READY4DC

D1.1 – First version:

MODELLING, SIMULATION FRAMEWORK AND DATA SHARING FOR MULTI-TERMINAL MULTI-VENDOR HVDC INTERACTION STUDIES AND LARGE-SCALE EMT SIMULATIONS

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.

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INTRODUCTION

Interaction studies play a crucial role in multi-terminal multi-vendor (MTMV) High Voltage Direct Current (HVDC) grids. These grids involve a complex network of stakeholders, including vendors, real-time simulation laboratories, system owners, developers, operators, and TSOs. All these stakeholders play a role in the design, manufacture, operation, and maintenance of HVDC assets. The 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. Developers also play a role in the planning and construction of HVDC infrastructure projects and may become part owners of the system. Interaction studies are essential in ensuring the safe and efficient operation of these HVDC grids with complex ownership and operation schemes.

With the increase in HVDC projects, there is a need to address the challenges and questions that arise when multiple vendors are working on the same project. Especially when there is a need for multi-terminal HVDC grids for which interactions 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. In the past, only one vendor and one integrator were involved in a single project. Now, with the involvement of multiple vendors, the roles and responsibilities of each stakeholder must be re-defined clearly to ensure a successful outcome.

Furthermore, 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. This makes it even more important to conduct thorough interaction studies to identify and mitigate any potential issues that may arise. It is important 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.

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. Another question that arises is whether it is acceptable for a vendor to provide a model or replica that will be used by another vendor for these studies, which is an aspect discussed in WG4 in the section of investment blocks. In the case of a model, even if the model is black boxed and subject to a Non-Disclosure Agreement (NDA), there are risks and liabilities to determine. While in this WG1 these questions are analyzed from the technical point of view, a legal perspective is discussed in WG2 task 2.1 on Intellectual Property (IP) and confidentiality for vendor control models. To prevent possible reverse engineering, a legal framework is established and described also in coordination with task 2.1.

Two types of MTMV HVDC projects need to be differentiated as well: is the complete system a new one or is it an expansion or interconnection of existing HVDC links. These two types of projects may have different requirements and therefore, different studies and methodologies would need to be applied.

Interaction studies of HVDC grids are crucial to ensure the proper functioning of the system within the power network. An integrator is responsible for conducting these studies and must identify any potential issues or conflicts that may arise with other components of the power network. It is important to note that in case of a vendor causing interoperability issues, solutions must be provided by this vendor. But this requires the solution suggested by the integrator to be accepted and endorsed by the vendor. Thus, the vendor must be fully committed to the project and provide expertise and capabilities in line with the project's requirements.

STAKEHOLDERS' DEFINITIONS

The different options for the organization and responsibility framework of HVDC system owners, operators and vendors are not detailed here. Please refer to READY4DC WP3 for the different options on this subject. Also, 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 14tilized14on 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 14tilized 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 BRIEF DESCRIPTION OF INTERACTION STUDIES

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)
- [Not yet published] CIGRE B4-81: Interaction between nearby VSC-HVDC converters, FACTs devices, HV power electronic devices and conventional, 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, April 2023
- [Ongoing] CIGRE B4-85: Interoperability in HVDC systems based on partially open-source software, July 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 1 according to new phenomena expected to appear in a MTMV HVDC environment.

LEGEND 1: 🔴 AC specific | 🟢 DC specific | 🟡 AC or DC **LEGEND 2:** Existing (REF) / *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 1. Categories of interaction studies proposed in CIGRE B4-81.

The list in Figure 1 is quite exhaustive, thus, 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 1.

2.1 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 2 denotes the zone for these interactions to occur.

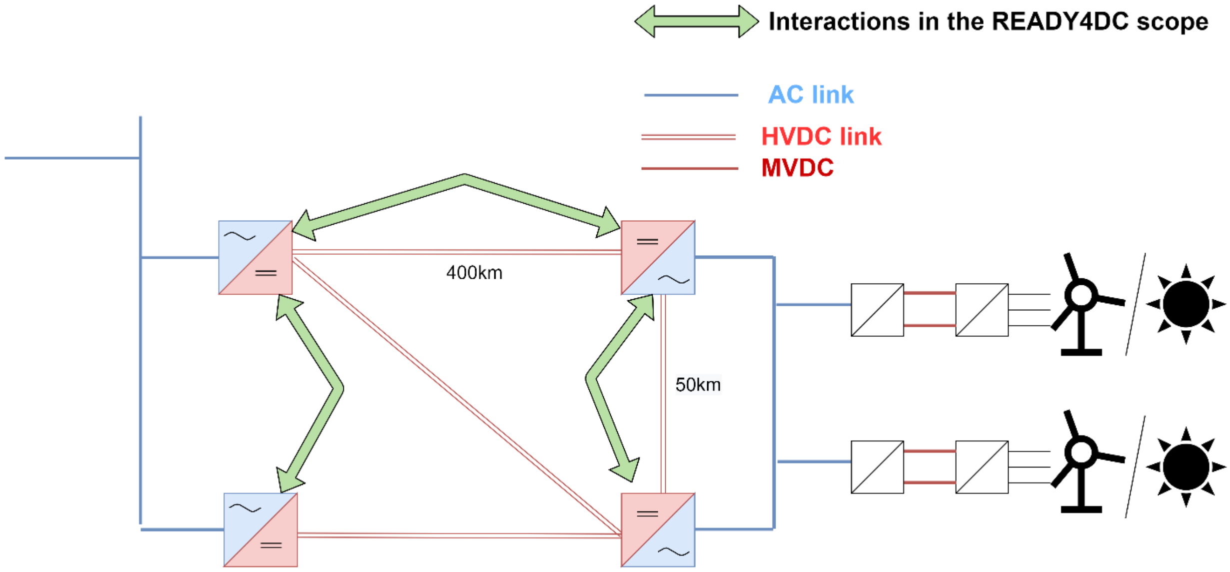


Figure 2. Illustation of DCside interactions use-case.

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 MMC-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 MMC-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.

2.2 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 3 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.

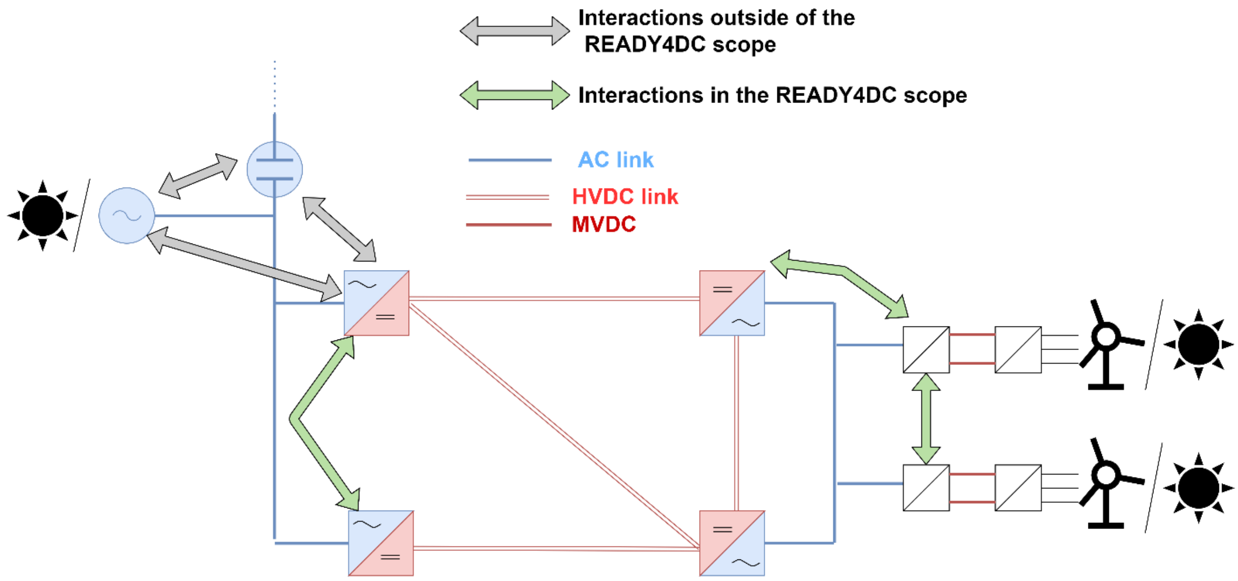


Figure 3. Interactions scope in READY4DC. The renewable energy sources can be offshore wind farms as well as solar PV plants. A recent paper (Wang et al., 2022) confirms the interaction of Solar DC sources and AC system.

A similar situation would occur on the case of "hybrid systems" (Figure 4): 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.

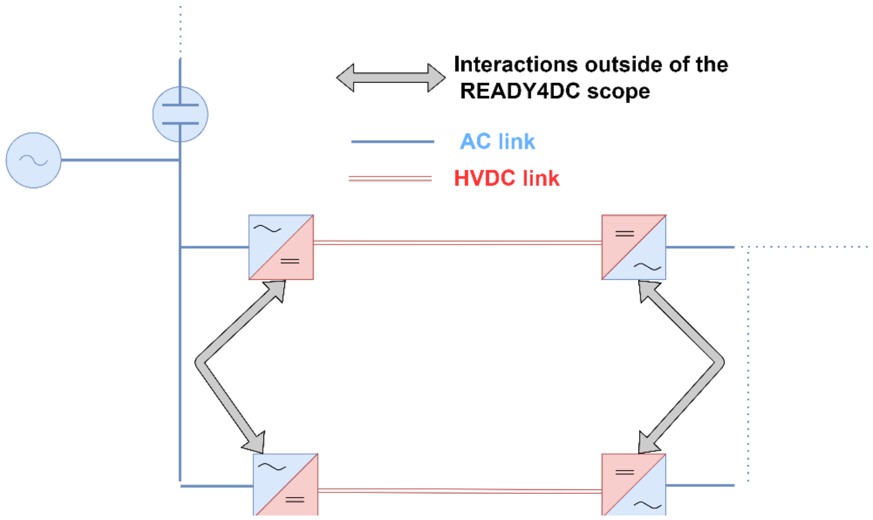


Figure 4. Multi-terminal scheme that is not under READY4DC scope since the DC side is not linked.

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 1. 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	TBD	Out of scope
AC grid elements (Generator, Series Compensation Capacitors…)	Out of scope	Out of scope	Out of scope	Out of scope

2.3 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.

2.4 When to perform interaction studies

In order to ensure the safe and reliable operation of multi-terminal HVDC grids, it is important to conduct interaction studies at different stages of development. The type of studies and simulation scenarios may vary depending on whether the project is an expansion of an existing grid or a new HVDC project.

For expansion projects, the analysis at bid and pre-design stages will rely more on interfacing with other equipment being demonstrated and modeled in real-time. For each development stage, the validation plan should include a simulation scenario that specifies the type of event, contingencies, faults, and short-circuits that will be used for the study.

The validation plan should also specify the simulation tool and computation time to be used for each scenario. Depending on the scenario, different simulation tools may be appropriate, such as phasor simulation, electromagnetic transient simulation, or real-time simulation in hardware-in-the-loop (HIL) or power hardware-in-the-loop (PHIL) setups. The range of frequency and the computation time/simulation time-step should also be specified in the validation plan.

To assess the interactions between the different stations in a multi-terminal HVDC grid, studies such as small signal analysis and sub-synchronous analysis should be performed. Small signal stability analysis is necessary to ensure that the system is stable, while sub-synchronous analysis can help identify and mitigate sub-synchronous resonances that can cause instability.

For multi-terminal multi-vendor and interaction analysis, new tests and processes may be required that are different from those used in single vendor point-to-point case. The relevant tests should be identified and incorporated into the validation plan. It may also be necessary to adjust the tests depending on the results obtained by other vendors in their tests, in order to ensure compatibility and consistency across the entire grid.

In conclusion, the validation plan should include a comprehensive set of studies and simulations that are appropriate for each stage of development in a multi-terminal HVDC grid. By conducting these studies and carefully analyzing the interactions between the different stations, engineers can design and operate multi-terminal HVDC grids that are safe and reliable.

2 MULTI-VENDOR INTERACTION STUDIES WORKFLOW

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 are discussed in section 1. The workflow proposed in this chapter is a proposition for generic steps in the development of a interaction study, meaning it can be applied at any step of the project development (system feasibility, pre-design, design, operation). The difference between the stages would be the tools (EMT simulation, offline or HIL, and others…) used to perform the interaction studies.

2.1 Description of a viable workflow

Performing interaction studies involves a defined workflow, clear roles and responsibilities, and a comprehensive validation plan. The TSOs and vendors must work together to ensure a successful outcome, with the TSOs taking responsibility over the validation plan and vendors providing support and fulfilling requirements. The following figure describe the overall workflow, with navigation between the different phases:

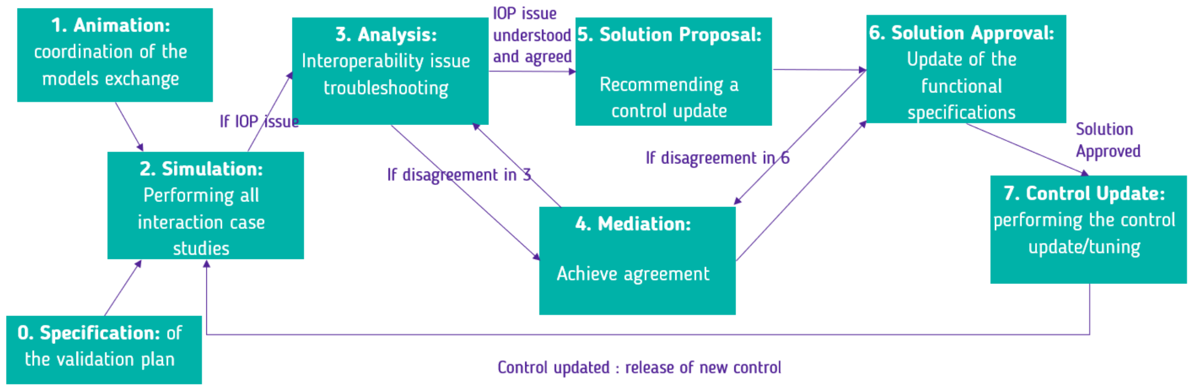


Figure 5. Flowchart of the multi-vendor interaction studies process.

Step 0: Specification of the validation plan

The first step is the specification of the validation plan. The HVDC system operator(s) is responsible for writing and providing a validation plan for the entity performing 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) that will be reached during the interaction studies.

Some HVDC system operator(s) may ask vendors to complete the list of test cases. In such case, HVDC system owner(s) will ask vendors to complete the validation plan, adding some tests to validate the different control stations for instance. However, ultimately the TSO is responsible for fulfilling the needs, while vendors are only responsible for achieving the requirements.

Step 1: Animation and coordination

This role involves coordinating the discussion between different vendors to agree on model requirements, such as the desired level of control model openness, step size, and compiler version, as well as exchanging models between vendors and ensuring that they meet the established requirements.

Step 2: Interaction tests (SIL or HIL)

The simulation step is where the actual interaction studies take place, following the validation plan established in step 0. The simulation includes the integration of models from different entities, the preparation of the simulation models, and the application of all test case scenarios. If any interoperability issues are highlighted, they are then analyzed and troubleshot as described in subsequent steps.

Step 3: Analysis

This step focuses on identifying the root cause of any interoperability issues that were identified in the simulation step. This typically involves reviewing simulation results and conducting further testing to isolate the problem. The analysis should be thorough and well-documented, for effective explanation and communication to main stakeholders.

Step 4: Mediation

If there is a disagreement between vendors, a mediation process is needed to come to a solution. This step is crucial in ensuring that all parties are satisfied with the proposed solution and that it is the best option for the system.

Step 5: Solution proposal

A solution is proposed by the vendor(s) responsible(s) for the problem identified in step 3. This solution should be well thought out and should consider the impact on the entire system, as well as the feasibility of implementation.

Step 6: Solution approval

The proposed solution is reviewed and approved by all stakeholders. This step should involve clear communication and documentation of any changes made to the functional, technical specifications or system design, depending on the phase of the project when the interaction study was performed (before or after tender).

Step 7: Mitigating actions

The control is updated according to the solution validated in step 6. This step should be closely monitored to ensure that the update is successful and that the system is working as expected.

It is worth noting that each step in this process is closely linked and interdependent. For example, a thorough and accurate validation plan in step 0 is crucial for the success of the interaction tests in step 2. Additionally, it is important to note that the animation and 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.

It is also important to consider the use of appropriate simulation tools and techniques, including software-in-the-loop (SIL) and hardware-in-the-loop (HIL) methods. These techniques can provide valuable insights into the behavior and performance of the HVDC grid under different conditions.

Overall, the MTMV interaction studies process is a complex and iterative process that requires close collaboration and communication between all stakeholders. By following a clear and well-defined workflow, and with the use of appropriate simulation tools and techniques, it is possible to ensure that the HVDC grid will operate in a safe and reliable manner.

Finally, it is important to ensure that the results of the interaction studies are thoroughly documented and reported, including any issues that were identified, the solutions proposed, and the results of the control updates. This documentation can be used to inform future studies and to ensure that the HVDC grid is operating at optimal performance.

2.2 Role's assessment for main stakeholders

The roles and responsibilities of the HVDC system integrator and vendors in the interaction studies workflow need to be clearly defined, since they both are the main stakeholders interested in solving interaction issues. This section aims at providing a clear understanding of their various roles and responsibilities in the proposed workflow to ensure effective communication and collaboration among all stakeholders involved in HVDC system interaction studies. To provide a comprehensive overview of the interaction studies workflow and the various roles and responsibilities involved , Table 2 indicates whether participation in each step is mandatory or optional for the HVDC system integrator and vendors.

Table 2. Roles of main stakeholders for each step in the interaction studies workflow. The different possibilities for the roles here colored in orange give different methodological options described in section 3.

ID	Stage	AC TSOs	HVDC system operator	HVDC system owner(s)	Vendors
0	Elaboration Validation Plan	Need to participate	Mandatory	Can participate	Need to participate
1	Animation: coordination of the models' exchange	Possible	Mandatory	Possible	Not responsible
2	Simulations: performing all case studies	Possible	Possible	Not responsible	Possible
3	Analyze the simulation results in case of interoperability issues	Mandatory	Mandatory	Not responsible	Possible
4	Mediation: In case of disagreement	Possible	Mandatory	Possible	Not responsible
5	Solution: recommending control update	Possible	Possible	Not responsible	Possible
6	Solution approval: update of the functional/technical specifications	Mandatory	Mandatory	Possible	Mandatory
7	Control Update: performing the control update/tuning	Not responsible	Possible	Not responsible	Possible

The HVDC system integrator plays a key role in the process, as it is responsible for performing the interaction studies and analyzing results. Furnished models must meet established requirements for interaction studies, so there is a need to coordinate the discussion between different vendors to ensure that. It is possible for the HVDC system integrator to coordinate this discussion, but HVDC system operator(s) must ensure this coordination is effective. Vendors, such as suppliers or manufacturers of the AC/DC converter station and DC grid controls, also play an important role. Certain roles and responsibilities are exclusive to HVDC system operator(s), who act as the customer of the project, while vendors do not typically endorse these responsibilities. Vendors must endorse the validation plan and their agreement, meaning they will be cooperative with the integrator for the interaction studies, especially in the case where the integrator is a competitor vendor or another entity different from the vendor itself like a real-time simulation laboratory.

2.3 Network code: European rules for interaction studies

Commission Regulation (EU) 2016/1447 of 26 August 2016 establishes a network code on requirements for grid connection of high voltage direct current systems (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. The document 32016R1447 (European Commission, 2016) specifies the methodologies for interaction studies at the AC connection point 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". Put in a scheme, Article 29 is concerned about interaction studies between converters at close vicinity in the AC network:

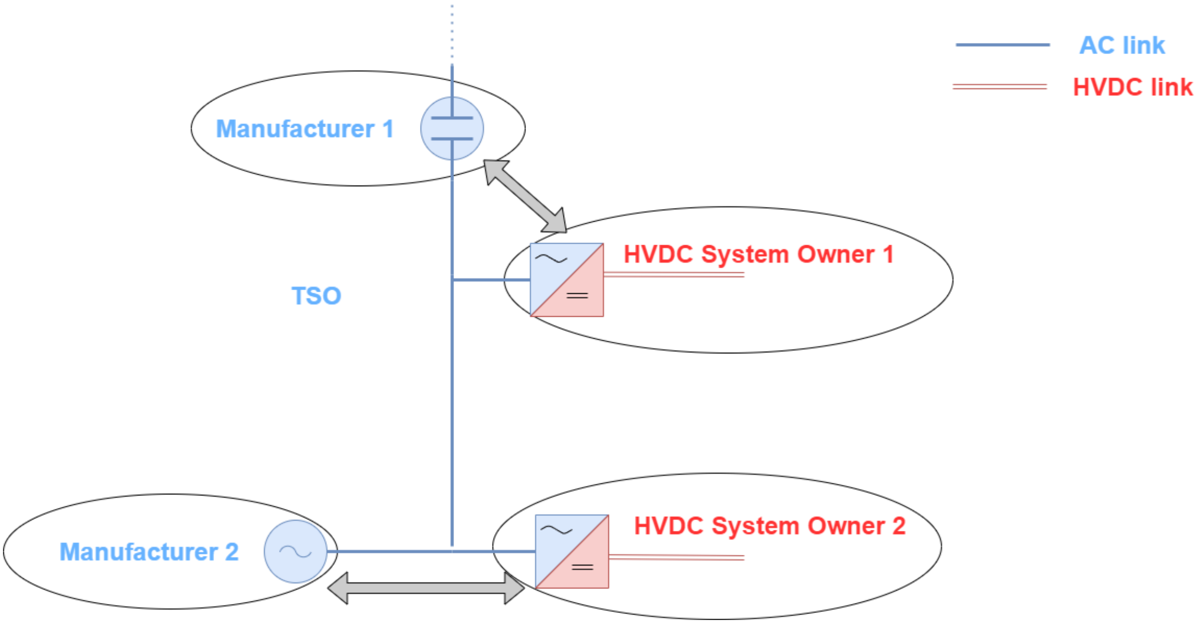


Figure 6. Perimeter of the interaction studies covered in Article 29 of the CR (EU) 2016/1447 of 26 August 2016.

2.3.1 Commission Regulation (EU) 2016/1447 of 26 August 2016

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:

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 of 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.
   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.

2.3.2 Adaptation to DC interaction studies

Commission Regulation (EU) 2016/1447 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. The following Figure 3 illustrates the different interactions and stakeholders involved in MTMV HVDC networks:

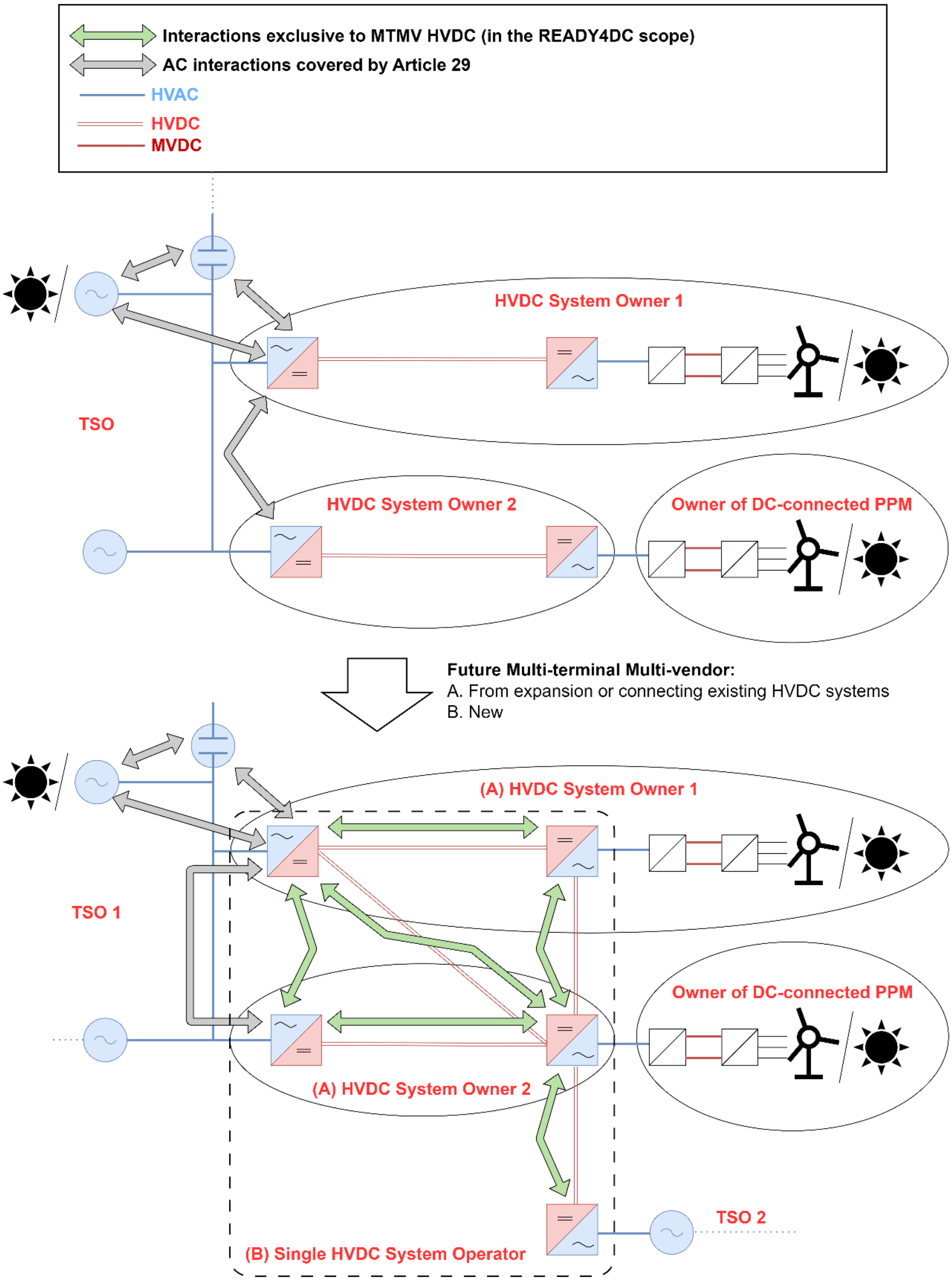


Figure 7.Illustrative scheme for interaction studies considered in CR (EU) 2016/1447 and identified gaps for MTDC grids.

Multi-terminal HVDC networks (MTDC) can be complex and challenging due to the potential for adverse interactions between the various HVDC converters, which may be provided by different vendors. To ensure that the system operates effectively and safely, interaction studies are necessary at the DC connection point. The HVDC Grid Operator, in the case of a new planned MTDC network, or HVDC System Owners, in the case of expansion or interconnection from existing HVDC systems, are responsible for coordinating these studies. They will do this in conjunction with all relevant parties, including TSOs from different countries or zones and vendors of the converters. The HVDC system integrator, which can be made up of owners or operators, vendors, or independent companies, will perform the interaction studies to ensure that the connection meets the requirements of this regulation and that any necessary mitigating actions are taken to protect the integrity of both TSO equipment and that of grid users in a manner consistent with national codes. Table 2 outlines the equivalent roles for interaction studies in the AC and DC domains.

Table 2. Making the parallel with the AC side, equivalence for the roles for interaction studies:

	AC/DC interaction studies today	HVDC MTMV interaction studies
Grid Operator	**TSO**	**HVDC System Operator:** 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.	Depending on how the MTMV system is developed: **- 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	**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.

Table 3 shows the extrapolation and matching of Article 29 from the network code and the proposed interaction studies workflow, specifying roles that should be endorsed by each of the different parties.

Table 3. Extrapolation and matching of Article 29 from network code and the proposed interaction studies workflow. HVDC system integrator is a role that can be fulfilled by HVDC system operators, owners, or vendors. The composition of the integrator depends on each specific context of development of a MTMV HVDC network: new or from expansion.

ID	Art.29	Workflow	**Role** within **studies (Art. 29)**	HVDC Point-to-Point Links in **AC** grids	**MTMV HVDC grids**
1	1	0	Identify the need of a study and its scope/extent	TSO	HVDC System Operator(s)
2	1	5	Identify possible mitigating actions	All parties	All parties
3	2	2	Undertake the studies and inform results to all parties	Connecting HVDC System Owner or TSO if decided otherwise by a Member State	**HVDC System Integrator** or HVDC System Operator(s) if decided otherwise by a European regulator
4	2	0	Identify relevant parties taking part in the study	TSO	HVDC System Operator(s)
5	2	0	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])
6	3	2	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
7	3	1	Collect contributions and models/data, and pass it to study makers where applicable	TSO	HVDC System Operator(s)
8	4	3	Assess the results and request further studies	TSO	HVDC System Operator(s) and **HVDC System Integrator**
9	4	NA	Perform further studies by TSO request	HVDC System Owner	**HVDC System Integrator**
10	5	6	Review or replicate some/all studies and mitigating actions	TSO	HVDC System Operator(s)
11	5	NA	Provide relevant data/models for some/all studies replication	HVDC System Owner	**HVDC System Integrator**
12	6	7	Apply any necessary mitigating actions	HVDC System Owner	HVDC System Owners (supported by vendors)
13	7	0	Specify transient levels of performance for individual HVDC system or collectively across commonly impacted HVDC systems	TSO	HVDC System Operator(s)

The regulation regarding HVDC systems, specifically network code article 29, requires clarification on several points. Regarding 5-2-0, it is expected that the HVDC System Operator(s) will have the ability to choose the party responsible for conducting studies, particularly under the role of HVDC system integrators. These integrators, who initiate the request and possess the necessary expertise, would make recommendations that would need to be approved by a public entity, like the process in which a TSO's recommendation is approved by a national regulation entity for AC interaction studies (such as Ofgem in the UK). The HVDC system integrator may subcontract an HVDC real-time simulation laboratory for conducting or supporting interaction studies. In addition, the replication of interaction studies as outlined in 10-5-6 of the regulation may be feasible in certain situations; however, replicating interaction studies for multiple HVDC systems connected to the grid may prove complex and costly, and may not always be practical. Alternative options, such as using HIL labs with the capability to reconfigure replicas and conducting scattered simulations, are areas of research in the field.

In conclusion, the current legislation is not equipped to fully address the unique characteristics and complexities of MTMV HVDC systems, which could lead to a lack of understanding or underestimation of potential risks and impacts. Studying interactions in these systems is challenging due to the fast electromagnetic phenomena that occur and the need for specialized analysis tools and a deep understanding of converter control interactions.

3 METHODOLOGICAL SCENARIOS FOR MULTI-VENDOR INTERACTION STUDIES

Without going into detail of the type of interaction studies or tool used to perform them, it is possible to analyze several methodological options to perform Interaction studies. With the stakeholder's descriptions and the roles defined in STAKEHOLDERS' DEFINITIONS, we can define several possible methodologies, roles and responsibilities among the main stakeholders involved in the interaction studies. Main stakeholders include vendors, HVDC System Integrator, HVDC system operators and HVDC system owners. For the topic of offline vs real-time studies please refer to section 5. Types of interaction studies and where in the project they are needed are subjects discussed in section 1.

Here are the different scenarios to perform interaction studies regardless of the tools and models used. A description and pros and cons analysis will be provided next:

- **Scenario 1: HVDC system integrator delegates interaction studies exclusively to vendors.** In this option, the vendors are responsible for conducting interaction studies and resolving any interoperability issues. The HVDC system integrator is only involved in coordinating and defining the acceptance criteria and validation plans. While it may also conduct parallel studies on their side, the ultimate responsibility for the outcome lies with the vendors.
- **Scenario 2: HVDC system integrator performs interaction studies with vendors' strong support.**
  In this option, the HVDC system integrator is responsible for conducting the interaction studies. It can be done by the integrator itself (HVDC owners and/or operators) or can be delegated to an independent third party such as HVDC real-time simulation laboratories. While the vendors provide strong support in analyzing and resolving any interoperability issues, they propose and submit solutions. This option requires close cooperation between the interaction studies executor and vendors, with a strong level of confidence among parties.
- **Scenario 3: HVDC system integrator performs interaction studies with vendors' limited support.**
  In this option, the HVDC system integrator has complete control over the interaction studies and solving any interoperability issues. The vendors only provide updated controls according to new specifications and may not actively participate in the solution process.
- **Scenario 4: HVDC system integrator performs interaction studies without vendors' support.** In this option, the HVDC system integrator can manage all aspects of the interaction studies independently, for instance, providing that vendor controls are white boxed. However, this option requires a high level of technical expertise and resources, which may not be available to all HVDC system integrators.

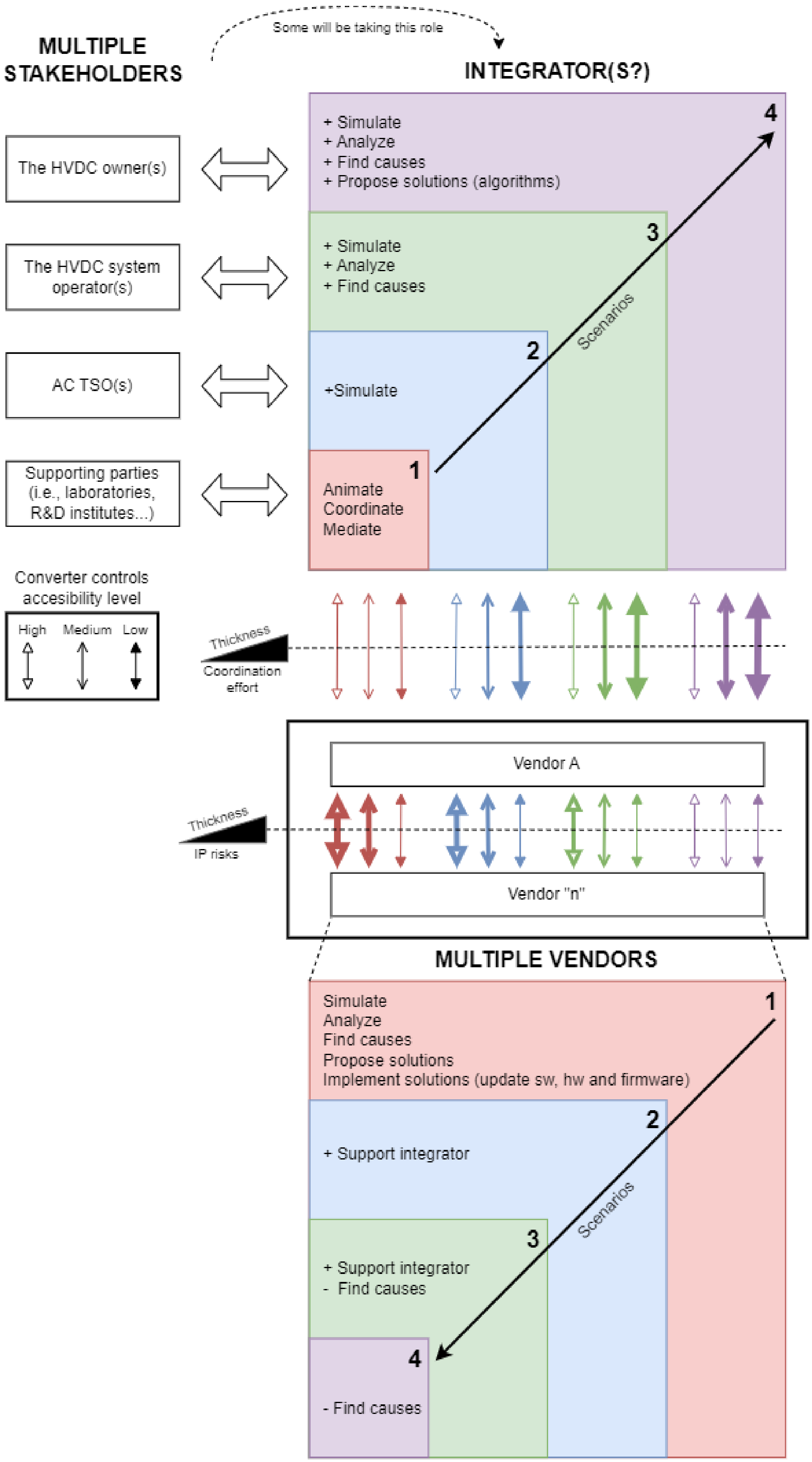


Figure 8. Complexity of MTMV interaction studies scenarios interrelating different kinds of stakeholders.

Table 4 shows the stages of the interaction study workflow and which stakeholders are involved in each stage. It outlines the responsibilities of the HVDC system integrator (which can be the HVDC system owner, operators or a third party) and vendors in scenarios 1,2,3 & 4.

Table 4. Roles of the different stakeholders in the interaction studies workflow for the proposed scenarios.

	Scenario 1								Scenario 2								Scenario 3								Scenario 4							
Workflow step	0	1	2	3	4	5	6	7	0	1	2	3	4	5	6	7	0	1	2	3	4	5	6	7	0	1	2	3	4	5	6	7
HVDC System Owners	X						X		X						X		X						X		X						X	
HVDC System Operators	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
HVDC System Integrator	X	X		X	X				X	X	X	X	X				X	X	X	X	X	X		X	X	X	X	X	X	X		X
Vendors			X	X		X	X	X			X	X		X	X	X			X			X	X	X			X				X	X

Workflow steps:
0- Validation plan
1- Animation
2- Interaction tests
3- Analysis
4- Mediation
5- Solution proposal
6- Solution approval
7- Mitigation action

Scenarios:
1- Integrator delegates interaction studies to vendors.
2- Integrator-led interaction studies with strong vendors' support.
3- Integrator-led interaction studies with limited vendors' support.
4- Integrator-only interaction studies.

Each project may fall on a different scenario, depending on the specific requirements and resources of the HVDC system developer. While choosing a methodology for interaction studies, it is crucial for the developer to clearly identify boundaries: knowing where the responsibility of each stakeholder on each role starts and ends. This will ensure smooth and efficient framework for MTMV interaction studies.

3.1 Scenario 1: closest scenario to current status quo

In this method, the HVDC system integrator is either constituted by vendors or delegate to vendors the responsibility of performing interaction studies on their own, and further tuning their control systems. The vendors are responsible for their control and send detailed models, not generic models, to the other vendors for studies under clear and defined circumstances. This is the scenario described in (T&D Europe, 2022), three stages by Figure 9.

The multi-vendor interaction study in scenario 1 involves vendors sharing required information directly through the HVDC system integrator, constituted by TSOs or HVDC system owners like in Figure 9. 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 study is conducted in three stages:

- 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 by the other vendor(s).
- 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).

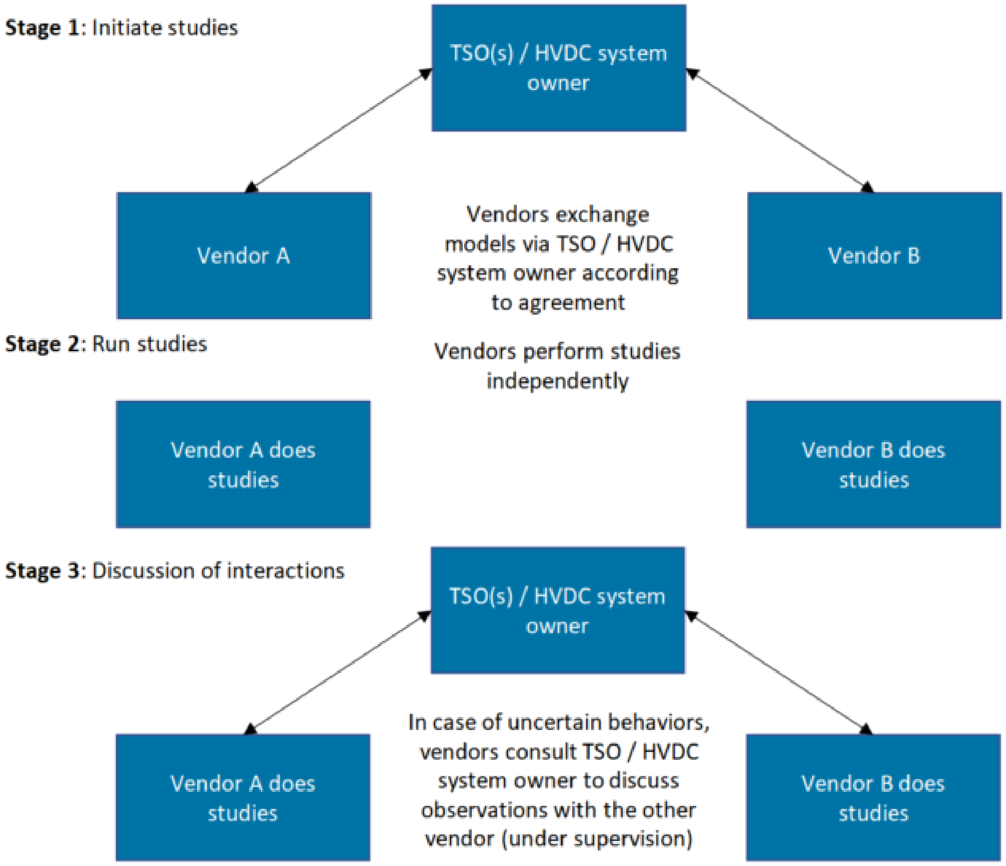


Figure 9. Integrator, here represented by TSOs and/or HVDC system owners, delegate interaction studies to vendors, who due to IP protection prefer to perform interaction studies independently, exchanging respective, black-boxed models.

In the event of an unresolved issue, an external mediator may be assigned by the TSOs or HVDC system owners (integrator) to coordinate the discussions between the vendors. Vendor IP protection is guaranteed through the signed agreement and NDA. This option does not prevent the HVDC system operators (TSOs operating the DC system) to replicate studies on its own to verify/validate the outcomes.

3.1.1 Advantages

In scenario 1, the vendor is responsible for performing the studies, reducing the number of entities involved in the process (this may only be valid if a few vendors are involved as it will be seen in a later section about multiplication of vendor exchanges). This means that the vendor has a clear responsibility for the control of the system, differently to when the control is tuned by a third party, in which case the vendor does not take responsibility for that tuning. Additionally, this scenario also reduces the time and risk effort needed for the whole process, as everyone participates.

3.1.2 Drawbacks

There are also several drawbacks and challenges associated with scenario 1. One of the main challenges is the potential for legal issues when sending a model to a competitor, even through the integrator. The vendor is implicating that they will perform studies with the other vendor’s models, and this raises questions about how detailed and realistic the model given to another vendor must be. Everything must be specified in a legal contract to ensure models protection, but this still requires a significant amount of legal protection between all vendors. This method has not been experienced before, thus integration in simulation tools of other vendors' models is a significant challenge.

Another challenge is the technical difficulties that may arise when one vendor updates its control and the others need to retrieve these new releases. Multi-lateral maintenance contracts need to be set in place to avoid the risk of an HVDC company leaving and not being able to retrieve these releases. Since HVDC market perspectives are positive, this risk should be considered low.

Another issue is defining the responsibility of vendors in case of issues after the engineering phase, such as a few years after commissioning for post-failure analysis. The TSOs are concerned that vendors may not feel responsible, or they may put the responsibility on others. Vendors on their side have no interest on delivering converter stations that are not running, as it would impact their credibility. To avoid this, mediation through the integrator is important, as well as multi-lateral maintenance and support contracts of vendors with the integrator body (HVDC owners and operators).

Finally, there is a concern about integrators, especially HVDC system operators, losing information about the system if they do not perform the interaction studies. They could and should replicate the studies with vendor models to validate their capability of performing interaction tests. Then, they will need to perform tests on future operating conditions to plan network evolutions.

In conclusion, scenario 1 seems to have several challenges or points of attention to be addressed in comparison to a few advantages, including legal issues, technical difficulties, and responsibility issues. When falling into this scenario, all these needs to be considered and tackled to ensure a successful outcome.

3.2 Scenarios 234: Integrator-led interaction studies

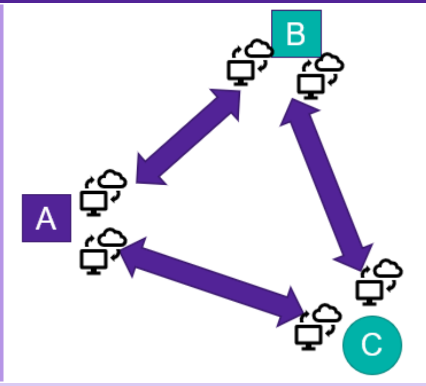
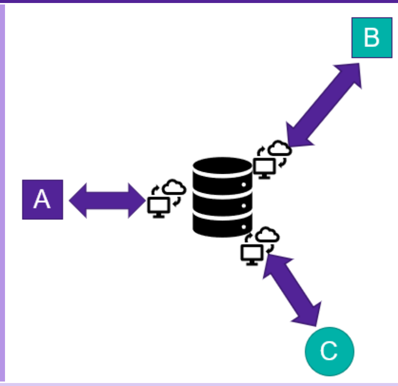
In scenarios 234 integrators are leading interaction studies, not the vendors. That means, integrators can decide if one of the HVDC system owners, HVDC system operators or even a third party is performing interaction studies. As mentioned before, there are three options under this scenario, with different ratios of vendor contribution in the interaction studies (c.f., Table 4). One example is explained in (T&D Europe, 2022) sections 4.2 and 4.3 where it is announced that new regulations in Great Britain will oblige vendors to pass models to a third party under NDA agreement to perform interaction studies. This third party could be a real-time simulation laboratory, but the GB example is just one possibility of how regulators may play a role in establishing rules for MTMV interaction studies in the EU. As reminder, real-time simulation laboratories can be co-owned today by operators or national regulators (e.g., OFGEM), as it is today the case of the National HVDC Centre in GB or at RTE international.

3.2.1 Potential advantages

The use of an integrator in HVDC systems has several advantages, including:

1. **Reduced flow of Information:**
   The need for vendors to send their models to other vendors is eliminated, which could reduce also the number of model integrations and communication links between stakeholders compared to an option with less involvement from an integrator. For example, in a case with three vendors the number of model integrations would be reduced from 6 to 3, as shown in Figure 10. This means

that the size of the HDVC system has less impact on the complexity of arranging interaction studies, both from legal and technical point of views.

	Vendors as integrators (scenario 1)	Scenarios with HVDC system integrator (234)
		
N: number of vendors	*3, 4, 5**	*3, 4, 5*
Number of model integrations	$= N(N-1) = 6, 12, 20$	$= N =$ *3, 4, 5*†
Number of communication channels	$= \binom{N}{2} = \frac{N(N-1)}{2} = 3, 6, 10$	$= N =$ *3, 4, 5*†

**Relative impact of this comparison criteria, it depends on the likelihood of more than 3 vendors being involved in the same MTMV project.*

† Uncertain numbers since a pending vendor concern is whether the integrator role will effectively remove vendor roles such as integration testing. Vendors claim that under any scenario, vendors must re-validate through integration tests the modifications of the system.

Figure 10. Comparison of integration scenarios for interaction studies in a three-vendor MTMV HVDC system.

2. **Potentially Experienced Integrators:**
   Depending on the composition of the HVDC system integrator (HVDC TSOs, Owners…) and who they delegate to perform system interaction studies (third party real-time simulation laboratories), there is high potential for integrators and associated third parties to accumulate experience in a variety of multi-terminal projects and with a wide range of distinct vendors over time. This would result in smoother and more efficient interaction studies (the composition and roles of integrators and third parties are still to be explored in the InterOPERA project, for example).
3. **Expansion Project Support:**
   Integrators may be necessary for expansion projects on a pre-existing HVDC network, where the participation of historic vendors may be limited.

3.2.2 Potential drawbacks

However, there are also some drawbacks to consider, including:

1. **Increased Costs and Extended Project Duration:**
   In scenarios 2, 3, and 4, there is a dependency on the integrator to successfully identify and solve interaction issues. The integrator may have a low stake in the project in comparison to vendors, Hence, owners may have to engage the vendors anyway, leading to added costs and prolonged project duration. Thus, even if feasible, scenario 2 has the risk of being less effective than scenario 1 if the integrator is not a responsible or high impact stakeholder.
2. **Time-Consuming Issue Replication:**
   Vendors participating in scenario 2 may need to recreate the issue to provide a resolution, which could prove to be time-consuming and may not always be necessary. However, this step may be viewed as necessary to ensure confidence in the recommended solution.
3. **Challenges in Understanding the Entire System:**
   In scenarios 3 and 4, it may be challenging for the TSO or third-party integrator to comprehend the entire system, leading to difficulties in accurately determining the source of interoperability issues. Vendors' cooperation may still be required for role analysis in scenario 3.
4. **Difficulty in Tuning All Controllers:**
   In scenario 4, it may prove difficult for a single third-party integrator to tune the controllers from multiple vendors. Some functions may need to be made accessible, which may raise security concerns.

3.3 Assessment of scenarios against interaction study tools and project phases

When considering the alternatives to scenario 1, where the integrator is one of the vendors, it is important to assess the potential drawbacks of scenarios 2, 3, and 4. These drawbacks may include increased project costs and duration, difficulties in identifying the source of interoperability issues, and challenges in tuning the controllers from all vendors. It is crucial to carefully evaluate each scenario based on its specific advantages and disadvantages to determine the most suitable option for a given MTMV HVDC system.

The type of tools (SIL or HIL) and timing inside the project (specification or post-tender) are also very important factors to consider. Case studies (T&D Europe, 2022) conducted in the UK (the HVDC Centre) and France (RTEi Lab) are mainly focused on interaction studies conducted in HIL environments, although it is possible to perform interaction studies at earlier stages of development and during the operational lifetime of the system. This offers the opportunity for a wider range of entities to contribute to interaction studies and increase understanding of new interaction issues. For instance, offline simulation studies use typically generic models conceived by experts (from TSOs, academia, labs, vendors…). When these studies include software certified by vendors (they consider them to be representative replicas of the real software) then it can be used to perform interaction studies in a Software-in-the-loop (SIL) real-time simulation. This software is then integrated in the real hardware to be installed in the HVDC system; its replica can be used for interaction studies in a hardware-in-the-loop (HIL) real-time simulation. The following section analyzes the types of studies that can be performed at different stages of an MTMV HVDC project. The following hypotheses were considered for this analysis:

- **Specification and pre-design phases (pre-tender):** vendors cannot be considered at this stage, thus, interaction studies can only be performed by an integrator (scenario 4).
- **Design phase:** the detailed design and engineering oversees vendors and EPCs, only scenario 1 is possible, integrators performing interaction studies at this stage may be considered redundant and not effective.
- **Validation phase:** system design is validated by upgrading interaction studies done in specification and pre-design phases by realistic models. It is possible for all stakeholders to perform interaction studies.
- **Running stage:** system installed and running, any stakeholder can perform interaction studies according to the tools/methods at their disposal (models, replicas, SIL, HIL, etc...).

3.3.1 Specification and pre-design phases (pre-tender)

The specification phase is a critical step in the preparation of functional and technical requirements for the MTMV HVDC project. During this phase, feasibility and pre-design studies are performed in preparation of functional and technical requirements. Various simulation studies can be conducted to understand the interactions between the different components of the system. These studies can help to identify potential issues and to specify the requirements for interoperable systems.

If interaction studies where to be made during this stage, **scenarios 1,2, or 3 are not applicable**. Indeed, this phase is expected to happen before the vendors have been selected by the HVDC system operators and owners.

Contrarily, scenario 4 may be considered: HVDC operators and owners could perform interaction studies using any of these tools under scenario 4 as follows.

3.3.1.1 Offline SIL: use of generic offline models

Only applicable to **scenario 4**, it could be possible to anticipate interaction studies using generic models known by control experts. These studies can help to understand interactions between different control structures and to specify the requirements for interoperable MTMV systems already from the specification phase. 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 systems. Additionally, the use of a variety of models will enable operators and owners to understand the sensitivity of interactions against different types and combinations of models within the same MTMV grid. As the massification of these types of systems occurs, it is expected that the models will improve over time, much like it happened with the models of every component in the AC system. The HVDC operators and owners can consult all vendors to provide models for pre-qualification by the integrator in the specification stage, as was done in the GB model. Overall, while the use of offline SIL with generic models may have some limitations, it can still provide valuable insights during the specification phase of a MTMV HVDC project.

3.3.1.2 Real-time SIL: use of real software replicas

This method of interaction studies is only applicable to **scenario 4**, where HVDC system operators and owners act as integrators to conduct interaction studies within real-time simulation setups including replicas of vendor software (running in generic hardware) to address potential issues with multi-vendor interoperability. However, several considerations need to be taken into account, including the following:

- The interest and potential benefits of using real software replicas for interaction studies need to be validated or justified, particularly for converter or grid control, to ensure that this method can uncover new kinds of interaction issues that cannot be detected using generic offline models.
- The interest of performing such studies at the specification phases also needs to be justified to ensure that they provide value in the early stages of the project.
- Integrators must have access to the necessary vendor replicas of the software, and the feasibility of the study will depend on the integrator's experience and the number of software replicas they have in their inventory.
- The likelihood of vendors allowing the integrator to provide and/or reconfigure software replicas for testing interactions in other systems also needs to be assessed.
- The risk of using pre-existing software in the generation of opportunities for innovative technologies and solutions and the exclusion of vendors whose software is not already in the integrator's inventory and can thus not be pre-qualified also needs to be considered.

3.3.1.3 Real-time HIL: use of real hardware replicas

Only applicable to **scenario 4**, it may be possible for HVDC system operators and owners acting as integrators to use hardware replicas perform interaction studies and 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 it may also limit opportunities for innovation as hardware replicas may be outdated versions with older functionalities.

It is worth to mention that depending on the specific context for the HVDC MTMV development, the usefulness of these three tools in scenario 4 may be analyzed differently. It could be indeed the case for when a MTMV system evolves from existing HVDC links rather than being a completely new system design.

3.3.2 Design phase

During this phase, converters are designed to operate in a MTMV grid setup. In a MTMV set-up, each vendor would be expected to design its own converter. In a MTMV system where the links are existing already, this design phase would be more related to the re-configuration of converters so that they admit a new system constraint (the new interconnector) smoothly. In any case, the design or re-design of the converters will be required.

Another system that must be integrated and designed is the DC grid control, which usually is not expected to produce interactions. Interactions happen usually at the very physical level and are produced by control interactions at lower levels. However new kind of interactions not seen at the transient level but maybe at a static or dynamic levels could arise depending on how the DC grid is controlled. These kinds of interactions are more related on how the DC grid manages the control modes of converters, the different set points and roles to ensure proper dispatching and repartition of roles of converters. This may not fall into the definition of interaction studies defined for this whitepaper and are most certainly issues to be addressed in the overlapped InterOPERA project.

3.3.2.1 Offline SIL: use of generic offline models

In **Scenario 1**, interaction studies using generic models can begin once the vendors have been identified (T&D Europe, 2022). The vendors and HVDC system integrator can exchange generic models of the real converters to identify any interaction issues in the design and software before the hardware is built. This will help to validate the design and reduce the potential sources of interaction issues. In **Scenarios 2 and 3**, and **4**, interaction studies by integrators may be redundant with those of vendors during the design stage.

3.3.2.2 Real-time SIL: use of real software replicas

In S**cenario 1**, interaction studies can be conducted using real-time software replicas from vendors once they have been identified (T&D Europe, 2022). The vendors and HVDC system integrator can exchange real-time software replicas of the converters to identify any interaction issues and validate the design. This will further reduce the potential sources of interaction issues. Indeed, software replicas may be ready earlier than hardware replicas, and may procure an easier black-boxing method. In **Scenarios 2 and 3**, and **4**, interaction studies by integrators may be redundant with those of vendors during the design stage.

3.3.2.3 Real-time HIL: use of real hardware replicas

In the case of MTMV developed from expansion of an existing system, vendors in charge of designing the system could decide to make partial use of HIL testing for instance using replicas from existing system. In **Scenarios 2 and 3**, and **4**, interaction studies by integrators may be redundant with those of vendors during the design stage.

3.3.3 Validation phase: multi-vendor conformity checks and commissioning tests

The validation of the design is an important step in the development of the MTMV HVDC project, as it is an opportunity to test the functional and performance of the software and hardware.

3.3.3.1 Offline SIL: use of generic offline models

Possible by all stakeholders depending on availability of tools and methods.

3.3.3.2 Real-time SIL: use of real software replicas

Possible by all stakeholders depending on availability of tools and methods.

3.3.3.3 Real-time HIL: use of real hardware replicas

In **Scenario 1** it is possible; this is the purpose of a hardware replica. 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 **Scenarios 2, 3 and 4 it is** also possible. 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. Support can be either strong (2), light (3) or no support (4) for interaction studies.

Depending on the choice of methodology (2, 3 or 4), vendors would still need to have access to their control cubicles to troubleshoot the interoperability issue or test an updated version of the control. To do so, it is possible to provide vendors with remote access to different workstations into 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. For instance, this methodology is used for instance in the RTE-international laboratory.

In another example, the methodology used in China for multi-vendor support and maintenance involves the following steps. First, the vendors test their equipment on their own side. After that, the vendors provide their equipment to a third-party (like the integrator) for further analysis. The third-party keeps a replica of the equipment to handle any post-commissioning studies. Vendors send their engineers to tune the controllers. In this case, the vendors are responsible for the tuning of the controllers. In the event of an interaction problem, the three possible scenarios 2,3 and 4 compare as follows:

- **Scenario 2:** the integrator shares the data for analysis with the vendor. The third-party analyzes the results and presents them to the vendor along with the relevant data and information. The vendor then understands the problem, proposes a solution and updates the control.
- **Scenario 3:** the integrator analyzes the interaction problem itself and applies a solution only if the solution requires high-level control tunning. Otherwise, it is still able to identify the solution and deliver a new specification of control to the vendor. The vendor updates the control and delivers the new control version.
- **Scenario 4:** all of the above but the integrator can now propose control modifications by itself. In this scenario, the vendor control model needs to be tunable and accessible to a certain level, meaning that a certain set of control parameters must be accessible and defined in advance for updating.

3.3.4 Running system: multi-vendor support and maintenance

In a running system with multi-vendor support and maintenance, the focus is on ensuring that all the components and systems from different vendors are functioning optimally and efficiently. To support a multi-vendor system, organizations typically have teams that are trained in the specific systems and technologies used, as well as a clear understanding of how the components interact with each other. Regular maintenance activities such as software updates and security patches are also critical in a MTMV system to maintain optimal performance and protect against security vulnerabilities. Organizations need to have processes in place to manage the maintenance of multiple systems from different vendors to minimize downtime and ensure that systems are kept up to date with the latest software and security features.

3.3.4.1 Offline SIL: use of generic offline models

It is possible in **Scenario 1** to perform offline studies by vendors to replicate interaction issues observed in real operation. If one single vendor is performing the study, this vendor needs to have black-boxed offline models from other vendors. Also possible for **Scenario 2, 3 and 4** by a HVDC system integrator who assumes responsibility of the interaction studies at this phase using offline generic models endorsed by vendors to replicate and investigate real interaction phenomena.

3.3.4.2 Real-time SIL: use of real software replicas

All scenarios are possible by using software replica to avoid using HIL which may be more difficult. Trying to replicate interaction issues observed in real operation. Can be done by vendors alone in scenario 1, or with different levels of support to integrators in 234.

3.3.4.3 Real-time HIL: use of real hardware replicas

All scenarios are possible using and maintaining the HIL lab to try replicating interaction issues observed in real operation and try mitigating actions in field conditions. Can be done by vendors alone in scenario 1, or with different levels of support to integrators in 2, 3 and 4.

3.4 Summary and recommendations

Table 5 resumes all pros and cons of the methodological options discussed in this section. The table is pre-filled, from authors appreciation, but it is to be refined by stakeholders wanting to engage in this analysis (notably form WP1, READY4DC and InterOPERA participants).

Scenarios 1,2,3 and 4 have been proposed to describe the organizational and decision-making responsibilities of the stakeholders involved in the interaction studies workflow. There is another perspective to be considered from a technical point of view. Indeed, interactions are strongly linked to converter controls, originated by physical interactions but highly influenced and even amplified by the control software. Modular multi-level converters are the dominating technology in today's implementation of HVDC transmission.

*Table 5. Risk analysis of the proposed methodological scenarios. *New scenarios require more analysis to assess.*

Scenario	1	2	3	4
Complexity of legal framework	Medium	Unknown*	Unknown*	Unknown*
Risk for IP confidentiality	Low	Low	High	High
Risk increasing redundancy of the studies	High	Medium	Medium	Low
Maintainability complexity after commissioning	Medium	Medium	Low	Low
Clear share of responsibility	Low	Medium	High	High
Number of communication loops	Low	Medium	High	High

1. Integrator delegates interaction studies to vendors.
2. Integrator-led interaction studies with strong vendors' support.
3. Integrator-led interaction studies with limited vendors' support.
4. Integrator-only interaction studies.

4 REQUIREMENTS ON MMC CONTROL ACCESSIBILITY

MMC controls are critical components that can impact the power system's integrity, and the role of vendors in supporting this process is vital as they have the most developed knowledge in the development of MMC controls. A balance between the protection of intellectual property (IP) and accessibility to MMC control systems is critical for the future large MTMV MTDC system's integrity. Indeed, the application of the different methodological scenarios for interaction studies presented previously can be affected by the degree of accessibility to MMC control layers. This white paper proposes to study the impact of different scenarios of MMC control accessibility on the methodological scenarios 1, 2, 3, and 4 for performing interaction studies. But first, it is important to recall firstly the main functions inside an MMC converter prior to understand how these can impact the interaction study methodology on each of the previous scenarios.

This section offers another perspective on how main stakeholders in the interaction studies as depicted in the workflow will be impacted in performing such studies by the level of accessibility of MMC converters. This includes determining what parts of the MMC control model are provided by a manufacturer of the converter stations, what is provided by another entity (such as an integrator or DC Grid controller manufacturer), and what is accessible in the control functions provided by the converter station manufacturer.

MMC functions can be classified according to their proximity to the MMC hardware, those being close to it are low-level functions and can impact the integrity of the MMC converter or it's optimum life span, while those at a high-level have more influence on the HVDC system behavior. This is indeed what is proposed in (Jahn *et al.*, 2022) and also the scope of CIGRE Working Group B4.85.

Requirements for model compatibility and clearly defined vendor interfaces are outlined in section Control Model Integration for SIL and HIL Interaction Studies of MTMV HVDC Systems5.3. Additionally, recommendations for the validation of control and component models can be found in section 5.1.2. The current section will provide an overview of the different options available for the distribution and accessibility of control models, along with the pros and cons of each approach. First, a quick recall on MMC control layers.

4.1 Reminders on MMC control functions

The Modular Multi-Level Converter (MMC) control is a key component for the operation and performance of HVDC transmission systems. The MMC control 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. MMC control is 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 control is 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 level of control 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 the valve switching and submodule balancing, modulation, and hardware protection.

Another important feature of MMC control is its flexibility and adaptability. The MMC control system can be customized and configured to meet the specific needs and requirements of the HVDC system. The control 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 MMC control system must be open and accessible, allowing for easy integration and communication with other systems and components. This is especially important in systems that involve multiple vendors and different types of control 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 are recalled.

Table 6. Main levels of control in an MMC and associated control functions.

Level of Control	Main Control Functions
High-level control (outer)	DC Node Voltage Control
	Protection, Supervision, Converter 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 control (inner) Inner High	Internal Converter Controls
	Fast Current Control Loop
	PLL
	Current Regulation
	Phase/Arm Energy Balancing
Inner Low	Valve Switching
	Submodule Balancing, Modulation
	Hardware Protection

4.2 On the degrees of accessibility for MMC controls

Before developing on each degree of accessibility, a concise definition of the proposed degrees of accessibility for MMC controls is provided hereunder:

1. **Low-degree:** the vendor provides black-boxed control at all levels of the converter station. This vendor is responsible for understanding, developing, and providing all converter control layers. For interaction studies, the vendor ensures providing interfaces that are necessary for DC grid coordination and control. In case of interaction issues, since the control structure is not accessible, only this vendor can do propose and apply modifications to solve the issue.
2. **Medium-degree:** the vendor provides a minimum level of access and parameterization of the control by another party. In this case, vendors need to develop functions, interfaces, and documentation to enable an integrator to modify the configuration and parameterization of the converter control. This allows for some degree of customization and optimization of the system.
3. **High-degree:** there is a split of layers at some level of the converter control, the splitting criteria is still matter of research, e.g., (Jahn *et al.*, 2022). One of the options for this splitting is to split functions into hardware relevant and system relevant. Hardware relevant functions in this scenario remain visible only for the vendor. On the contrary, system relevant functions could be

visible to enable integrators to co-design these layers and propose algorithms with the aim of solving interaction issues.

For the sake of higher clarity Table 7 highlights relevant functions to the hardware and system and describes some of the stakeholders' responsibilities for each degree of MMC control accessibility. It shows to which extent the controllers can be provided by station manufacturers or other entities such as an integrator or a DC Grid controller manufacturer.

Table 7. Options for repartition of system relevant functions (outer loops) in a MTMV HVDC.

Degree of accessibility of MMC control	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, with reconfigurable parameters accessible to integrators
High-degree: High-level MMC controls can be co-designed/modified by an integrator.	Provided by station manufacturer as black boxed functions	Provided by manufacturer as white-box functions to integrators

4.2.1 Low-degree: full-vendor approach

In this option, the converter station manufacturer is fully responsible for the MMC control, and the control functions are not accessible to external entities (black-boxed). This means that if an integrator is performing interaction studies with these black-boxed models, it can only manage interoperability issues by requesting control modifications from the vendor.

However, with the use of a DC grid controller (even if it is supplied by another vendor), some parameters may be accessible, and the DC Grid controller may have input initial schedules that the integrator can change to validate the entire system. Relying on the tunable parameters of the DC Grid controller alone may not always be enough to solve an interoperability issue, in which case the control model would still need to be modified.

The integrator, on the other hand, is a third-party entity that is responsible for coordinating the different vendors involved in the HVDC project and ensuring that the system is integrated and functioning properly. The integrator may also be responsible for performing simulations and analyzing results to identify and solve interactions issues. In low degree, the HVDC owner may have limited involvement in the control update process but would need to ensure that the data sharing, and legal protection/framework is in place for the vendors to properly update and provide appropriate control models/replicas.

The HVDC system operator and the integrator could have the responsibility of managing and coordinating the different vendors involved in the project, such as the converter station manufacturer and the DC Grid controller supplier. The integrator, who is responsible for ensuring the interoperability of the different systems and components, works closely with the HVDC operator to ensure that the control functions meet their specific needs and requirements.

The DC Grid controller, which is supplied by a vendor, provides access to certain parameters and an interface for the integrator to adjust and fine-tune the control functions. The DC Grid control receives inputs from an AC/DC dispatch center with operator initial schedules, control modes, etc. so that the integrator can adjust these input values and validate the overall system performance. This allows- for more flexibility and control over the MMC control architecture, while still utilizing the expertise and knowledge of the vendors.

When it comes to MTMV interaction studies, the following tasks can be performed by the integrator or HVDC system operator and vendors:

Table 8. Limitations for stakeholders participating in interaction studies in case of low-degree control accessibility.

ID	Workflow activity	Vendor	HVDC System integrator
2	**Simulations:** Performing all case studies	Possible	Possible
3	**Analysis:** Analyze simulation results in case of interactions issues	Possible	Possible
5	**Solution:** Recommending control update	Possible	Very Limited
7	**Control Update:** Performing the control update/tuning	Possible	Impossible (needs to ask vendor)

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

Three options for editing the MMC control parameters are possible:

- **Configuration tool:** an easy-to-use interface designed for the integrator. This tool includes consistency checking, calculation of secondary parameters, a button to reset all functions to the vendor's initial tuning, and a tuning guide for editable functions. The tuning guide provides the integrator with a detailed description of each editable control parameter and the functional behavior of the corresponding control function. This guide should include information such as the inputs and outputs of the function, the range and limitations of each editable parameter, and the impact of each parameter on the function and the overall system. The tuning guide can be a valuable resource for the integrator when adjusting control parameters and understanding the behavior of the MMC control architecture.

- **Simple Mask:** a user-friendly interface for editing parameters.
- **Using Input Pins:** used in the Johan Sverdrup project.

Table 9. Pros and Cons of Options to Edit MMC 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.			

4.2.1.1 Advantages

This option has several advantages, such as an optimized software/hardware interface between the MMC control and the rest of the system, and vendors having the best expertise on MMC control. Additionally, vendor IP is protected and control delays inside the power electronics control are optimized.

4.2.1.2 Drawbacks

However, there are also some drawbacks to this option. Since converters control functions are black boxed, in scenario 1, it complexifies the development of a stable control and protection grid strategy for the different vendors. For scenarios 2,3 and 4, it also hardens the ability of integrators to understand and solve interoperability or interactions issues. Any interaction issues would require vendors to update and send their control according to depicted solutions, which increases the amount of back-and-forth communication and trials. Establishing clear protocols for communication and data sharing between the integrator and the vendors would reduce the time to send and receive models to minimum. However, the coordination among different parties, the legal aspects, and the testing and validation of the proposed solution altogether can be cumbersome and time-consuming.

4.2.2 Medium-degree: accessible functions parameters

In this option, the control of the MMC remains with the converter station vendor, but some of its functions and parameters are accessible for testing new control parameters under vendor supervision. Additionally, some internal signals can be accessible for debugging purposes, allowing the integrator to perform a portion of the analysis and troubleshooting process. The integrator can change some control parameters, but the responsibility for tuning the control remains with the vendors. The integrator can only make recommendations and apply vendor updates. Selection of accessible parameters and signals will be based on a compromise of the following criteria:

- Ease of debugging and troubleshooting
- Importance of the parameter in solving interaction issues
- Risk of disclosing intellectual property (IP)

The table below outlines what part of the MTMV interaction studies can be performed by the integrator or vendor in this option.

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	**Simulations:** Performing all case studies	Possible, but with higher risk of IP disclosure to other vendors	Possible
3	**Analysis:** Analyze simulation results in case of interactions issues	Possible	Possible
5	**Solution:** Recommending control update	Possible	Possible but limited based accessible parameters and level of reconfigurability
7	**Control Update:** Performing the control update/tuning	Possible	Possible but limited based accessible parameters and level of reconfigurability

4.2.2.1 Advantages

Low-degree represents the current approach in which the responsibility of the solution lies solely with the vendors. Medium-degree, on the other hand, increases the capacity of an integrator to analyze the outcomes of the simulations and try to solve interaction issues by itself. Both options share some advantages.

One of the main shared advantages between both options is the proximity to the HVDC-links turnkey solutions, for which vendors are used to have full control over modifications at every control layer. This also optimizes their ability to improve software and hardware interfaces between the MMC control and the rest of the system. Additionally, vendors are currently the most knowledgeable about MMC control and have the most expertise in this area. This can ease improvement and optimization of control delays within the power electronics control.

A specific advantage of medium-degree is that the integrator gets more access to the control. This means that studies can be completed more efficiently, as in some cases, it may not be necessary to regenerate a model and obtain it from the vendor. Instead, the integrator can directly update the parameter value specified by the vendor. However, it is important to note that in some cases, tuning a parameter may not be sufficient and it will still be necessary to regenerate and re-send the updated model. Troubleshooting is also facilitated, especially in medium-degree-1, as it allows for a more streamlined and efficient process.

The involvement of an integrator represents a new player in the traditional TSO/Vendor project development process, which may not be required in a point-to-point configuration. However, in a MTMV project, the presence of an integrator can offer benefits by streamlining communication among stakeholders through centralization of interactions, as depicted in section 3.2.1.

4.2.2.2 Drawbacks

The use of vendor control in the integration process can have several disadvantages for integrators. Firstly, the limited level of accessibility may not be sufficient for integrators to understand and solve interaction problems. This can hinder their ability to carry out their tasks effectively and efficiently. Additionally, vendors may choose to give access to certain parameters without fully describing them if they are deemed sensitive, further complicating the situation for integrators.

Another issue is that it can be unclear whether a problem is caused by the vendor's initial tuning or the integrator's adjustments. This can make it difficult for integrators to identify and solve interaction problems. Moreover, integrators may only be able to change parameters under vendor supervision, which can limit their ability to solve problems on their own. Furthermore, integrators may have low expertise in MMC control, which can make it challenging for them to improve or solve interactions problems independently. They may also have to rely on vendor supervision or recommendations to make changes, which can create additional limitations.

There is also a risk of disclosing some intellectual property when using vendor control. This raises questions about whether this risk is worth taking and whether vendors would want to reveal more information than necessary. The real IP risk involved is the possibility of a different vendor suspecting patent infringement when the results of studies, performance, and responses are shared and analyzed. This can lead to legal proceedings, consume significant resources, and incur costs for the accused party. However, the T&D Europe white paper mitigates this risk by providing guidelines and recommendations to avoid such IP infringement. Therefore, it is important to consider the T&D Europe white paper as a comprehensive reference to minimize the IP risk involved in integration and interaction studies.

Finally, maintaining and testing the interface to give access to certain parameters can be an additional burden for vendors, especially in medium-degree-1 and B-2, where vendors are required to provide a user interface. This extra work can increase the workload for vendors and decrease their efficiency.

In conclusion, Medium-degree increases the capacity of the integrator to analyze the outcomes of the simulations and try to solve interaction issues, while some functions and parameters remain controlled by the vendor. Medium-degree-1 provides the best advantages as it offers a configuration tool with a high level of usability, readability, and assistance in troubleshooting. The integrator can make recommendations and apply vendor updates but the responsibility for tuning the control remains with the vendors. This high-degree brings additional advantages to the MMC control interaction studies, such as improved control efficiency and the presence of a new party to understand the system. However, the limited level of accessibility may have disadvantages for integrators.

4.2.3 High-degree: part of the MMC control designed and implemented by an integrator.

In this scenario, the upper-level MMC control functions are designed and implemented by a third-party integrator, who will then be able to specify the grid control at different levels (including DC grid control level) to vendors to further design their system with reduced risk of interactions. The converter station manufacturer is responsible for only the low-level control. Throughout this section, the term "integrator" corresponds to the definition given in STAKEHOLDERS' DEFINITIONS.

As depicted in the figure below, the ideal situation would be to have system-relevant functions exclusively in the upper-level control and hardware-relevant functions solely in the low-level control. However, in practice, some low-level control functions can affect the system, and conversely, some upper-level control functions can also have an impact on the hardware.

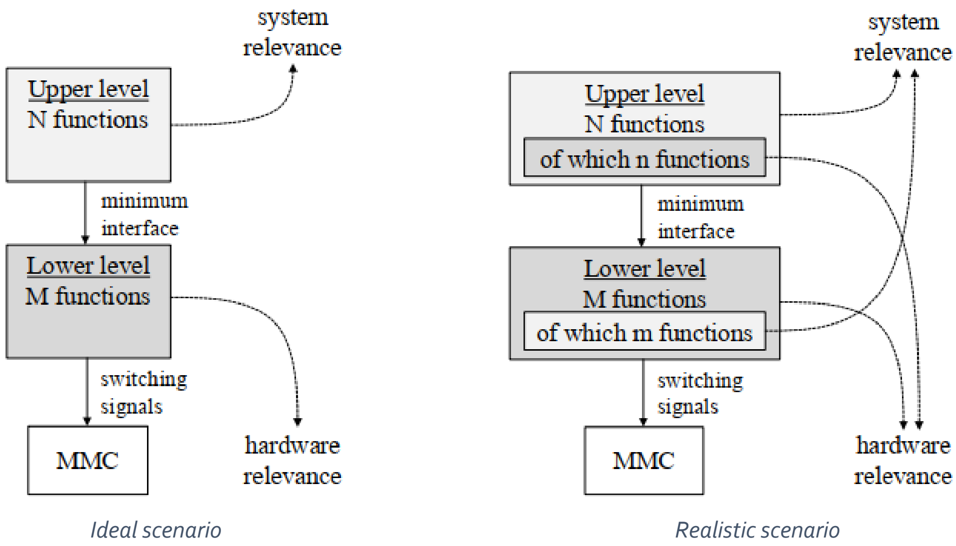


Figure 11. High-level idea of MMC control partitioning (Jahn et al., 2022).

To ensure proper functioning of the system with optimized interactions between the upper-level and lower-level control, it is important to allocate mostly system-relevant functions to the upper-level control and hardware-relevant functions to the lower-level control. A recent graph theory method, as described in (Jahn *et al.*, 2022), has been proposed to achieve this optimized partitioning. Minimizing the physical interfaces between the upper and lower-level functions also needs to be considered. There is a trade-off between functional partitioning and minimizing interfaces, and the graph theory solution in (Jahn *et al.*, 2022) optimizes the partitioning but not necessarily the physical interfaces. One limitation of this approach is its practical feasibility, as the MMC control functions have IP value and cannot be fully shared.

Manual partitioning is also an option, but it can be a long and challenging task as there may be differing opinions on what constitutes upper-level and lower-level functions, and reaching a single partition for all vendors' specific controls can be complicated. There are three variants of manual partitioning:

1. An integrator oversees developing the MMC high-level control functions and has the knowledge and ability to modify it during studies.
2. A group consisting of TSOs, vendors, and academics is responsible for the MMC high-level control. This can be seen as a special case of C.1 where the integrator is supported by other entities.
3. The manufacturer of the DC Grid controller oversees all MMC high-level control system-relevant functions for all stations in the system. All stations would have the same high-level control.

In variants 2 and 3, the integrator has access to some parameters of the MMC high-level control developed by the group or vendor, but this would also result in adding a new hardware and physical interface.

In variant.1, if the control is to be implemented in the hardware of the converter manufacturer, technical and liability issues may arise, such as the responsibility for the hardware and primary equipment, and the cost in case of failure. As a result, even in this variant, the integrator may need to implement the control within a hardware provided by a subcontractor and endorse the full responsibility of this high-level control, like in variants 2 and 3. It is worth recalling that the openness of the high-level control, whether open-source or not, is being analyzed in CIGRE Working Group B4.85 from a more technical approach.

Here is listed which role of the MTMV interaction studies can be done in theory by who in that option:

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	**Simulations:** Performing all case studies	Possible, but with higher risk of IP disclosure to other vendors	Possible
3	**Analysis:** Analyze simulation results in case of interactions issues	Possible	Possible
5	**Solution:** Recommending control update	Possible	Possible and limited to the accessible control functions
7	**Control Update:** Performing the control update/tuning	Possible	Possible and limited to the accessible control functions

4.2.3.1 Advantages

One advantage of this approach is that Interoperability and Performance (interoperability) issues can be anticipated from the design stage by a common entity. This is because functions that are "system-related" are delivered by a specific entity, rather than by each vendor individually. This can lead to a more streamlined and efficient design process.

Another advantage is the possibility of using open-source solutions. This can help to avoid legal and intellectual property (IP) issues surrounding data sharing between vendors. This can create a more collaborative and transparent environment in which to develop and implement the control system.

4.2.3.2 Drawbacks

One drawback of this approach is that it is far from the current architecture of the Multi-Machine Control (MMC) system. This could pose challenges in terms of the integration of the new design into existing systems. Another drawback is the lack of experience of the integrator or consortium in developing MMC control. Integrators need to provide the hardware, otherwise providing only the software on another entity's hardware could cause technical and liability issues. This could be a significant barrier to the implementation of this approach. The addition of a communication layer between the upper-level and lower-level control systems between two different parties could also be challenging. Finally, this approach could limit innovation and competition in the development of MMC controls, as the role of station vendors may be limited. This could lead to a loss of expertise in this area and result in a less dynamic and innovative development process.

One major issue with this option, or any other option where the DC grid control vendor is different from the converter vendor, is the allocation of responsibility and liability for the expensive converter hardware and primary equipment. The integration of software-only control by a third-party integrator raises questions about who is ultimately responsible for the functioning and maintenance of the equipment. The liability of the integrator is likely to be minimal compared to the significant investment made in the equipment procured from vendors. Therefore, in case of system failure or damage to the hardware, it is unclear who will be left with the non-functional system and who will bear the costs associated with any repairs or replacements needed. This mismatch in remits and liabilities could create significant challenges and risks for all stakeholders involved in the project.

4.3 Summary and recommendations

After comparing the three degrees of accessibility of MMC controls to perform interaction studies (in a MTMV context with the participation of an integrator), each option has its own advantages and disadvantages. Low-degree, where the interface between MMC control and the rest of the system is ensured by vendors, offers full protection of vendor IP and the use of their expertise in MMC control, but limits the integrator's autonomy to analyze and propose solutions after performing interaction studies with black-boxed models or replicas. On the other hand, high-degree offers complete accessibility to control functions, ease of troubleshooting, and decentralization of interactions, but requires a higher level of expertise in MMC control by the integrator. Even if medium-degree presents a balance between these two extremes, with increased level of accessibility to control functions, ease of troubleshooting and centralization of interactions, it does not seem an easier option. Indeed, it requires high level of interaction between the integrator and vendor since the level of accessibility of the MMC control is limited to parameters setting and not freedom to modify the high-level control structure.

Ultimately, the best option will depend on the specific requirements and priorities of the project at hand, the number of vendors and how the MTMV HVDC grid is developed. Another example to assess the three degrees of accessibility in function of its advantages and drawbacks is provided in Table 12. This is to be reviewed and not a final assessment of each degree of accessibility.

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

Evaluation criteria	Comments
Incentives technological innovation	No comments yet.
Incentives market competitiveness	No comments yet.
Optimized software/hardware interface between MMC 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 MMC 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 leak.
Optimized control delays in power electronics control	No comments yet.
Integrator's autonomy to analyze outcomes and solve	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

problems, and dependence on vendors	become control experts as well. The higher the level of accessibility to certain control functions, the less dependency of non-vendor integrators.
Burden on vendors to maintain and test interfaces	Responsibility lies purely on vendors when accessibility is at the lowest. It is shared with vendor or non-vendor integrators when accessibility is higher.

Despite the uncertainty of how all these factors will combine, MMC controls understanding is the main axis of development to enable secure and reliable MTDC systems. Thus, it is also important to evaluate the effect of the degree of MMC control accessibility on the various methodological scenarios (1, 2, 3 and 4) proposed for conducting interaction studies. Table 13 gives the compliance and level of adequation of each methodological scenario for each degree of accessibility of the MMC control which has been qualitatively assessed by working group participants.

Table 13. Compliance of scenarios 1234 against different options of MMC control accessibility.

Degree of accessibility of MMC control	Methodological Scenarios for Interaction Studies			
	1-Integrator delegates interaction studies **to vendors**	**2-Integrator-led** interaction studies **with strong vendors' support**	**3- Integrator-led** interaction studies **with limited vendors' support**	**4-Integrator-only** interaction studies
Low-degree	Possible	Not practical[3]	Not practical	Not possible
Medium-degree	Not practical[1]	Possible	Possible	Not practical
High-degree	Not practical[2]	Not practical[4]	Possible	Possible

1. Not practical for vendors as it needs significant effort to develop functions and interfaces to configure converter controls without unveiling the control structure.
2. Not practical in a MTMV scenario to rely on other vendors for interaction studies. Recall the example of 3 vendors, 3 communication channels, 6 model integrations.
3. Not practical for integrators to analyze interaction studies with no clue on MMC control structures.
4. Not practical for integrators having to deal with configuration functions/interfaces from multiple vendors.

Methodological options described by Scenarios 1,2, 3 and 4 are not suited to all degrees of openness/accessibility of the MMC control. A recommendation is that each one of the stakeholders in the project qualify these options at the beginning of a MTMV project, assigning priorities to the more or less advantageous characteristics so that a choice can be thoroughly made considering stakeholders' interests and comfort to deliver their contributions.

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

This chapter aims to provide a comprehensive analysis of the various Electromagnetic Transient (EMT) simulation tools available for conducting multi-vendor interaction studies. The study will focus on two types of simulations: offline and real-time software-in-the-loop (SIL) simulations (5.1) and real-time hardware-in-the-loop (HIL) simulations (5.2).

It is important to recall the main differences between offline and real-time simulation to avoid confusing with terms. An offline simulation will calculate EMT equations solving all equation variables in a time that does not respect the deterministic and constant time step of the simulation clock. On the contrary, real-time simulations will always solve EMT equations faster than the time step window so to be able to deliver variable values in a syncrhonized manner with this time step. This is comprehensively described in Figure 12.

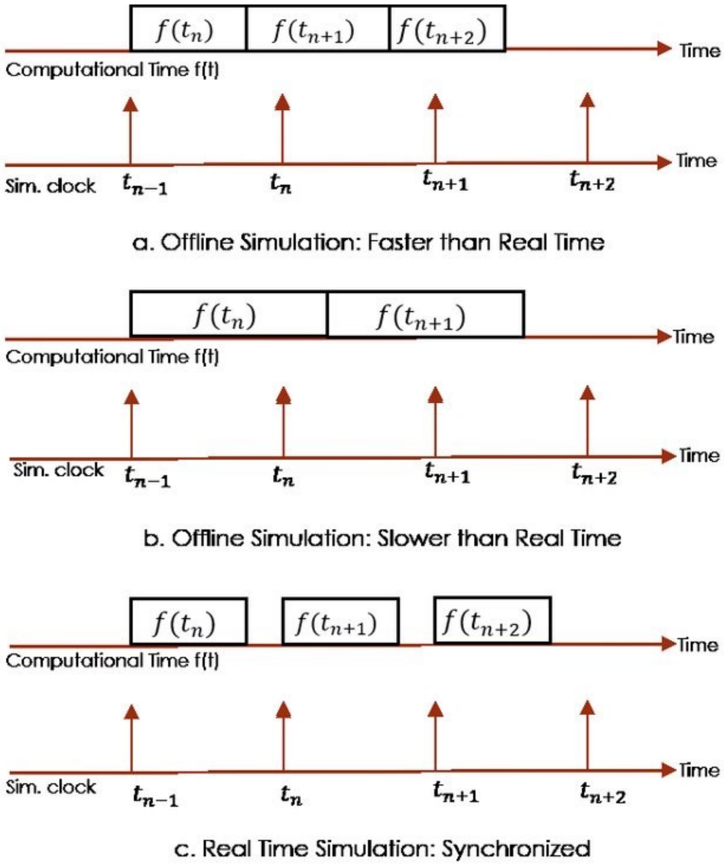


Figure 12. Offline and real-time simulation illustrative meaning from (Noureen et al.*, 2017).*

Indeed, processors performing offline simulations will sometimes be faster and sometimes slower than real-time, but usually slower when it comes to complex power system such as multi-terminal HVDC networks where there are high amounts or non-linearities to be solved. When using real-time simulations, not only the solver must be syncrhonized with the simulation clock rhythmed by the time step. In adition, the time-step of the simulation clock must respect the nyquist rule, meaning that it must be at least two times faster than the studied phenomenon. In MTDC systems this time step is very small, some orders of magnitude of usual EMT simulation time steps compatible with the study of power electronics based systems are illustrated in Figure 13.

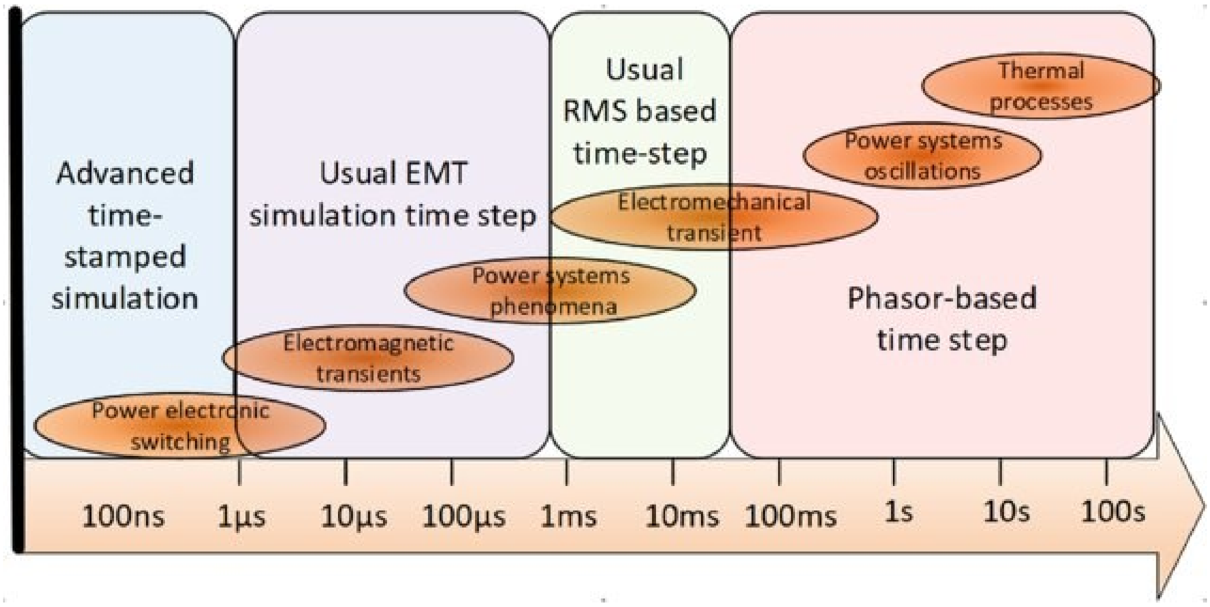


Figure 13. Time step values for different power system studies from (Campos-Gaona and Anaya-Lara, 2019).

In general, performing offline simulations requires less computing power and are thus less costly than real-time simulations, which is why it is important to determine when, by whom and what kind of interaction studies require the use of one or another time of simulation studies.

In this chapter generalities regarding the integration of converter control models for SIL and HIL interaction studies will be discussed in section 5.3. In section 5.4, a comparison will be made between software models and hardware replicas to help determine the most suitable option for a given scenario. Finally, in section 5.5, a summary of the key findings and recommendations will be provided, helping to guide future decisions regarding the use of EMT simulation tools. In this section, we clarify the question of when to use models and when to use replica/cubicle and analyze their respective pros and cons.

5.1 Offline and real-time software-in-the-loop (SIL) simulations

5.1.1 Description

Software-in-the-loop (SIL) simulations are a type of computer simulation used to test the behavior of software models in a simulated environment. SIL simulations can be performed either in real-time- or offline mode, depending on the scope of the interaction study, one or the other will be most suitable and bring the most meaningful results. The two types of SIL studies possible considered in this comparison are:

1. Offline SIL studies without parallelization, running on a computer. Also, the electrical plant and control models run on the same simulator.
2. (Parallelization) Offline SIL studies with parallelization, using several CPUs in parallel on a simulator, but without the constraint of fitting calculations within a fixed time step. The

parallelization can be used to solve controls in different processors, or to segment large system EMT models into smaller portions to perform faster offline simulations.

3. (Parallelization) Real-time SIL studies with parallelization, using several CPUs in parallel on a simulator, with the constraint of fitting calculations within a fixed time step. The parallelization is used here to solve controls in different processors and to segment large system EMT models into smaller portions to be able to ensure real-time.

4. (Real interfaces) Real-time SIL studies with parallelization, as in 3 but this time using real-time to be able to interconnect control and protection algorithms through real interfaces (e.g., industrial protocols).

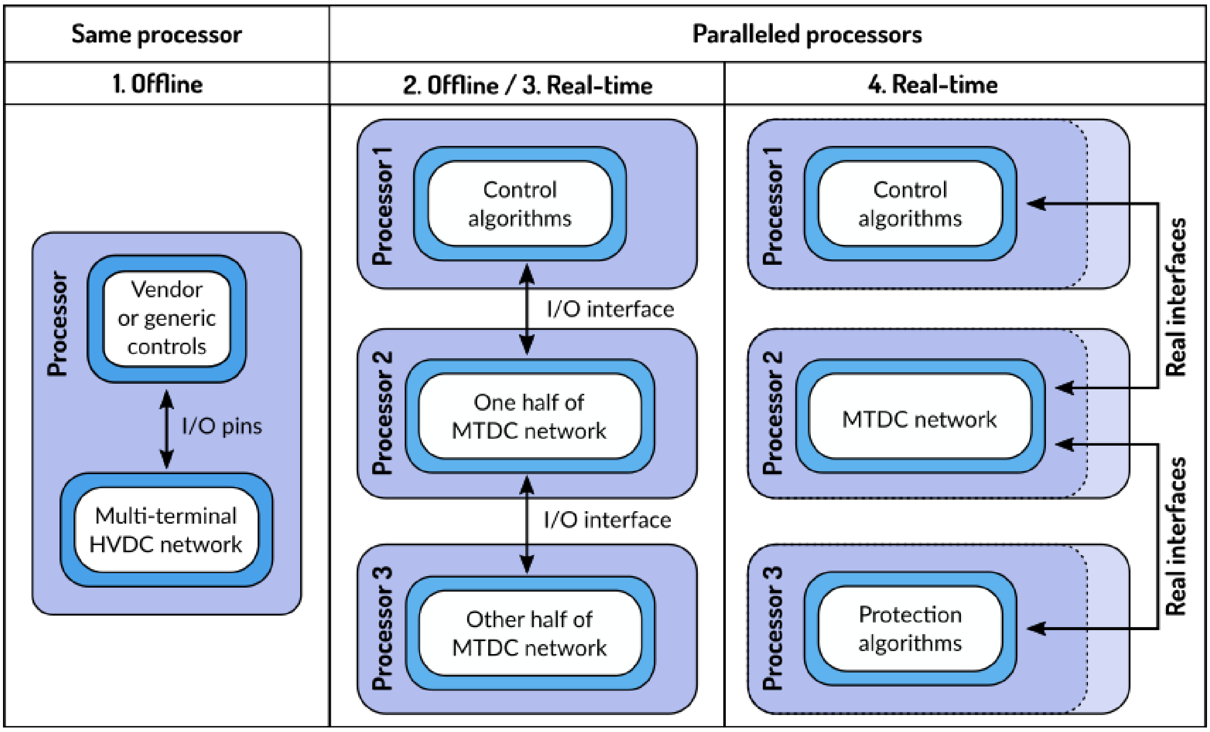


Figure 14. Different possible arrangements for SIL interaction studies with either offline or real-time simulations.

Some advantages of offline simulation compared to real-time are:

1. Significantly lower cost, as it does not require a powerful simulator.

2. Potentially better accuracy of the physical model, as there is no constraint to fit calculations within a fixed time step, allowing for no simplification, solver optimization, or modeling approximations. However, real-time simulators nowadays ensure acceptable levels of accuracy.

3. For systems of low complexity, setting up an offline simulation with minimal training may be easier and faster compared to real-time SIL simulations. The level of difficulty generally increases from arrangements 1 to 4 in Figure 14, with case 4 being the most challenging, as it requires running the plant and control models on separate simulators, which involves configuring the actual communication interfaces. However, for more complex systems, where the time taken to perform an offline simulation is significantly longer than real-time simulation, the total time, including preparation and simulation time, may become interesting in real-time once more.

4. Compatible with black-boxed models provided by manufacturers, which may be a large file requiring a very small resolution time-step. Black-boxed models are more difficult to include in real-time simulations.
5. Solutions providers for offline simulations often offer a software license per computer, which is less expensive and demands lower maintenance than real time simulation licenses. This is mainly due to the hardware and software architecture usually more complex in real-time requiring a more complex licensing and maintenance schemes (one per simulator, one per processing unit in the simulator…).

Advantages of real-time simulation compared to offline:

1. The ability to upgrade the setup into HIL in a modular manner, for instance, replacing one by one the processors dedicated to control with real hardware of control cubicles or protection relays. At some point the simulation will be a mix of models and hardware replicas.
2. Faster simulation speeds than offline tools when using a powerful simulator, in the case of no parallelization of tasks.
3. HIL, enabled by real-time simulation, is the only solution for de-risking highly complex systems that are difficult to model due to the large amount of intelligent electronic devices such as power electronics in large power systems (converter controls, grid controls, protection algorithms, modern communication interfaces). This makes of HIL the best tool for FAT and SAT testing, operation and maintenance support and multi-vendor software and hardware interoperability testing.

The choice between real-time and offline simulation may also depend on the level of detail of the model; for detailed models, real-time simulation may be more suitable due to its faster speed. The option of offline simulation tools running on simulators combines the advantages of accuracy and computational speed. Indeed, real-time simulators have the advantage on running on specialized operating systems that allows for efficient parallelization of EMT calculations, being even able to perform "faster than real-time" simulations (a. in Figure 12).

With advancements in technology, offline simulation tools are becoming faster through parallel computing and high-performance computing. These parallelized tasks can be run on a powerful laptop or a dedicated simulator. Currently, offline simulation tool suppliers do not provide custom simulators as a turnkey solution, but this may change in the future, depending on their commercial strategies.

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

Simulation Type	Cost	Computation Speed	Ensure accuracy	Complexity of setup †	HIL Compatibility
Offline SIL W/O parallelization	Low	Slow*	Easy	Low	No
Offline SIL With parallelization	Medium	Medium	Easy	Medium	No
SIL Real-time W parallelization	High	Fast	Medium	Medium	Yes
SIL Real-time W real interfaces	High	Fast	Hard	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 Use of models during the project lifecycle

5.1.2.1 "Standalone" Validation of model

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 15 shows the flowchart of the validation process of a model by vendor and how it is linked to the interaction studies.

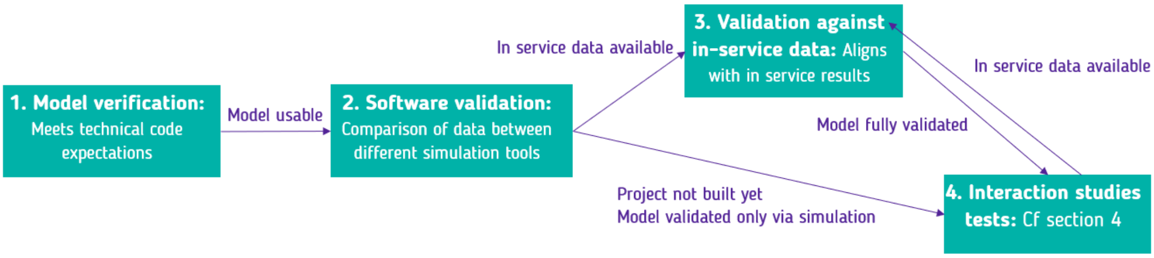


Figure 15. Standalone model validation process.

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).

5.1.2.1.1 Model verification

The main objective of model verification is to ensure that the model is usable in simulation and meets the technical requirements and expectations for further validation and interaction studies. To verify the model, the vendor must perform several checks and evaluations.

First, the vendor must confirm that the model can be compiled for the desired software environment and integrated into the desired simulation tool. This step is important because the model must be compatible with the simulation environment to be useful.

Next, the vendor must assess whether the model represents valid physics and technology. This includes verifying that the model's sensitivity is sufficient for further validation studies and interaction studies. The vendor must also ensure that the model meets technical code expectations, such as computation power, to be used for meaningful simulations.

Finally, the vendor must evaluate whether the model is fit for purpose. This means that not only must the model be suitable for a range of necessary simulations, but it must also include all relevant functions and make it clear what unmodelled functions do and when they should be considered and represented.

5.1.2.1.2 Software validation

The model verification is an important step in the development of HVDC systems. However, before the system is built, there are two possible solutions to validate the model before interaction studies:

comparing simulation results with in-service data of another different but similar HVDC system, or software validation of the model. The latter is preferred because the difference between two tools is smaller than the difference between two electrical systems.

Software validation of the model is the first step of validation that needs to be done once the model is verified. The vendor model should be validated only via software studies. There are different software validation possibilities, including validating a new control model in an existing, proven system inside one specific simulation tool, and comparing simulation results of the model with two simulation tools or two different simulation environments.

A few examples of software validation in the HVDC industry could be:

- Validation of the new control model in an existing, proven system, by comparison of simulation results with real-life data from similar HVDC systems. This approach is used to increase the confidence in the model but is considered too complex and time-consuming by many stakeholders.
- Validation using two different simulation environments, such as offline SIL studies and HIL studies, or PSCAD vs EMTP (one of the models must have been already validated as mentioned before). This approach allows the validation of the control model in real-world conditions, helping to catch any potential issues early in the development process.
- Model validation using statistical analysis of simulated data. This approach involves comparing simulation results with expected performance data to validate the accuracy of the model. For example, the vendor may use a Monte Carlo simulation to validate the performance of the control model in various scenarios.

Comparing the results of a new control model with two different simulation tools, such as PSCAD and EMTP, or with two different simulation environments, such as offline SIL studies and HIL studies, can increase the confidence in the model, but it remains the risk that both simulation tools would give similar but incorrect results. This is why it is important to validate the model first in an existing, proven system with one simulation tool, and only after, check if it can be integrated successfully with at least two simulation tools. Such software validation could give more confidence that the contractors' control functions are implemented correctly, and lessons learned from previous projects could be included as well.

5.1.2.1.3 Validation against in-service data

This type of validation can only be done once the project is built and commissioned, or at least some of the devices are ready for FAT (Factory Acceptance Test). In-service data validation helps determine if the model performance aligns with actual performance and if the necessary actions are being taken to track relevant changes.

There are two types of validation tests against in-service data: planning in-service test scenarios and using in-service data from unplanned events. Planning in-service test scenarios involves testing specific scenarios within the actual electrical system to reproduce simulation scenarios previously tested with software tools and comparing the results. On the other hand, using in-service data from unplanned events involves reproducing the conditions of an unexpected event that occurred in operation and comparing the simulation results to validate the model. The second type of validation is easier to perform as it does not require any on-site testing, while the first type of validation requires more effort and raises questions about its necessity in validating the model.

The need for validation with in-service data arises as equipment ages, and the model needs to be updated to be consistent with the equipment's performance. The validation with site data is proposed to be performed every 5 years (Grid, 2022). The validation will be limited to events such as start-up, ramp-up, and not DC faults, among others.

One of the challenges faced in performing in-service data validation is the need to share real data from the system among different stakeholders. Once a system is commissioned, the manufacturers are no longer the owners of the data, and the TSOs (Transmission System Operators) take over. Sharing TSO data can be sensitive, especially in the case of unexpected event data, as the cause of a disturbance may lead to economic queries from another TSO.

To share sensitive data, the TSO must provide explanations along with the unexpected event data, and confidentiality clauses must be established and adapted on a case-by-case basis. The field data, including TFR (Transient Fault Recorder), must be covered by the legal framework (link with WP2). TSOs are usually open to sharing their data with parties with whom they have signed agreements for a specific project, but they will not share the data with anyone.

5.2 Real-time hardware-in-the-loop (HIL) simulations

Hardware-in-the-loop (HIL) simulations are an important part of the development and testing process for HVDC projects. Currently, each hardware control replica is specific to a particular project and converter station from one manufacturer (see Figure 16).

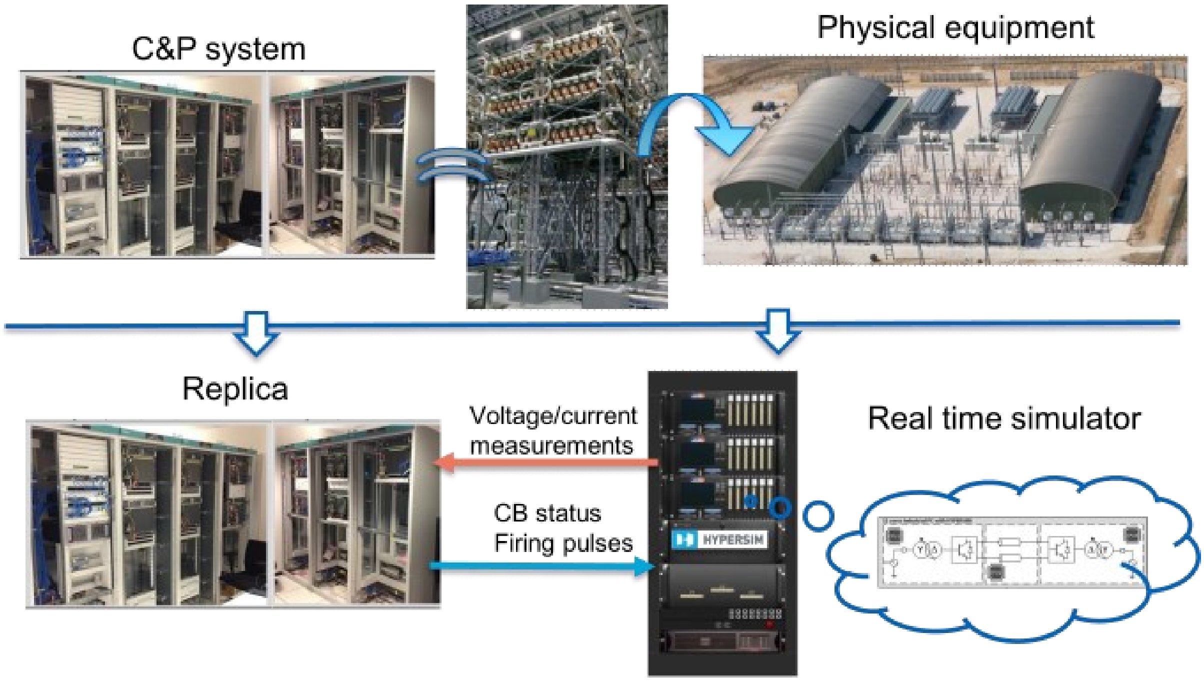


Figure 16. Overview of an HIL setup of a real HVDC link using replicas (Pisani et al.*, 2019).*

Here is detailed methodology of hardware-in-the-loop studies, a technique in which replicas of control cubicles are really needed, not models. For HIL real-time simulations with cubicles and replica, a common space needs to be used to host the different cubicles from different vendors. Indeed, it is harder to restrict the access on hardware than to a black-boxed model (even if some solutions may exist)

5.2.1 Hardware-in-the-Loop (HIL) Interaction Studies in Common Labs

Hardware-in-the-Loop (HIL) interaction studies are critical in assessing the behavior of power systems in real-time environments. In a MTMV project, each vendor may have their own lab or simulation facility where they can perform HIL studies on their own equipment. However, to simulate the interaction between different vendors' equipment, some coordination and cooperation are necessary. In such cases, it is recommended to establish a common lab or simulation center where the different vendors' equipment can be brought together for testing and validation.

The question of who should perform these studies in common labs is an essential one. To proceed with HIL interaction studies, integrators need to work with vendors to enable the cubicle's provision, as vendors master their control replicas. Scenarios two and three are possible, with an integrator performing the HIL interaction studies with the help of vendors. The center should have strict access control and security measures in place to protect the confidentiality and security of the vendors' equipment and software. However, it is also important for the vendors to be involved in the simulation studies and to witness, supervise, or drive the studies as necessary. As such, troubleshooting and solution recommendations are likely to remain on the vendor's side.

In addition to the options discussed above, there is also the possibility of combining HIL testing with real-time software-in-the-loop (SIL) testing. This option involves one vendor conducting HIL testing of their physical control system in a simulation environment using a black-box model of other vendor controls. While this approach may not be as accurate or thorough as full HIL testing, it could potentially allow a project to advance more quickly.

To describe: Example of CIGRE B4.81

5.2.2 Characteristics of a center for HIL studies

HIL studies require a specialized testing facility where different vendors can integrate and test their control systems in a realistic and dynamic environment. But who would be responsible for creating and operating such a center, and what are the essential characteristics of such a facility? It can be private entities, but also TSOs (or association of TSO) would need to open this kind of center (like RTE international) to host the different replicas of stations connected to their network. In this section, we will explore the measures taken in such HIL simulation centers to protect the IP of vendors and projects and answer the question of whether this methodology can be extended to two and more vendors.

5.2.2.1 Methodology used in National HVDC Centre to let vendors perform studies themselves in their TSO simulation facility:

The national HVDC centre provides a common hosted network analysis environment where confidential TSO network models formulated in real time RTDS study can be run with a range of confidential models of existing connections, as supplied through normal planning liaison and translated into real time can be integrated with vendor specific models / replica hardware of existing or new projects. real-time study is an I/O interface environment whereby a vendor or developer may run their own model/ hardware within a larger study environment, yet only see the behavior of that model in detail- seeing the system only as an I/O interface, and only being able to initiate conditions relevant to that model/ hardware. The center is configured to physically segregate the environment- such that only the vendor/ developer relevant to that model and limited relevant Centre personnel may have access to the room in which that model/ hardware is hosted.

These measures protect both the IP and confidentiality of vendor and project within a common environment where wider confidentialities must be respected- allowing Centre personnel to in turn to see the overall behaviors, whilst the IP of the vendors equipment is protected. Such vendor models/ hardware can be encrypted within this environment, as the extent of test and cross verification with other data (such as factory acceptance tests and in service experience, together with the completeness of the real time environment itself) will test equivalent to FAT stage the validity of each model being used.

The center achieves this by having heads of agreement with all the major vendors, controlled access and data management arrangements, cyber security and physical security arrangements, security vetting, limited accessibility and by being a co-signatory via its host TSO of the System Technical Code in GB, which manages the exchange of planning and operational data across the TSOs.

5.2.3 HIL simulations of several connected HVDC systems

A special case could cause problems in a longer-term future where we want to connect two DC grids together: if the two DC systems are simulated into two different centers, how to perform the HIL studies of the connected full system?

First thing to note is that using co-simulation, via cloud real-time simulation is not a viable solution because it is not made for HIL tests. Because of the different communication delays, for HIL tests, we need local simulators.

Then 3 options are proposed:

- Establishing one unique European-level center hosting all DC projects in Europe seem to be the ideal solution, even if it's not that easy to put in place. This unique center could be publicly owned and funded by EU, but countries like UK and Norway who are not EU members but could be connected to a common HVDC grid would need to find bilateral agreement with the EU to be part of the initiative.
- Another option would be that, when two HVDC systems simulated in different labs are to be connected, the cubicles are moved to one of the labs that becomes the lab of the new connected system. Eventually, if all European HVDC systems are connected, this would end-up like the first option. The difference is that the problem is postponed being treated only when it arises.
- Last option would be to perform hybrid simulation setups on each of the lab: we keep the hardware cubicles of each system on each lab, and we add to these hardware setups the models for the other system in SIL real-time simulation, running on real-time simulators (or alternatively with generic hardware option). This option is quite different as in that case we do not have the simulation with all replicas. We only have several setups with a mix of hardware replicas and software models, so that the simulation set-up is not as accurate as it would be only with replicas.

This leads to a large number of hardware replicas being required, whis is not cost-effective. To reduce the number of hardware replicas needed, the idea of having configurable generic hardware has been proposed. There are two potential variants of this solution:

1. **Generic hardware:** this solution would involve hardware that can be configured with the firmware of any vendor, with the control of any specific project.This is considered a challenging solution as it is a departure from current replica developments. However, it would increase the flexibility of

HIL studies and reduce the number of replicas required for a real-time simulation laboratory. This option is similar to the option of SIL real-time simulation, where a model runs in real-time in a simulator provided by simulation tool suppliers. The main difference is that the hardware would be an industrial controller provided by a vendor.

2. **One configurable hardware per vendor generation:** in this solution, each vendor would provide one hardware per generation (product line), which could be used for several projects. The hardware would be configured by downloading a firmware and software code provided by the vendor specifically for the converter station of the project. This solution is closer to the current solution, but still causes a number of practical issues. A real-time simulation laboratory would need fewer hardware replicas than with the current solution, but more than with the generic hardware option. They would need to have, for each vendor, the number of hardware corresponding to the maximum number of converter stations a vendor owns in a single HVDC project.

5.2.3.1 Concerns on generic and configurable hardware for converter control

Some may wonder if the use of generic hardware for lab setups could lead to its adoption in on-site control systems, ultimately eliminating the need for multiple hardware suppliers in HVDC projects. With this in mind, we can explore the specific practical issues associated with the use of both configurable and generic hardware options for converter control in MTMV projects.

There are several practical issues with each option. The option of one replica per vendor generation has the potential issues of not being able to update some specific low-level controls and impacting the real-time performance of the control cubicle. The generic hardware option has the issue of it not being feasible to execute a vendor's software on any hardware. The timing, real-time performance, jitter, etc. behavior of such a generic hardware setup would be different from the manufacturer's setup, which would be delivered to site. For both configurable and generic hardware options, the real-time performance would be worse than the original hardware, leading to over-design. In the unlikely event that it outperforms the original hardware, it might give people a false sense of security and lead to more problems later during on-site operation. This approach cannot be handled in practice and is not relevant for MTMV projects.

To summarize, the choice between these two options depends on the specific needs and requirements of a project. In general, if a project requires a large number of hardware replicas, the option of one configurable hardware per vendor generation might be the better choice, as it would reduce the number of replicas needed compared to the current solution. On the other hand, if a project requires a high degree of flexibility, the generic hardware option might be the better choice, as it would allow for more freedom in terms of configurability. Ultimately, the choice between these two options will depend on the specific requirements of each project.

5.2.3.2 Advantage of generic and configurable hardware for large EMT interaction studies in a MTMV HVDC context

Let N be the number of HVDC projects in Europe that need to be simulated in hardware-in-the-loop (HIL) with replicas. Let n_i denote the number of stations for the i-th HVDC project ($i = 1, 2, \ldots, N$). Further, let n_{iA} denote the number of stations from vendor A for the i-th HVDC project ($i = 1, 2, \ldots, N$). Then, we have the following relationship between the number of stations:

$$n_i = n_{iA} + n_{iB} + n_{iC} + \ldots$$

where n_{iB} and n_{iC} denote the number of stations from vendor B and vendor C, respectively, for the i-th HVDC project.

Also, Let n_{max} denote the maximum number of stations among all HVDC projects, i.e.,

$$n_{max} = max(n_1, n_2, \dots, n_N)$$

Similarly, let $n_{max,A}$ denote the maximum number of stations from vendor A among all HVDC projects, i.e.,

$$n_{max,A} = max(n_{1A}, n_{2A}, \dots, n_{NA})$$

Now as an example, let's consider a scenario where there are 5 MTMV HVDC projects in Europe, with 3, 3, 4, 4 and 5 stations respectively. There are 3 main vendors (A, B, and C), each of which never has more than 3 stations inside one of the 5 systems. Here is the recap table of the three options: generic hardware, one hardware per vendor and one replica per project station (current option), giving the number of hardware that are needed in general and with the data of the example:

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

	Generic hardware	One hardware per vendor	One replica per project station
Number of hardware needed	n_{max}	$n_{max,A} + n_{max,B} + n_{max,C}$	$n_1 + n_2 + \dots + n_N$
Number of hardware needed with example data	5	3 + 3 + 3 = 9	3 + 3 + 4 + 4 + 5 = 19
Potential impact on flexibility	Very High	High	Current option
Control model accuracy	Accuracy similar to SIL real-time option: the hardware is different than on-site cubicle	Very good accuracy: hardware identical to the on-site cubicle but configured differently	Exact copy
Complexity and practical issues	Very High	High	None
Distance from current option	Very High	High	None

The hardware-in-the-loop (HIL) simulations offer a powerful tool to assess the behavior of power systems in real-time environments. The real-time HIL simulations can provide a good accuracy, in terms of control model, as well as a high degree of flexibility. Among the different available options, the real-time hardware-in-the-loop (HIL) simulation approach with configurable hardware presents a high level of complexity and practical issues, making it a challenging option to implement. However, given its potential impact on the overall accuracy and flexibility of the simulations, it is still worth considering as a viable approach for future investigations. Given the complexities involved in the configurable hardware option, it is recommended that a thorough investigation of this approach is conducted. This should include a detailed analysis of the available hardware options, the development of adequate testing procedures, and the identification of the most effective strategies for implementing the configurable hardware option.

5.3 Control Model Integration for SIL and HIL Interaction Studies of MTMV HVDC Systems

In this section, we will discuss the methodology for interfacing one or multiple vendor control models or replicas with the simulation model for complete integration in SIL or HIL studies. The purpose of this section is to provide practical recommendations and guidelines for model 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).

In section 5.3.1, we will discuss the technical recommendations and solutions to facilitate MMC control integration, including standardization of MMC control interfaces, technical documentation of the MMC control interfaces, and a description of the workflow of model integration.

Sections 5.3.2 and 5.3.2.1 will focus on the integration of vendor controls for real-time SIL studies, including the difficulties encountered in model integration for offline studies. This will include practical difficulties specific to a simulation tool, generic practical difficulties, and difficulties in integrating several models from different vendors into the same simulation environment.

Section 5.3.2.2 will address the requirements for simulation compatibility for offline studies, including requirements for the file format, compiler, dependency on other software, and time step for simulation compatibility.

Finally, section 5.3.3 will discuss possible solutions and guidelines to facilitate integration for both offline and HIL studies. This will include guidelines on interfacing control cubicles/replicas for HIL studies.

All-in-all this section aims to provide a comprehensive overview of the challenges and best practices in integrating vendor control models or replicas into simulation models for SIL and HIL studies in MTMV HVDC systems. The information presented here is intended to assist integrators, model suppliers, control suppliers, and simulation tool suppliers in ensuring successful and efficient integration of control models into simulation models.

5.3.1 General Technical Recommendations and Solutions for MMC Control Integration

5.3.1.1 Standardization MMC Control Interfaces

One of the key objectives in the integration of MMC control models for HIL (Hardware-in-the-Loop) studies is to have a standardized interface. This standard should not only apply to the communication protocol but also to the software model interface. A proposal has been made by ENTSO-E but it falls short in providing important details such as the interpretation of signals, resolution, and sampling. For any non-standard interface, proper documentation should be provided as discussed in section 4.3.1.2.

Standardization of the MMC control interface refers to the standardization of the Input/Output (IO) listing, fixed order, and names of IOs. A standardized format of the model file is not considered a standard interface but rather a standard file format. The latter is described in another section of the document.

Some of the advantages of standardization are:

1. Facilitating the import of models from different vendors into a single simulation tool. The standard interface would allow for the control model of the MMC to be treated as a black box that can be easily connected to any MMC electrical model via the same IO signals. (cf., CIGRE WG B4.82)
2. The standard could be updated to accommodate technical improvements through a consulted process between different parties. This process could happen less frequently than without a standard, which would help facilitate integration and hardware interfacing (e.g., update of the FPGA model).

Also, some requirements for a standard interface include:

1. The standard interface should not restrict the innovation possibilities that are a key aspect of competition between converter manufacturers.
2. The interface should not limit the type of signals that can be interfaced.

Finally, there are several challenges that will need to be addressed:

1. Standardization is generally a difficult and long-term task that requires a lot of effort and collaboration.
2. The interface for MMC-VSC converters is rapidly changing due to the relatively recent technology and frequent innovations.
3. The process of updating the standard could be too constraining, resulting in a lack of flexibility and effectiveness in incorporating technical changes to the interface.

In comparison, LCC (Line-Commutated Converter) technologies are more mature (about 50 years old) and therefore have fewer innovations and are easier to standardize. The technology is also less complex, resulting in simpler interfaces.

5.3.1.2 Technical documentation of MMC control interfaces

Proper technical documentation of MMC control interfaces will ease the tasks of an integrator when performing interaction studies in a MTMV HVDC project. It is essential that the documentation provides clear and comprehensive information about the interfaces to ensure that they are properly understood and integrated by all stakeholders, including integrators, manufacturers, and end-users. The lack of standardization for MMC control interfaces calls for specific guidelines for documenting these interfaces. The following recommendations can help to ensure that the technical documentation for the MMC control interfaces is clear, complete, and easily understandable.

• Clear description of the signal: The documentation should provide a clear and concise description of the physical representation of each signal interfaced. This information should clearly explain the purpose and function of each signal and how it relates to the overall system.

• Resolution of the signal: The documentation should specify the resolution of each signal, which refers to the level of detail or accuracy that can be measured. This information is critical for ensuring that the signals are properly interpreted and processed.

• Sampling: The documentation should describe the sampling rate of each signal, which refers to the frequency at which the signal is measured. This information is important for determining the accuracy and reliability of the signal.

• Latency: The documentation should specify the latency of each signal, which refers to the time delay between the measurement of the signal and its processing. This information is crucial for ensuring that the system functions in real-time.

• Measurement, filtering, precision, and jitter: The documentation should explain how each signal is measured, filtered, and processed, including information about the precision and jitter of the signal. This information is important for ensuring that the signals are accurate and reliable.

By providing clear and comprehensive information about the MMC 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 an MMC interface specification 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 MMC	Measured using a high-precision voltage sensor	±0.5-2.5 kV	1-5 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	1-5 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	1-5 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	1-5 kHz	1-10 ms	± 0.1 – 0.5%	< 10 µs
Control	The control signal from the control system to the MMC	ADC with a low-pass or band-pass filter, 1-5 kHz cut-off frequency.	12-16 bits for ADCs	Depending on converter manufacturer (5-20-100kHz)	10-100 µs	± 0.1-1 %	< 1 µs

5.3.1.3 Workflow Description for Model Integration

In general, model generation refers to the process of creating a digital representation of a physical system, such as an MMC or converter in a High Voltage Direct Current (HVDC) system in this case. The model generation process is an important step in the overall workflow of integrating the MMC/converter model into the overall system interaction studies. There are several options for generating models, each with its own strengths and weaknesses.

- One option is **manual modeling**, which involves creating a model from scratch using a software tool, such as MATLAB or Simulink. This option requires a significant amount of technical expertise and time, but it allows for the most customization and control over the model.
- Another option is **automatic code generation**, which involves using a software tool to generate code from a high-level model specification. This option is faster than manual modeling and requires less technical expertise, but it can be more limited in terms of customization and control.
- A third option is **using pre-existing models**, such as commercially available models or open-source models. This option is the quickest and requires the least technical expertise, but it may not accurately represent the specific MMC/converter being modeled.

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

1. The first step is to **determine the type of model that is needed**, based on the requirements and constraints of the overall system.
2. Once the model type is determined, the next step is to **gather information about the MMC/converter being modeled**, such as electrical characteristics and performance data.
3. Next, the **model is created or selected**, and validated to ensure that it accurately represents the MMC/converter. This may involve testing the model using simulation or real-world data and adjusting as necessary.
4. Once the **model is validated**, it is integrated into the overall system, which may involve interfacing with other models and/or hardware components. The model interfaces should be well-documented to ensure that the integrator understands how to properly use and integrate the model.
5. Finally, the **overall system is tested and validated** to ensure that it is functioning as intended. This may involve conducting SIL and HIL studies, or other types of testing to verify the performance and reliability of the system.

5.3.2 Guidelines for integrating vendors controls for offline SIL studies

These guidelines are proposed to ensure that the control systems are functioning correctly and meeting the required performance specifications for MTMV interaction studies. To this end, it is assumed that the configurations parameters of the tools will be agreed upon before the models are built by the vendors. 5.3.2.1 describes the difficulties encountered during the integration of the models into the simulation environment for offline studies. These difficulties include specific difficulties related to the simulation tool, generic practical difficulties, and difficulties in integrating models from different vendors into the same simulation environment. 5.3.2.2 outlines the requirements for simulation compatibility in offline studies. These requirements include file format requirements, compiler requirements, dependency on other software requirements, and time step requirements. It is essential that these requirements are met in order to ensure accurate and reliable results from the offline studies.

5.3.2.1 Difficulties in components model integration for offline studies

Integrating a control or component model from a vendor into a simulation tool is a challenge that is particularly crucial in the context of MTMV studies. The integration of several models from different vendors into a single simulation environment increases the complexity of the task and requires careful attention to ensure successful integration. This section will provide an overview of the difficulties that can be encountered during the integration process and why integration in a simulation tool is difficult.

One of the main challenges in model integration is the need to interface the control model with the rest of the simulation model. The model users need to have a full description of the interface and its inputs and outputs (I/O), but the description must not disclose the model content, as this may be considered confidential or proprietary information. This can be a challenge as the interface needs to cover everything necessary for the simulation to work properly, but it must also not reveal any confidential information about the model.

Another challenge 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. This can make it difficult to integrate the models into a seamless simulation environment. To overcome these difficulties, 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 converter model that is being integrated.
- Vendor: The name of the vendor who developed the model.
- Version: The version number of the model that is being used.
- File Format: The file format of the model, such as .xml,. mdl, etc.
- Compiler Requirements: The specific compiler requirements for the model, such as software provider (MATLAB or Simulink, EMTP, PSCAD...).
- Compiler versions related to previous compiler requirements.
- Dependencies: Any dependencies on other software, such as libraries or tools, that are required to use the model.
- Time Step Requirements: The minimum time step requirements for the model, depending of the kind of studies, here interactions starting from microseconds up to milliseconds.or more.
- Inputs/Outputs: A description of the inputs and outputs of the model, including the data type, unit of measurement, and any other relevant information.
- Usage Rules: Any specific usage rules for the model, such as the conditions under which it can be used, limitations, or restrictions.
- Model Documentation: A link to the model documentation, including the user manual, technical specifications, and any other relevant information.

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. By establishing clear requirements for simulation compatibility, the different models can be integrated into the simulation environment in a way that ensures they are compatible with each other and can be used to run simulations without errors.

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.

However, there is no guarantee that this will always be the case, as updates to the model may affect its compatibility with the simulation tool. In conclusion, integrating a control or component model from a vendor into a simulation tool is a complex process that requires careful attention and planning. The difficulties in model integration for offline studies are related to the need to interface the model with the rest of the simulation model, the different approaches used by different vendors to develop their models, and the compatibility issues that may arise during the integration process. To ensure successful integration, it is important to have a clear understanding of the requirements for simulation compatibility and to be aware of the difficulties that may be encountered.

5.3.2.1.1 Generic practical difficulties

Some generic practical difficulties may arise during the integration of simulation models and pose challenges for users. One such difficulty is related to the use of 32-bit and 64-bit DLLs. DLLs are dynamic link libraries that contain code and data that can be used by multiple programs. The issue with DLLs is that if a DLL has been generated with a 32-bit compiler, it cannot be integrated within a 64-bit version of a software, and vice versa. This can create compatibility issues and lead to the need for additional resources and time to resolve the issue.

Another generic practical difficulty is related to the use of LIB files. LIB files are library files that are attached to a specific compiler version and are linked at the end of the compilation process. While this makes it easier for the one who generates the LIB file, it can be more challenging for those who maintain the model. The issue arises when the compiler version changes, and the LIB file is no longer compatible, requiring additional time and effort to resolve the issue.

5.3.2.1.2 Practical difficulties specific to a simulation tool

Practical difficulties in model integration are specific to the simulation tool being used and can vary greatly between software programs. For example, in some simulation tools, the generated model is limited to a single "layer", meaning that the model cannot be structured using subsystems. Subsystems are separate and organized parts of a larger system which often helps to simplify a complex system, making it easier to manage and understand. This limitation can create difficulties for integrators when they try to integrate vendors models, as they may be forced to conform to the single layer structure imposed by the software. This can result in a loss of functionality and a decrease in the model's overall usefulness. The integrator (another vendor, an owner, operator, or real-time simulation laboratory) may need to spend extra time and resources adapting their models to the single layer structure, which can be time-consuming and result in wasted effort.

Similarly, the implementation of feedforward controls may not always be possible if the software is not capable of storing values in memory. Additionally, not all tools use compilers, which can also present challenges for model integration.

To address these difficulties, it is important to work with the simulation tool supplier to understand the limitations of the tool and how they may impact the model integration process. If the issue is a bug or specific problem with the software, the supplier can often provide support to resolve it. However, if the difficulty is a limitation of the software, it may not be as simple to find a solution. Simulation tool suppliers are often aware of these limitations, which may result from a technical or strategic decision that balances pros and cons. It is important to understand the capabilities and limitations of the simulation tool being used before beginning the model integration process. This can help to ensure that the integration process goes smoothly and that the final model accurately represents the system being studied. Additionally, if the simulation tool does present limitations for a particular application, it may be necessary to consider alternative tools that may be better suited for the specific requirements of the project.

5.3.2.1.3 Difficulties integrating models from different vendors into the same simulation environment.

Practical difficulties in integrating models from different vendors into a single simulation environment will be a recurrent issue in MTMV HVDC systems. The integration process becomes more complex when different vendors use different file formats, simulation tools, and licensing requirements. In this section, we will discuss some of the difficulties encountered during the integration process and propose solutions to facilitate it.

File format compatibility is a major issue in MTMV systems. To integrate the models from different vendors, all files must be in a format that can be imported into a common simulation tool. Moreover, different vendors may use different software to generate the models, which may result in compatibility issues between the simulation tool and the models. To overcome this challenge, standardization of file formats can be recommended, or the use of conversion tools to ensure compatibility with the simulation tool.

Another challenge is the use of different licensed software to generate the DLLs, which can be even more critical in the MTMV case as different licenses may be required to integrate all vendor models. For example, the MATLAB run-time library is required if the model was compiled with the MATLAB compiler. This can be a major cost factor for the model user and may force them to use a specific software tool. To address this issue, it is recommended to use open-source simulation tools that are freely available and do not require additional licenses. Otherwise, by implementing a licensing agreement between the vendors to ensure that a common licensed software is used.

Additionally, the use of a fixed time step in EMT simulation tools can also pose a challenge as different vendor models may run on different time steps. To overcome this, it is recommended to have a discussion with vendors to require a common time step, to support a fixed time step but in a reasonable range, or to use simulation tools that allow for variable time steps.

In conclusion, to facilitate the integration process, standardization of file formats, the use of open-source simulation tools, enforcing a common time step, and implementing a licensing agreement between vendors are recommended solutions. This will reduce the cost for the model user, minimize compatibility issues, and streamline the integration process. Additionally, it is important for vendors to be open to discussions and collaboration to make the integration process as smooth as possible.

5.3.2.2 Requirements for simulation compatibility in offline studies

To ensure compatibility and ease the integration process, it is crucial to consider certain requirements that are essential for simulation compatibility in offline studies. This section will discuss the key requirements for simulation compatibility, including file format requirements, compiler requirements, dependency on other software requirements, and time step requirements.

5.3.2.2.1 File Format Requirements

Integrating models from different vendors into a single simulation environment can be challenging due to differences in the development approach of each vendor. Vendors have developed their own expertise and philosophies, which has led to divergent choices in terms of architecture, usage procedures, and software generation. This can be exacerbated by the absence of a clear and agreed-upon specification for the model setup when it is requested from a vendor. To facilitate the integration process, it is necessary to provide guidelines and specifications for a single, unified process to generate the model for integration with offline simulation tools.

Two main options are used today to generate black-boxed models - LIB files and Dynamic Link Libraries (DLLs). LIB files are attached to a specific compiler version and are linked at the end of the compilation. This means that the same compiler version must be used to make it run. While this is more convenient for the person generating the model, it can be more challenging for those who are responsible for maintenance. On the other hand, DLLs are more flexible and easier to integrate, as they are linked during the execution of the code. This requires the specification of an interface, but it prevents any compiler issues. The question arises as to whether to recommend or require only the DLL/SO format from different manufacturers for integration and interaction studies. While this would simplify the integration process, it would also require a long-term effort, with step-by-step progress, to implement such a requirement. It would be difficult to impose this change overnight, so a gradual transition may be necessary.

- **IEEE/Cigre real-code DLL interface standard effort:** it is a collaboration aimed at standardizing the real-code DLL interface for electrical power system simulation. This effort is being carried out by the Institute of Electrical and Electronics Engineers (IEEE) and the International Council on Large Electric Systems (CIGRE), two well-respected organizations in the electrical engineering field.
  The standard is being developed through collaboration between industry experts and stakeholders, with the aim of establishing a widely adopted, industry-recognized standard for real-code DLL interfaces. This effort focuses on developing a set of standard guidelines for creating and integrating real-code DLLs for power system simulations to ensure compatibility and ease of use for all involved parties. The DLL standard includes exported functions that can be called, definitions of all inputs, outputs, and parameters (including variable types, units, array dimensions, minimum and maximum allowable settings, etc.), and a sample time step at which to call the controls each step. The DLL only needs to be updated whenever the code is changed or released.
  Program developers include a DLL import tool, which is run once by the end user for major program versions. The tool first opens and queries the DLL to get the inputs, outputs, parameters, and sample time, and then creates any interfacing code for that particular program version. The tool may need to be re-run for each version update, but the model source code is not needed. The DLL can be used for all future program versions. For end users, the process is simple: they get the DLL from the manufacturer and run the DLL import tool once.
  This standardization effort serves as an example of the need for clear and agreed-upon specifications in this field, reducing the difficulties encountered during integration of models from different vendors into the same simulation environment.

In summary, to ensure that the models from different vendors can be integrated into a single simulation environment, it is necessary to have a clear set of file format requirements. This may include specifying the use of a particular file format, such as DLLs, as well as ensuring that the generated model follows a standardized structure and format. Additionally, it may be necessary to develop guidelines for the conversion of models from one file format to another, in order to accommodate vendors who are unable or unwilling to switch to the recommended file format.

5.3.2.2.2 Compiler Requirements

In order to ensure simulation compatibility in offline studies, it is important to consider the compiler requirements. Currently, one solution is for the vendor to specify the compiler used to generate the model, and for the model user to comply with that compiler. This is particularly important when a LIB file is used, as it can be linked to a specific compiler version. However, this approach may lead to compatibility issues if the model user uses a different compiler.

To overcome these compatibility issues, the ideal solution would be for the model not to require any specific compiler. This would allow the model user to use the compiler of their choice, without encountering any compatibility issues.

One way to achieve this is by using a Dynamic Link Library (DLL). A DLL is a binary file that acts as a shared library and can be used by multiple applications. The advantage of using a DLL is that it does not require a specific compiler, and therefore does not introduce any compatibility issues. This approach has been confirmed by simulation tool suppliers and vendors as a viable solution.

5.3.2.2.3 Dependency on other software Requirements

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.

5.3.2.2.4 Time step Requirements

When integrating multiple models from different vendors into a simulation, it is crucial to ensure compatibility with each other in terms of time steps. The simulation time step determines the frequency at which the simulation updates the models' state and output, and it is an important factor affecting the accuracy and performance of the simulation. Finding the right balance between the time step size and simulation performance is a complex task that requires careful consideration of the requirements of each model and the limitations of the available interpolation techniques. Some models may have different time step requirements due to the nature of the underlying physics or the specific needs of the application. For instance, models that simulate high-frequency dynamics may require a small time step size to ensure accuracy, while models that simulate low-frequency dynamics may be able to use a larger time step size without affecting accuracy. Therefore, it is important to carefully consider the requirements of each model when selecting the time step size for the simulation.

Imagine models from different vendors having different time steps, such as vendor A with a model running at 5 µs, B at 4 µs, and C at 7 µs. To integrate these models into a single simulation, the simulation time step must be set to the lowest time step of all models. There are several options to achieve this.

- **Option 1:** require a specific **common time step** for all models from all vendors. This option involves requiring all vendors to adhere to a specific, common time step for their models to make them compatible with each other, ensuring seamless integration into the simulation. However, having a common time step for all vendors is challenging because the desired time step for each vendor to ensure the accuracy of its model may be different. Vendors cannot increase the time step of their model too much since this can affect the models' accuracy, but if the common time step is rather too low, the simulation may take too long to run. A trade-off is choosing a common time step that is low enough for all vendors to ensure accuracy but still allows correct simulation performances.
- **Option 2:** allow **different time steps** for the models requiring them to be multiples of each other. For instance, vendors ABC must modify time steps choosing between 5 µs, 10 µs, 15 µs or 20 µs. This option allows for different time steps for each vendor's model but requires that they be multiples of each other. This approach allows the simulation to be run at the lowest time step of all models, ensuring that all models are compatible with each other. Like with option 1, vendors may need to redo their models to comply with the requirement. Then, when integrated in the same simulation environment, either the software allows multiple time steps to run together, or the time step is defined by the minimum among the models provided by vendors.
- **Option 3:** allow **any time step** for the models from vendors, that are not necessarily multiples of each other. There are two possibilities in that case:
    - the simulation user must either use the **greatest common divisor** of the models' time steps (e.g., 1 µs in the example of vendors ABC). This option allows for complete freedom for vendors in terms of choosing their time step. In this case, the simulation would use the greatest common divisor of the model's time steps which is lower than the time step in options 1 and 2 (1 µs in example ABC), leading to poorer simulation performance (slower simulations).
    - or use the **lowest time step** and the solver uses some **interpolation techniques** (e.g., 4 µs in the example of vendors ABC). This option allows vendors complete freedom in terms of choosing their time step and allows the simulation to be run at the lowest time step. The simulation tool would use interpolation techniques to handle models with different time steps. This approach provides a flexible solution that does not impose any restrictions on the time step for each vendor's model. However, the limitations of this option would need to be further explored and the simulation tool need to have this type of solvers. For instance, some interpolation techniques may introduce additional errors into the simulation, which could compromise the accuracy of the results. Therefore, it is important to carefully evaluate the performance of the interpolation techniques and choose the one that provides the best balance between accuracy and computational efficiency.

5.3.3 Guidelines for integrating vendors controls for real-time SIL studies

If real-time SIL studies finds its place in the context of interaction studies for MTMV HVDC systems, integrating vendors' controls requires consideration and planning. This section aims to outline the key challenges and guidelines for successfully integrating control models from different vendors into real-time SIL simulations.

Ensuring compatibility with regards to time step requirements also applies to this type of simulation. The MMC control models usually run at a low time step, which can already be a technical challenge. If models from different vendors must be integrated, this can make the task even more complex. As mentioned in section 4.3.2.2.4, the time step of the models from each vendor may vary, and to ensure compatibility, the simulation time step may need to be lower than what any single vendor's model would require. This may difficult the realization of real-time simulations since the lowest the time step the harder for the solver to ensure refreshing outputs in a deterministic and synchronized time period.

Another challenge is the compatibility of the control models with the real-time simulation tools. To successfully integrate vendors' control models for real-time SIL studies, it is important to choose a real-time simulation tool that is compatible with the file format of each vendor's control model. The models to be run would not be a DLL running on Windows, but rather a different specific file format (like .a). This means that the source code would not need to be used, which can cause problems of portability between offline and real-time simulation tools. The tool should also be able to handle the low time step requirements of the models and have the capability to perform real-time simulations with multiple 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.

Finally, it is important to consider the technical expertise and support available from the vendor and simulation tool provider. The vendor should be able to provide support and technical expertise in integrating their control model into the real-time simulation environment, while the simulation tool provider should be able to provide support and technical expertise in running real-time simulations.

5.3.4 Guidelines on interfacing control cubicles/replicas for HIL studies

The objective of this section is to provide guidelines on interfacing control cubicles or replicas for Hardware-in-the-Loop (HIL) studies in the context of MTMV HVDC systems. The HIL studies are crucial for evaluating the performance of control systems in a real-time environment. 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.

5.3.4.1 About interfacing protocols

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 MMC 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. 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.

When dealing with software models, interaction studies of HVDC system expansions for instance may suffer from compatibility issues when integrating models of a new HVDC station. Indeed, simulations may have been performed with previous versions of control and simulation softwares. In such a case, unless retro-compatibility is ensured, one of the vendors must agree to upgrade their control model to the new software version to ensure compatibility. This upgrade process requires involvement and coordination with vendors to generate a model for a specific software version. In conclusion, while the hardware version remains constant, compatibility issues in software models can arise and may require a significant effort to resolve.

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.

Finally, it is important to note that the frequency of control updates also differs between software models and replicas. Software models are typically updated every 5 years, as they are updated with on-site data. Replicas, on the other hand, are updated only if the on-site cubicle is updated.

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 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 level of accuracy of the hardware representation in a model is a crucial factor to consider. In the case of an offline model, the hardware dynamics of the control cubicle are not represented, nor are the communication dynamics. If a hardware that is different from the on-site cubicle is used, the impact of communication issues can be tested, but the hardware dynamics will not be accurate, which may lead to false confidence in performance.

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 computer workstations and Hardware-in-the-loop 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 where real-time simulations are required.

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. 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.

The main comparison criteria for model performances are accuracy, proximity to real controls, compatibility with FPGA implementation of low-level MMC 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. Preliminary evaluation of EMT simulation tools for MTMV HVDC interaction studies.

		Type of EMT simulation tool						
	Comparison Criteria	Offline	Offline +	Real-time SIL	Real-time SIL +	Real-time HIL	Real-time HIL ++	Real-time HIL +++
Setup characteristics	Type of model	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		
	Commonly used in interaction studies	Very common		Uncommon		Rare		Common

Simulation performances	Complexity to solve electrical models accurately	Normal		Moderate		Hard		
	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 MMC 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 and its requirements (new HVDC multi-terminal, expansion, 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 ultimate 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 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.

CONCLUSION

Not applicable to this first version.

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
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
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

REFERENCES

Campos-Gaona, D. and Anaya-Lara, O. (2019) *Modelling platform for control design purposes and large-scale power system studies*.

ENTSO-E (2018) 'Interactions between HVDC systems and other connections: ENTSOE guidance document for national implementation for network codes on grid connection'.

ENTSO-E (2021) 'Workstream for the development of multi-vendor HVDC systems and other power electronics interfaced devices'.

European Commission (2016) *Commission Regulation (EU) 2016/1447 of 26 August 2016 establishing a network code on requirements for grid connection of high voltage direct current systems and direct current-connected power park modules (Text with EEA relevance)*, *OJ L*. Available at: http://data.europa.eu/eli/reg/2016/1447/oj/eng (Accessed: 1 February 2023).

G. Andersson et al. (1997) '119 Interaction between HVDC convertors and nearby synchronous machines. Working Group 14.05'.

J. A. Jardini et al. (2013) '563 Modelling and simulation studies to be performed during the lifecycle of HVDC systems. Cigre WG B4.38'.

Jahn, I. *et al.* (2022) 'On the Partitioning of MMC Control Systems Using Graph Theory', *IEEE Open Journal of Power Electronics*, 3, pp. 611–620. Available at: https://doi.org/10.1109/OJPEL.2022.3204558.

Ming Cai et al. (2021) 'Technical Consultancy for the NSWPH Consortium'.

Noureen, S. *et al.* (2017) 'Real-Time Digital Simulators: A Comprehensive Study on System Overview, Application, and Importance', *International Journal of Research and Engineering*, 4, pp. 266–277. Available at: https://doi.org/10.21276/ijre.2017.4.11.3.

Pisani, C. *et al.* (2019) 'Functional validation of a real VSC HVDC control system in black start operation', in *2019 AEIT HVDC International Conference (AEIT HVDC)*. *2019 AEIT HVDC International Conference (AEIT HVDC)*, pp. 1–6. Available at: https://doi.org/10.1109/AEIT-HVDC.2019.8740646.

Q. Guo et al. (2022) '864 Guide to develop real-time simulation models for HVDC operational studies. CIGRE WG B4.74.'

S. Dennetière et al. (2021) '832 Guide for Electromagnetic Transient Studies Involving VSC Converters'.

Seitz, K. *et al.* (2019) 'Work Package 7.5, D7.9: Regulatory and Financing principles for a Meshed HVDC Offshore Grid'. Progress on Meshed HVDC Offshore Transmission Networks.

T&D Europe (2022) 'White Paper: Studies for Interaction of Power Electronics from Multiple Vendors in Power Systems'.

APPENDIX

Not applicable to this first version.