cubicles in each lab while adding models for the other system in real-time simulation. While not as accurate as full replicas, this setup reduces hardware requirements.

This leads to a large number of hardware replicas that risk of becoming cost-intensive. To tackle the issue of hardware replication, the concept of configurable generic hardware has emerged, featuring two potential variants:

- **Generic hardware**: this option involves configurable hardware that can accommodate firmware from any vendor and specific project controls. Although challenging, it increases flexibility and reduces the number of replicas needed for real-time simulations.
- **One configurable hardware per vendor generation**: vendors provide one hardware per generation, configured with firmware and software specific to the project's converter station. While closer to the current approach, it still presents practical challenges.

Examining the concerns associated with adopting generic and configurable hardware options for converter control reveals that both alternatives present practical challenges. The option of having one replica per vendor generation could potentially impact low-level controls and real-time performance, while the use of generic hardware might face limitations in executing vendor-specific software optimally due to differences in timing, real-time performance, and other behaviors. Determining the most suitable approach depends on the specific needs of the project, requiring a careful consideration of the balance between the number of replicas needed and the desired level of flexibility in the simulations.

Consider a scenario with N HVDC projects in Europe requiring HIL simulations with replicas. Let n_i denote stations for the i-th project, n_{iA} from vendor A, and n_{max} the maximum station count among projects. As an example, five MTMV HVDC projects have 3, 3, 4, 4, and 5 converter stations, respectively, with three converter vendors (A, B, C). Table 15 compares different setup alternatives:

Table 15. Comparison of HIL setup alternatives in a MTMV HVDC project.

	Number of hardware needed	Potential impact on flexibility	Control model accuracy	Complexity and practical issues	Distance from current option
Generic hardware	**5**	Very High	**Similar to SIL** Hardware is different than on-site cubicle	Very High	Very High
One hardware per vendor	3 + 3 + 3 = **9**	High	**Very good** Hardware identical to the on-site cubicle but configured differently	High	High
One replica per project station	3 + 3 + 4 + 4 + 5 = **19**	Current option	Exact copy	None	None

5.3 Integrating models and replicas for interaction studies

The purpose of this section is to provide practical recommendations and guidelines for model and replica integration in MTMV HVDC systems. Before proceeding with the discussion, it is important to note the following terminology used in this section:

- "**Integrator**" refers to the entity responsible for integrating a model and/or control hardware supplied by others. This may not necessarily be the HVDC system owner or the global integrator in the sense used for methodological discussion (entity integrating all models from all converter manufacturers). If vendors need to integrate a model from another vendor, they are endorsing the "integrator" role and can be referred to as the "model user" in the case of SIL studies.
- "**Model supplier**" refers to the entity responsible for generating a model that needs to be integrated into a software. This may be a converter manufacturer or another entity.
- "**Control supplier**" refers to the entity responsible for providing control hardware to be interfaced with a real-time simulation, most likely a station manufacturer.
- "**Simulation tool supplier**" refers to the organization responsible for developing and commercializing simulation software tools (real-time or offline).

5.3.1 Workflow for Model Integration

The process of model integration involves generating a digital representation of a physical system, such as an converter or converter within an HVDC system. This is a pivotal phase in the overall workflow of converter/converter model integration for system interaction studies. Different options exist for generating models, each with its own strengths and weaknesses.

- **Manual modeling:** creating models from scratch using software tools like MATLAB or Simulink. This approach demands technical expertise and time but offers maximum customization and control over the model.
- **Automatic code generation:** utilizing software tools to generate code based on high-level model specifications. This option is quicker than manual modeling and requires less technical expertise, although customization might be limited.
- **Using pre-existing models:** incorporating commercially available or open-source models. This approach is speedy and requires minimal technical expertise but might not perfectly represent the specific converter/converter.

Regardless of the option chosen, the workflow for converter/converter model integration typically involves several steps.

1. **Determining model type:** based on system requirements and constraints, deciding on the appropriate model type is the starting point.
2. **Gathering information:** collecting details about the converter/converter being modeled, including electrical characteristics and performance data.
3. **Model creation and validation:** developing or selecting a model, and then validating its accuracy in representing the converter/converter. This validation could involve simulations or real-world data testing, followed by necessary adjustments.
4. **Integration into the system:** incorporating the validated model into the broader system, which might entail interfacing with other models or hardware components. Comprehensive documentation of model interfaces ensures effective utilization and integration.

5. **System testing and validation:** thoroughly testing and validating the overall system to ensure it functions as intended. This testing phase may encompass SIL and HIL studies or other forms of testing to validate system performance and reliability.

5.3.2 Specifying converter C&P model interfaces

Integrating converter C&P models for interaction studies necessitates a standardized interface, encompassing communication protocols and software model interfaces. An attempt at standardization has been made by ENTSO-E; however, it lacks crucial details like signal interpretation, resolution, and sampling. Standardizing the converter control interface entails standardizing the Input/Output (IO) listing, IO order, and IO names. It's important to distinguish between a standardized interface and a standardized file format; the latter pertains to another section of this document. The advantages of standardization include:

- Simplifying the integration of models from diverse vendors into a single simulation tool. A standard interface enables converter C&P models to be treated as black boxes, effortlessly connecting to any converter electrical model through the same IO signals. (cf., CIGRE WG B4.82).
- The standard can be updated through a collaborative process among stakeholders to accommodate technical advancements. This process may occur less frequently than without a standard, fostering integration and hardware interfacing, such as FPGA model updates.

Some requirements for a standard interface encompass:

- Ensuring that standardization doesn't hamper innovation, a critical aspect of competition among converter manufacturers.
- Allowing flexibility in interfaced signal types.

However, several challenges need addressing:

- Standardization is a complex, long-term endeavor demanding substantial effort and collaboration.
- converter-VSC converter interfaces are evolving rapidly due to recent technology, posing challenges for standardization.
- The standard update process might become overly rigid, limiting flexibility and responsiveness to interface changes.

In comparison, LCC (Line-Commutated Converter) technologies, being more mature, experience fewer innovations and are relatively simpler to standardize.

While discussing the standard interface for facilitating the import of models from different vendors into a single simulation tool, it's pivotal to understand its application. It has been a recurrent theme in discussions, and to make it clear, the standard interface should only be applied at the extremities of the control and protection system, specifically when addressing an individual vendor C&P model. Implementing this within the individual vendors' C&P solutions is not recommended. The rationale behind this approach is to ensure that vendor-specific nuances and intricacies within the control and protection system aren't overridden or overlooked. By focusing on the extremities, the integrity of the individual vendor's model remains intact. In the broader context, treating the control model of the converter as a black box and connecting it via standard IO signals to any converter electrical model (as noted by CIGRE WG B4.82) makes sense. However, the internal structure, operations, and algorithms within each vendor's C&P model shouldn't be standardized, as this could lead to oversimplification or missing out on specific vendor optimizations. Most stakeholders do not find an internal standardization relevant primarily due to these reasons. Therefore, while external interfacing and integration will benefit from standardization, internal processes and functionalities must retain their unique designs and structures.

Comprehensive documentation is crucial for integrators, manufacturers, and end-users to understand and integrate the interfaces effectively. In the absence of standardized converter control interfaces, specific guidelines for documenting these interfaces are warranted. The following recommendations enhance clarity, completeness, and comprehension of technical documentation for converter control interfaces:

- **Clear signal description:** concise, lucid descriptions of the physical representation of each interfaced signal. This explanation must clarify the signal's purpose, function, and relevance to the overall system.
- **Signal resolution:** denotes the level of detail or accuracy measurable. This detail ensures accurate signal interpretation and processing.
- **Sampling rate:** indicates its measurement frequency. This information influences signal accuracy and reliability.
- **Latency:** represents the time delay between signal measurement and processing. This metric is critical for real-time system operation.
- **Measurement, filtering, precision, and jitter:** these details contribute to signal accuracy and reliability.

By providing clear and comprehensive information about the converter control interfaces, the technical documentation helps to ensure that these interfaces are properly understood and integrated into the system. This, in turn, helps to ensure that the system functions as intended and delivers reliable and high-quality results.

Table 16. An example of converter interface specifications that can be found within its documentation. Values are purely indicative and do not reflect real values from a specific manufacturer.

Signal	Description	Measurement/Filtering	Resolution/ accuracy	Sampling	Latency	Precision	Jitter
DC Voltage	The DC voltage measurement from the high voltage side of the converter	Measured using a high-precision voltage sensor	±0.5-2.5 kV	1-10 kHz	1-10 ms	± 0.1-0.5%	< 10 µs
DC Current	Measurement of high-voltage DC current using appropriate transducers, such as Hall-effect sensors, Rogowski coils, or current transformers.	Measured using a high-precision current sensor	± 4-20A	1-10 kHz	1-10 ms	± 0.1-0.5%	< 10 µs
Grid Frequency	Measurement of grid frequency using techniques like zero-crossing detection, phase-locked loops (PLL), or discrete Fourier transform (DFT)	Filtering using low-pass or band-pass filters with a cut-off frequency of around 10-100 Hz to remove noise and harmonics	1-10 mHz	1-10 kHz	1-10 ms	± 0.01-0.1%	< 10 µs
DC Power	Measurement of high-voltage DC current and voltage using appropriate transducers (e.g., Hall-effect sensors for current and resistive voltage dividers or capacitive voltage transformers for voltage).	Filtering using low-pass or band-pass filters with a cut-off frequency of around 10-100 Hz to remove noise and harmonics	±10 MW	1-10 kHz	1-10 ms	± 0.1 – 0.5%	< 10 µs
Control Command	The control signal from the control system to the converter	ADC with a low-pass or band-pass filter, 1-5 kHz cut-off frequency.	12-16 bits for ADCs	5-20-100kHz*	10-100 µs	± 0.1-1 %	< 1 µs

* Depending on converter manufacturer

5.3.3 Model Integration strategies for Offline SIL studies

To ensure the successful integration of control and component models into a simulation environment for offline studies, specific considerations are essential. This section outlines the key requirements for achieving simulation compatibility, encompassing file formats, compiler usage, software dependencies, and time step alignment.

Integrating control and component models from various vendors into a unified simulation environment presents a significant challenge, particularly within the context of MTMV studies. Combining models from diverse sources heightens complexity and demands meticulous attention for seamless integration. Models from different vendors must be in a format compatible with a common simulation tool. A recommendation is to standardize file formats or use conversion tools to ensure compatibility.

One of the main challenges in model integration is the need to interface the control model with the rest of the simulation model. While complete interface descriptions (i.e., I/O or inputs and outputs) are necessary for proper simulation operation, these must avoid revealing proprietary model content that could be deemed confidential.

Another difficulty in integrating models from different vendors into the same simulation environment is the lack of a clear and agreed specification defining the model tool, version, usage rules, and setup. Frequently, this leads to divergent approaches in model development by different vendors, resulting in different file formats, compiler requirements, dependencies on other software, and time step requirements. To overcome all these challenges, it is important to establish a clear and agreed specification for simulation compatibility in offline studies. This will ensure that the models are compatible with each other and can be seamlessly integrated into the simulation environment. For instance, a model specification table could be a useful tool for coordinating the integration of converter models into a simulation environment. The following list of characteristics should be included in such table to ensure seamless models' integration:

- **Model Name:** the name of the integrated converter model.
- **Vendor:** the developer of the model.
- **Version:** the model's version number.
- **File Format:** the model's file format, e.g., .xml, .mdl.
- **Compiler Requirements:** specific compiler prerequisites, e.g., MATLAB, Simulink, EMTP, PSCAD.
- **Dependencies:** requisite software dependencies such as libraries or tools.
- **Time Step Requirements:** minimum time step requisites for different study types.
- **Inputs/Outputs:** description of model inputs/outputs, including data types, units, and relevant details.
- **Usage Rules:** specific usage constraints or limitations.
- **Model Documentation:** links to model documentation, user manuals, technical specs.

Having a clear and agreed-upon specification table in place can help ensure that the integration of converter models into a simulation environment is seamless and successful. The first import and integration of the model is often the most time-consuming, but even after the first integration, there are many tasks that need to be performed each time the model is updated:

- Verify that the updated model still meets the specifications outlined in the clear and agreed specification for simulation compatibility.
- Update the simulation environment to be compatible with the updated model, including any necessary changes to the interface between the model and the rest of the simulation.
- Test the updated model to ensure it compiles and simulates without errors, and that its interface with the electrical model remains valid.
- Validate the updated model by comparing its results to previous simulations or to real-world data to ensure it accurately represents the behavior of the HVDC system.
- Repeat any necessary tests and simulations with other models in the simulation environment to ensure seamless integration with the updated model.
- Document the changes made to the model and the simulation environment for future reference and to assist with future updates.
- Monitor the performance of the updated model to ensure it continues to meet the requirements for simulation compatibility and accuracy.

5.3.3.1 File Format and Compiler Requirements

Standardizing a unified process to generate integration-ready models becomes imperative. Two prevailing options include Library (LIB) files and Dynamic Link Libraries (DLLs). LIB files are compiler-specific and linked during compilation, while DLLs offer more flexibility, aiding integration without compiler constraints.

Another notable challenge involves the use of 32-bit and 64-bit Dynamic Link Libraries (DLLs). These libraries, containing code and data for multiple applications, introduce compatibility issues when generated using different compiler bit versions. Similar challenges arise with the usage of Library (LIB) files, which are linked to specific compiler versions, complicating maintenance efforts as compilers evolve. While current approaches involve adhering to a vendor's specified compiler, this can lead to compatibility issues when different compilers are used. A resilient solution would be to adopt DLLs as they circumvent compiler-related complications, ensuring seamless integration across different environments.

Additionally, using various licensed software for DLL generation intensifies the challenge. In the MTMV context, distinct licenses for each vendor's model can escalate costs. Open-source tools or mutual licensing agreements could mitigate this concern.

Efforts to standardize the real-code DLL interface serve as an example. Collaborative work by IEEE and CIGRE aims to establish a recognized standard for DLL interfaces in power system simulations. This entails defining functions, inputs, outputs, parameters, and sample time steps. A DLL import tool simplifies end-user integration, obviating the need for model source code.

5.3.3.2 Time step requirements

Standardizing time steps is also pivotal. Disparate time steps among vendor models necessitate discussions for common time steps or adjustable steps within a reasonable range. This balances accuracy and performance.

Harmonizing time step requirements for models from distinct vendors is a pivotal challenge. The simulation time step determines how frequently the simulation updates models' states and outputs, influencing accuracy and performance. A balance between accuracy and computational efficiency must be struck.

Three approaches to handling time step differences are considered:

- **Common time step:** all vendors adhere to a common time step. This ensures compatibility but requires trade-offs to maintain accuracy and performance.
- **Time steps that are multiples of each other's:** vendors select time steps that are multiples of each other. This preserves compatibility while accommodating some flexibility.
- **Interpolation Techniques:** vendors choose arbitrary time steps. Interpolation techniques bridge time step differences, balancing accuracy and performance, albeit with potential errors.

The chosen approach hinges on project goals and model characteristics, aiming to strike the ideal balance between compatibility and accuracy while catering to the unique needs of each vendor's control systems.

5.3.3.3 Model integration into different simulation tools

Practical challenges in model integration differ across simulation tools and can significantly impact compatibility. Some tools restrict generated models to a single "layer," limiting the organization of subsystems within models. This limitation forces integrators to adapt vendor models to adhere to the software's structure, potentially impairing functionality. Implementation of feedforward controls may be hindered by software constraints that prohibit value storage in memory. Additionally, varying tool usage of compilers introduces further complexities. Efficiently addressing these challenges necessitates collaboration between users and simulation tool providers. Understanding tool limitations and collaborating on solutions or seeking support are crucial steps. Selecting tools aligned with specific project requirements can also enhance integration outcomes.

The existence of dependencies on other software greatly complicates the integration of models, as well as their portability. Ideally, a Dynamic Link Library (DLL) should not be dependent on any non-free to use software or third-party library. This would offer the advantage that the integrator would not need additional software or licenses to integrate the DLL into their simulation environment.

However, making a DLL completely independent can be a restrictive and limiting process. It may require a lot of effort, potentially many years of development, to achieve this ideal. Additionally, it may not be feasible in some cases to make the DLL completely independent, especially if the functionality offered by third-party libraries is required.

If a DLL is still dependent on other software, it is important to specify these dependencies so that the user is aware of what they need to be able to run the DLL. This information should be readily available and easy to understand, so that users can assess whether they need to purchase additional licenses or install extra software. For example, the Functional Mock-up Interface (FMI) standard, a tool-independent interface for exchanging dynamic models between simulation tools, provides guidance on minimizing dependencies. According to the standard, dependencies on the target platform should be minimized, and operating system services should be accessed only through standard libraries. Any special run-time requirements should be documented in the appropriate directory inside the ZIP file.

5.3.4 Model integration strategies for real-time SIL studies

Ensuring true real-time behavior necessitates addressing time step requirements, which applies to this simulation context as well. While converters’ control and protection models usually operate at low time steps, integrating models from various vendors can further complicate matters. Each vendor's model may have a distinct time step, demanding that the simulation's time step be set lower than any single vendor's model. Achieving this can pose a challenge, as excessively low time steps can impact the solver's ability to maintain deterministic and synchronized outputs, undermining the real-time nature of the simulation.

Another challenge is the compatibility of the black-boxed C&P models within the real-time simulation tools. The successful integration of vendors' control models into real-time SIL studies hinges on selecting a real-time simulation tool that aligns with each vendor's control model file format. Unlike a Dynamic Link Library (DLL), these models might adopt various file formats (such as .a). Consequently, the necessity for direct source code utilization may diminish. This alteration introduces the potential for portability issues between offline and real-time simulation tools. The chosen simulation tool should adeptly accommodate the low time step requirements of the models and facilitate real-time simulations encompassing multiple distinct models.

When the models are not using the same communication protocols, to ensure that they can exchange data and interact with each other during the simulation, interfaces must be developed in the simulation environment. The real-time simulation tool should be able to handle different kinds of communication protocols and the user must also understand them to create interfaces between them.

Lastly, the availability of technical expertise and support from both vendors and simulation tool providers should not be overlooked. Vendors should help in integrating their control models into the real-time simulation environment, while simulation tool providers should furnish support for executing real-time simulations effectively.

5.3.5 Replica integration strategies for HIL studies

Control cubicles or replicas are physical or black box representations of the control system hardware used in HIL studies. To ensure a successful and efficient interface between the control cubicles/replicas and the HIL setup, it is essential to consider some guidelines.

The control cubicles/replicas must be able to respond to inputs from the HIL setup within the specified time constraints. To ensure this, it is recommended to have a detailed understanding of the timing requirements. Also, the HIL simulation setup should provide a representative environment for the control cubicles/replicas to be tested. This means that the HIL setup should mimic the actual operating conditions of the MTMV HVDC system as closely as possible. To validate the accuracy of the HIL simulation part, it is recommended to perform tests and compare with results obtained in off-line simulations. Debugging tools should be available for the control cubicles/replicas and the HIL setup. This will allow developers to identify and fix any issues that arise during the HIL studies. To validate the effectiveness of the debugging tools, it is recommended to perform tests.

The control cubicles/replicas and the HIL simulation must be able to exchange data in real-time. This means that the data must be transmitted accurately and with minimal latency. To achieve this, it is recommended to choose an interfacing protocol that is capable of transmitting data efficiently. It is recommended to choose a widely used protocol with a well-established standard.

The communication protocols used for high-speed connections like AURORA, which uses SFP ports connected to an optical fiber, are commonly used by converter manufacturers. The vendor defines the interface with the converter control, which specifies the position of each signal that needs to be received in the IO cards (such as arm current, submodule states, or voltages). This information is then used by the integrator to create a real-time simulator using an FPGA model, which emulates the hardware interface. As FPGA modeling requires specialized technical skills, integrators may need to seek assistance from simulation tool suppliers or those with experience in FPGA.

If the technology evolves, the vendor may need to change this interface, which could result in updates to the FPGA model and a new bitstream for the simulator FPGA. It is important for the vendor to aim for stability in the interface. The lack of standardization in the industry means that vendors have the freedom to change the interface which is a pre-condition to allow technical evolution. The vendors should aim to keep the interface as stable as possible and only make changes when new parameters are required. Any change to the hardware interface should be properly documented to minimize the impact on the FPGA model and make it easier for integrators to update their simulators. The option of having a standard interface, as proposed by ENTSO-E, is under discussion and would still need updates to account for technical advancements.

5.4 Comparison among EMT simulation tools for multi-vendor interaction studies

The different tools to conduct these studies involve the use of software models or hardware replicas or a combination thereof. Both with their own advantages and disadvantages in terms of maintenance and accuracy, the following sections will summarize the discussions of the working group around this matter.

5.4.1 Difficulty of maintenance

The maintenance of both software models and hardware replicas is an important factor to consider when conducting interaction studies. Typically, an HVDC project would need a maintenance contract with the control manufacturer specifying that when the converter control is patched, both control models and control replicas would need to be updated.

Software models can encounter compatibility issues, especially in HVDC system expansions, when integrating models from new HVDC stations. The possibility of using previous versions of control and simulation software in simulations poses compatibility challenges. In scenarios where retro-compatibility is unattainable, one of the vendors may need to upgrade their control model to the new software version for seamless compatibility. However, this process entails significant coordination and effort with vendors to generate models that align with the specific software version. Consequently, software models present a risk of compatibility issues, unlike their hardware counterparts that remain relatively constant.

On the other hand, control replicas offer their own advantages for maintenance. For example, a new real-time code of the control is available by default, as it is provided for the on-site cubicles. As a result, updating the replica should not require any extra effort. Additionally, hardware often provides more accessible parameters that can be updated compared to the equivalent software model. This is because the IP risk for the vendor is lower for hardware that cannot be easily transferred or copied, as is possible with a software model. As a result, in certain cases, the integrator hosting the replica may be able to tune or update the control without the involvement of the vendor, especially for high-level control updates.

Furthermore, it's important to note that the frequency of control updates differs between software models and replicas. Software models are generally updated every five years, aligned with on-site data. In contrast, replica updates occur only when on-site cubicles undergo updates..

5.4.2 Level of accuracy

When it comes to evaluating the accuracy of a control model, two important criteria must be considered: representation of the hardware dynamics and software code accuracy. These two factors are critical in determining the level of accuracy of the model and its ability to provide reliable and accurate results for interaction studies.

In the case of a replica, it is often considered to be an exact copy of the on-site control cubicle, both in terms of hardware and software. However, this is a simplification of the reality, as there are many differences between a replica and an on-site control cubicle. For example, the input/output (IO) cards in the control cubicle may not be fully represented in the hardware replica, which is considered unnecessary for the purpose of performing interaction studies. Additionally, the software code running on the replica and on-site control cubicle is not an exact copy, but rather a close representation. The core control and protection functions should be the same, but some interfaces may be adapted and some unused signals may be disabled.

The accuracy of hardware representation profoundly impacts a model's fidelity. Offline models, however, don't encapsulate hardware dynamics or communication dynamics. Utilizing hardware different from the on-site cubicle enables testing of communication issues, yet the hardware dynamics might be imprecise, leading to a false sense of performance assurance.

Software code accuracy is another critical aspect that must be considered. Ideally, the software code provided by a vendor for a model or for the replica should be the same and come from the source code, but differences in the way the model or software code is generated can lead to differences in simulation and reduced accuracy. In practice, the software code running in real-time on a different hardware than the on-site one may need optimizations to run in real-time, which could result in less accurate software code compared to the offline model.

In conclusion, the level of accuracy in a model is determined by the software code accuracy and the hardware representation accuracy. A replica provides the most accurate representation of the on-site system for the purpose of interaction studies, while a software model may be sufficient if the software code is representative enough. However, the level of accuracy in a model will always be lower than in a replica.

5.5 Summary and recommendations

After considering the evaluation criteria for interaction study modeling tools, the question arises as to whether it is better to have an offline model throughout the project or to have replicas. This decision is outside the scope of this project, but some criteria for comparing modeling tools for interaction studies have been discussed that can provide a qualitative assessment of the available EMT simulation options. This information can assist decision makers in determining whether to use offline models, replicas, or a combination of both at various stages and times during a MTMV HVDC project.

There are two main types of EMT simulation tools for interaction studies: offline and real-time. Both support SIL simulations but only real-time support HIL simulations. Each of these types has different setup characteristics and simulation performances. The most common setups in the industry are offline EMT studies using normal CPU workstations and HIL studies using vendor control replicas. The interest in SIL simulations depends on the complexity of the study, as these simulations become more relevant for large HVDC systems. Indeed, replicating all components of MTMV HVDC systems alongside adjacent AC systems, particularly for large setups, can prove impractical and costly. To mitigate this, certain segments of the system might be retained within the simulation environment (SIL), while relevant C&P systems, such as new converters or terminals with risk of interactions, are performed by replicas. This hybrid SIL/HIL approach can effectively streamline space and hardware requirements.

The main comparison criteria for simulation performances are speed, accuracy, and cost of operation and maintenance. Although the accuracy level of offline and real-time simulators is similar, real-time simulators face more constraints in delivering calculations on time due to the management of I/O interfaces and overhead times. HIL setups must be compared with offline studies in terms of cost-effectiveness, especially for large, interconnected, MTMV HVDC systems expected to be developed in future power systems.

Some comparison criteria for model performances are accuracy, proximity to real controls, compatibility with FPGA implementation of low-level converter controls, and accuracy of hardware dynamics. Offline models are considered highly reusable, but they are black-boxed by vendors, which can lead to incompatibilities and additional maintenance costs. HIL studies use replicas of the actual controls to be implemented in the HVDC system, so interaction studies performed at this stage benefit from the latest version of the control and the most recent system possible.

Table 17 synthetizes the different tools and compare them with the proposed criteria.

Table 17. Preliminary evaluation of EMT simulation tools for testing interactions in MTMV HVDC systems.

		Type of EMT simulation tool						
	Comparison Criteria	**Offline** (state of art)	**Offline +** (state of art)	**Real-time SIL** (pure SIL)	**Real-time SIL +** (for Hybrid SIL/HIL)	**Real-time HIL**	**Real-time HIL ++**	**Real-time HIL +++** (current trend)
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

There is no clear answer on whether to use offline models or replicas for interaction studies in modeling tools, as it depends on the specific project development stage and its requirements (green field, brown field, large system, small system...). However, some criteria have been discussed for comparing different simulation options available. In large scale projects, black box models may be the only feasible option due to the large number of replicas needed, does this mean that the goal is to only work with appropriate offline models? It is important to consider the cost-benefit trade-off when making this decision. The goal is to find a balance between using enough replicas or models to accurately simulate the project and use a combination of models and replicas for different stages and moments in a project while also reducing costs and space requirements. Different projects may have different approaches, but the goal is always to find the most effective and efficient solution.

CONCLUSIONS

This whitepaper presented an analysis of MTMV HVDC grid interaction studies, covering various essential aspects ranging from interaction phenomena to the application of specific tools to study them.

In the first chapter:

- Different types of interactions and highlighted their importance were categorized.
- We identified a need to prioritize interaction phenomena, especially the risk of interaction on the DC side.

In the second chapter:

- We proposed a clear and organized workflow for interaction studies, aimed to align with current codes and state-of-the-art interaction testing procedures, then can be applied at any stage of the MTMV HVDC system development:

In the third chapter:

- We delved into the roles of different stakeholders involved in interaction studies.
- A methodology inspired by existing codes was proposed, highlighting the need for further information on the difficulty of role execution and technical/legal barriers.

In the fourth chapter:

- We discussed the impact of converter openness on interaction studies.
- Theoretical possibilities for splitting the functional blocks of MMC converters were provided, pointing out the importance of a balance between intellectual property protection and access to converter functions if considered useful to ease system design and interoperability in the future.

In the fifth chapter:

- We emphasized the importance of choosing appropriate EMT simulation tools, which depends on the availability of models/replicas and the MTMV HVDC project stage. The standardization of tools for consistency and reliability in interaction studies is emphasized.

In conclusion, this whitepaper provides a comprehensive look into the complexities of MTMV HVDC interaction studies. It is a first step towards the definition of new frameworks for interaction studies in the InterOPERA project, where tasks will encompass a rigorous review of the propositions presented herein, followed by crafting a holistic interoperability framework primed for testing in pioneering MTMV HVDC pilot systems. We extend our best wishes for their successful journey ahead.

ABBREVIATIONS AND ACRONYMS

ACCRONYM	MEANING
AC	Alternating current
CIGRE	The International Council on Large Electric Systems
DC	Direct current
DLL	Dynamic Link Library
EMT	Electro-Magnetic Transient
EMTP	Electro-Magnetic Transients Program
ENTSO-E	The European Network of Transmission System Operators for Electricity
FACTS	Flexible Alternating Current Transmission System
FAT	Factory Acceptance Testing
GB	Great Britain
HIL	Hardware-in-the-loop
HVDC	High Voltage Direct Current
IED	Intelligent Electronic Device
IO or I/O	Input outputs
IOP	Interoperability
LIB	Static Library
MMC	Modular Multi-Level converter
MTDC	Multi-terminal HVDC
MTMV	Multi-terminal Multi-Vendor
NDA	Non-Disclosure Agreement
OFGEM	The Office of Gas and Electricity Markets
PCC	Point of Common Coupling
PEID	Power Electronics Interfaced Devices
PLL	Phased-Locked Loop
PSCAD	Power Systems Computer Aided Design

RTDS	Real-time Digital Simulator
SAT	Site Acceptance Testing
SIL	Software-in-the-loop
TBD	To be determined
TFR	Transient Fault Recovery
TSO	Transport System Operator
VSC	Voltage Source Converter

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