

Testing models and physical C&P replicas prior to interaction studies in a MV and MT context

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SUMMARY

Against the backdrop of rapid grid developments and the massive integration of renewable energy sources, such as offshore wind turbines, the proliferation of point-to-point high voltage direct current (HVDC) links has become essential. Therefore, there is an urgent need to establish multi-vendor (MV) and multi-terminal (MT) HVDC grids. The ability to perform interaction studies using Electromagnetic Transient (EMT) models and replicas is crucial for ensuring the secure operation of these systems. However, system operators and integrators have so far faced challenges in assembling models and replicas provided by multiple vendors due to software incompatibility, different time steps, and numerical conflicts.

To address this, the InterOPERA project has defined minimum requirements applicable to the models and replicas provided by vendors [1], enhancing tool independence and facilitating their integration on multiple platforms. Then, as part of the InterOPERA project, seven participating vendors provided template models and replicas based on those requirements. Concurrently, two laboratories (TU Delft and RTE) prepared their simulation platform based on [2] and tested the integration of the models and replicas in multiple offline and real-time simulation environments.

This paper presents lessons learned from these tests, evaluating the success of the InterOPERA requirements and methodology. Also, it aims to identify areas for further development, recommendations and refinement to ensure the smooth integration of all models and replicas.

Among the key findings for the offline models, the vendors achieved the provision of control and protection Dynamic Link Libraries (DLLs) for converter stations, wind turbine controllers, power plant controllers, DC switching stations and DC grid controllers based on [3]. The laboratories successfully integrated these models into two EMT tools without any numerical conflicts, providing the chance for conducting the first MTMV interaction tests.

Regarding real-time replicas, although interface documentation requires significant effort from vendors, it has proven instrumental in successfully integrating their solution into two different real-time environments as a single-vendor. Furthermore, the laboratories are facing challenges in moving to multi-vendor simulations due to time step constraints. Therefore, further work on this topic is recommended to address this challenge more effectively in future projects.

KEYWORDS

Models, Replicas, Dynamic Link Library (DLL), Electromagnetic Transient (EMT) study, Integration tests.

1. Introduction

In multi-vendor (MV) and multi-terminal (MT) HVDC projects, interaction studies are crucial to ensure a secure and reliable operation of the AC and DC transmission systems. Consequently, to conduct those interaction studies, it is of utmost importance to integrate models and replicas provided by multiple vendors. Furthermore, a specific Electromagnetic Transient (EMT) tool is supposed to be used for a particular offline or real-time testing environment. Therefore, a set of minimum requirements has been proposed in the scope of the InterOPERA project [1]. Based on those requirements, seven vendors participating in the project have provided models and replicas and shared them with two laboratories, TU Delft and RTE, for testing.

To ensure that the models and replicas could be used for MV interaction studies, a specific integration process was proposed, which is illustrated in Figure 1 and further detailed in [4]. To this end, the requirements are initially defined for the vendors and laboratories to prepare models, replicas and

simulation platforms. Then, single-vendor tests are performed to ensure that these requirements are met. Next, the models or replicas are assembled in the same simulation environment, without an electrical connection. Thus, the risk of numerical and interface conflicts between the models/replicas is mitigated through these MV tests. Once all these steps have been successfully completed, the interaction studies can be initiated. This process anticipates multiple iterations to resolve potential issues, which are monitored using vendor-specific issue tracker documents.

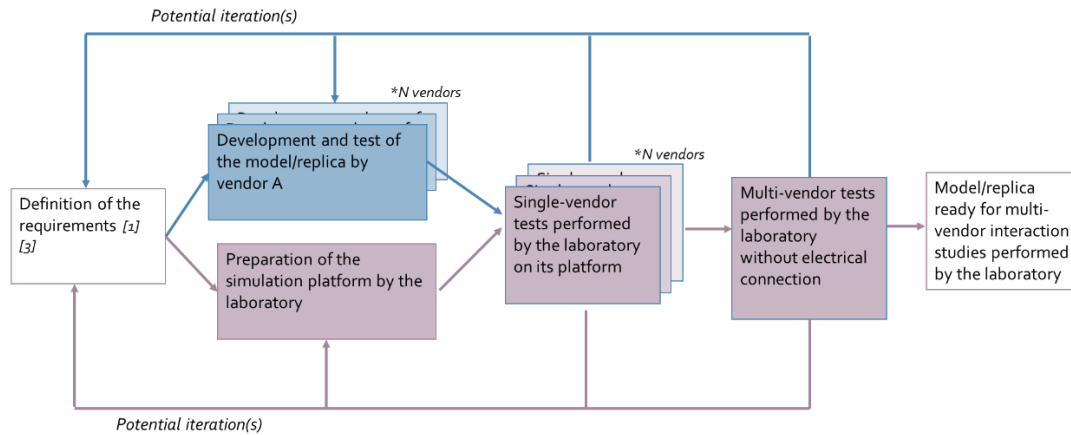


Figure 1 - Recommended methodology for a smooth integration of models and replicas in InterOPERA.

This testing activity lasted for more than one and a half years, and provided multiple lessons learned summarised as follows:

- on **the integration process** itself, from receiving the single-vendor models up to the first MV tests, as outlined in Section 2.
- on the **technical aspects** to be considered when providing **models**, as presented in Section 3.
- on the **key requirements** when working with **replicas**, as explained in Section 4.

These lessons learned are presented in the next sections, followed by concluding remarks in Section 5.

2. Importance of a rigorous and methodical integration process

The testing of MVMT HVDC system projects are becoming increasingly complex due to additional technical constraints, such as ensuring that all models can be assembled on the same simulation platform for interaction studies. From the planning perspective, the number of stakeholders who must work together is increased. Therefore, the integration process requires a much more rigorous and methodical approach, based on the key points mentioned below.

2.1. Documentation review

The integration process usually begins with a review of the documentation [4]. However, when there is a delay in the project, it is often tempting to share the model as soon as possible without the documentation in order to catch up. The InterOPERA experiment highlights that providing the documentation at the beginning is crucial to speeding up the integration process and ensuring efficient progress. Indeed, the documentation ensures that the vendor has performed the tests that will later serve as success criteria for the system integrator, i.e., all previously defined requirements are internally checked and the system integrator's use of the models is anticipated. Hence, it reduces the workload on the system integrator by explaining how to run the tests (e.g., where the necessary variables are located and how to connect the model to the test environment). It also prevents the need for multiple iterations since encountering issues involves spending more time reporting and discussing them with vendors to agree on solutions and a plan, waiting for updates, and re-running the tests.

As part of best practice, the documentation related to the partial model must be provided, even if partial model delivery is planned to secure progress. As experimented, this is particularly important in this case, since it enables the system integrator to adapt and prepare the test plan according to the available functionalities in this partial delivery. This avoids spending time on irrelevant tests and preparing subsequent issue reports for functionalities that are not yet available. Furthermore, some requirements,

such as providing a DLL that complies with [3], can significantly impact the implementation of the models. Otherwise, the system integrator may lose interest in performing tests and decide to wait for an update.

Documentation is even more important in MV projects where multiple stakeholders need to understand how to use the model. Relying on classical learning curves for each system integrator and dedicated clarification meetings with vendors is inefficient in the long-term in this context.

2.2. Integration in the test environment and initial single-vendor tests

Once the documentation has been checked, the single-vendor tests will begin. During this stage, the vendor's model is integrated into a test environment prepared by the system integrator, e.g., the AC grid for an onshore converter station. This step is unavoidable for MV projects, where each vendor's model must be extracted from its original file and integrated into a new composite model comprising all the vendors' models and the additional grid components prepared by the system integrator.

This activity has proven to be a significant milestone, offering valuable learning opportunities: the system integrator familiarises themselves with the model, learning how to integrate, connect and use it, and ensuring there are no dependencies with the original test environment. Issues may arise during this step, mostly with the initial deliveries. In this context, the need for a quick initial screening soon became apparent to sort out the important issues, allowing the corresponding vendor to be promptly notified of the required updates and allocating the system integrator's resources to other vendors.

In other occasions, rather than stopping the single-vendor tests and reverting to the vendors when issues are faced, it was important for the system integrator to be flexible with the testing strategy and make decisions on a case-by-case basis, taking into account multiple criteria. For example, what is the impact of the issue? Is it technically feasible to continue the tests? What additional effort is required from the system integrator to proceed to the next tests without validating the previous one? What are the benefits of continuing? How does this align with human resource availability and planning? How long would it take the vendor to solve the issue? And what is the level of confidence?

2.3. EMT tools' and versions' management

Within the InterOPERA project, it was decided to use several simulation tools so that the developed techniques would be as generic as possible and not specific to any particular tool. A second reason concerns the long-term availability of models and replicas, which makes it necessary to develop them independently of the simulation tools themselves. In most cases, the models were developed by vendors in a specific simulation tool, but they followed a set of rules to facilitate transfer to other simulation platforms, including:

- All electrical equipment was fully accessible to the end user (open representations and parameters), enabling manual transfer to another simulation tool.
- The representation of the control and protection (C&P) system followed the recommendations provided in [3].

Model transfer was successfully demonstrated during the integration tests carried out within the InterOPERA project. This activity requires personnel who are familiar with both simulation tools to ensure a reliable and accurate transfer.

Once the model had been transferred to another simulation tool, a set of tests was defined to benchmark the implementations across the different platforms. Because the treatment of nonlinearities can vary from one simulation tool to another, the selected tests were specifically designed to trigger saturation effects. When comparing the results, it is important to be aware that the modelling of the components and the solving methodology may be different, which leads to deviations in the results. It is worth highlighting that minor differences are expected with the relevant justification. Whatever the EMT tool, a simulation is an image of reality, not reality itself, and one must be aware of the limits and validity range of this image.

In addition to the variety of EMT tools in the market, the challenge of managing the version to be used has arisen for three reasons, even for a single EMT tool:

- As the single-vendor tests were conducted over a long period of time, different versions of the same EMT tool became available.

- DLL import tools compliant with the recommendations described in [3] were extensively exploited. While some EMT simulation tools provide built-in import capabilities, others required additional dedicated development, as detailed in Section 3.3.
- For Hardware-In-the-Loop (HIL) testing, vendors collaborated with real-time simulator suppliers to develop new interface solutions. Due to the short lead time between development and testing at the vendor's factory and in laboratories, it was necessary to temporarily use different non-commercial software versions for different companies. While managing different software versions is feasible during single-vendor testing, it must be closely monitored to ensure that a single version incorporating all the vendors' specific developments is ultimately made available by the real-time simulator supplier. Otherwise, this could be a blocking point for conducting the interaction tests.

Working with different simulation tool versions can influence the results obtained by the system integrator compared to those obtained by the vendors or even by the system integrator at a different point in time. Therefore, it is recommended that all versions of software used in a test are fully documented in the test report. It is also important to understand the differences between the versions in order to determine the need for non-regression testing.

2.4. Model's version management, iterations and issue tracking process

The versions of the models must also be carefully managed. Firstly, each version of a model should have a unique name to avoid misguided use of the model's documentation, test reports and issue trackers. In addition, clear documentation of model updates is essential for MV testing, as it provides precise details of the parts of the model that have been changed. Indeed, once a model has been integrated into a different composite testing environment, it is often easier to update only the relevant parts of the model instead of re-integrating the entire model and re-establishing all the connections with the subsystems and control blocks used for automated tests. This model's documentation is noticed during the first interaction tests, described in Section 3.2.

Once a new model has been received, it is also essential to have an up-to-date issue tracker to manage iterations and to know at any time which issues are current, which are under resolution and which have been solved. Hence, the system integrator can decide which tests must be repeated. Rigorous monitoring with written explanations, feedback and decisions, accessible to the relevant parties, is necessary, ensuring that multiple stakeholders involved in the tests are aware of the current situation.

2.5. Tests' and reports' automation

To facilitate and expedite test repetition, the laboratories adapted the test environment and model to enable automatic offline testing and developed scripts to automate as much as possible the preparation of test reports for both offline and real-time testing. This approach proved powerful given the high number of iterations encountered during testing for some vendors. It also led to the need for best practice in preparing models adapted to automatic testing, a topic discussed further in Section 3.

2.6. Data storage and data sharing

Data sharing is a complex task in MV projects due to confidentiality restrictions. Ad hoc sharing, which is sometimes used for single-vendor projects, was not appropriate when two laboratories worked together with a vendor. Alternatively, sharing on a platform provided by a specific vendor posed a risk of a confidentiality breach for the other vendors, which was not always acceptable. Based on these observations, the use of a neutral online platform with a high level of cybersecurity and a clear process for granting access rights to users is proposed.

2.7. Challenges of project management in a multi-vendor environment

In MV projects, the main difficulty is that the entire context must be considered to benefit the project as a whole rather than a single party for each decision. Indeed, each single-vendor decision influences and is impacted by the progress of the other vendors, from technical and organisational points of view. During this testing phase, these aspects had to be carefully assessed and coordinated to optimise the test plan, taking into account current and near-term availability, as well as the priorities to be addressed. For example, from an organisational perspective, the priority was set on newly delivered models in order to check as soon as possible that there were no blocking issues, thanks to a few screening tests, explained in Section 2.2. This

made it possible to revert to the vendor if necessary and perform extensive integration tests on the other available models for which there were no blocking issues while the vendor corrected their model. From a technical point of view, the system integrator must prioritise issues depending on their impact on MV testing. Does the issue prevent the model from being integrated into the MV environment, or only prevent it from being used for certain categories of tests? Or is it simply making the tests more difficult to perform? A concrete example is provided in Section 3.2.

3. Technical outcomes in offline

This section describes the technical lessons learned when handling offline EMT models from multiple vendors, from receiving the first model to conducting the initial interaction tests.

3.1. As single-vendor

As explained in Section 2.2, the system integrator performs single-vendor tests to corroborate the adequacy of vendors' model to the defined requirements, prior to MV integration. In the context of InterOPERA, the list of single-vendor tests was agreed with the vendors in advance, to ensure a common understanding of the tests and their success criteria.

To start the tests, quick initial screening tests are recommended according to InterOPERA experience. The most crucial of these screening tests include using a DLL format for the only external file (see Section 3.3 for more details), ensuring the model has the correct granularity (i.e., the entire model within a single block and clear separation between C&P, and between control and the electrical circuit), and ensuring the correct software format. These elements are absolutely necessary for a potential transfer to another EMT software.

Another worthwhile screening step involves identifying the functions that can be tested, how the control references are defined with their acceptable ranges, the capabilities of the model and the nature of the vendor's updates. For example, the initial delivery generally did not include protections, surge arresters or transformer saturation. This does not prevent an initial round of testing, even without performing the fault tests which are irrelevant. These elements can easily be updated in a later version without making too many changes to the model, so the automation process and most of the results would remain unchanged.

Given the risk of iterations, it is worth considering automation from the outset, rather than waiting for the final deliverable. This has several advantages such as facilitating discussions with the vendor thanks to rapid responses to updates as well as improving automation tools, which will increase efficiency during interaction testing. Additionally, the desire to automate the tests may result in additional requirements to enhance automation capabilities, such as a preference for timetable inputs that can be defined at the start of the simulation rather triggering event with manual actions during the simulation.

Finally, specific constraints arise from the presence of multiple models in the same canvas in simulation software. For example, signal names must be managed carefully and wireless connections should be avoided, bundles should be used for input/output, timesteps should be compatible with common pre-defined values (10 and 20 μ s in InterOPERA), without being hardcoded in multiple locations, the control framework in the DLL block should be broad enough to encompass all loops, to avoid burdening simulation time, and global variables should be avoided.

3.2. First interaction tests

Following the single-vendor tests, it was initially planned to conduct isolated MV tests. These involved repeating the single-vendor tests with all the vendors' models included in the same file, but without electrical connection, to ensure consistent results and identify any software implementation conflicts between the vendors' models. However, to save time, it has been decided to bypass those tests during the dry run phase and instead proceed directly with a fully connected three-terminal system, which also allowed testing of the basic control functionalities in a MV setup. The demonstrator system in Figure 2 consisted of five vendor contributions (Ven A–E): two converter stations (Ven A and Ven B1), five DC Switching Station (DCSS) units from two vendors (Ven B2–B3 and Ven C1–C3), one wind farm model (Ven D), and (Ven E) as a DC Grid Controller (DCGC). Vendor A operated in constant DC voltage control and vendor B1 in constant active-power control, while a generic converter at the southwest terminal provided V/f control for the wind farm. The system was successfully energised and remained stable for 60 s using a 10 μ s time step with the stable condition as depicted in Figure 2. On a standard personal computer (Intel 13th-generation CPU with 6 P-cores, 8 E-cores, and 32 GB RAM), a 5-second simulation required roughly 10 minutes.

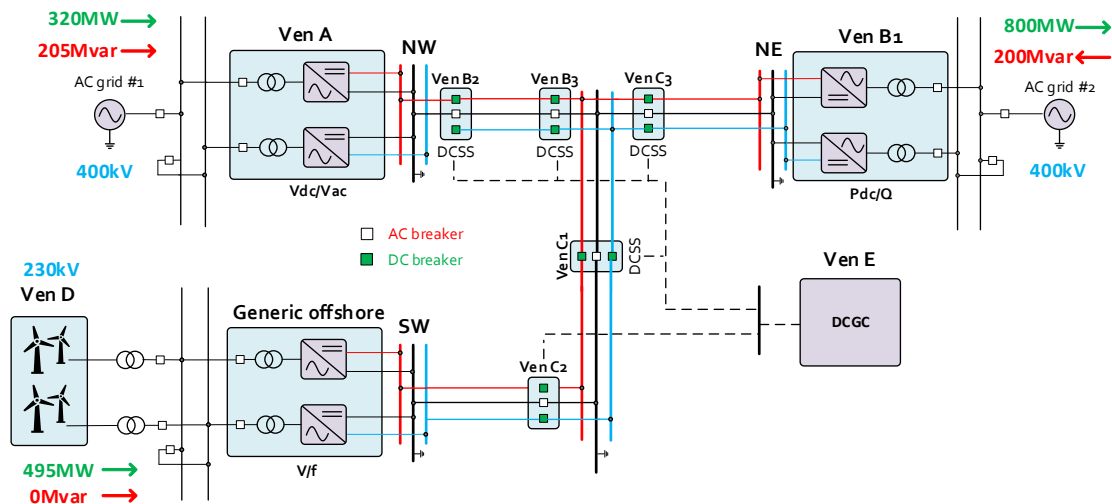


Figure 2 - Three-terminal HVDC grid with five vendors' models successfully energised during the preliminary tests

During integration process, several iterations of model tuning were required, revealing clear interactions between models and showing that difficulties can arise directly from not meeting the interoperability requirements defined in [1]. Requirements that are less important for single-vendor tests were revealed to be key in a MV environment. Consequences ranged from making it more difficult to prepare and perform the tests and slowing down progress, to being unable to integrate a specific model into the MV environment at all. For example, the system integrator faced blocking issues such as incompatible DLL architectures (32-bit vs 64-bit), which completely prevented further integration. Other non-blocking issues that significantly increased the integration workload include deviations of the delivered models from the required structure, undocumented updates, and dependencies on global variables or external configuration files, as well as missing snapshot support. Additional improvements that could facilitate integration include the ability to deactivate protection mechanisms of the DCSS units, more flexible control of converter stations and wind farms during energisation, replacing manual components with runtime-configurable components to support automation, and providing hinting flags during energisation to help identify issues.

Overall, when the models adhered to the requirements in [1] and followed the IEEE/CIGRE DLL conventions [3], the integration proceeded much more smoothly and the energisation sequence could be carried out efficiently.

3.3. Lessons learned on the IEEE/CIGRE DLL

The DLL format, based on the IEEE/CIGRE brochure [3], is a new methodology that was designed to enable C&P models to be used with simulation tools. This brochure was released during the InterOPERA project. Consequently, InterOPERA was often the first application for vendors and was used as a testing ground where bugs could be quickly identified and updates released.

However, identifying the root cause of errors when interfacing with a DLL can be challenging, as the correct behaviour of the model is not always apparent to the system integrator, who may lack an in-depth understanding of the vendor's technology. Errors could arise from multiple causes, such as the import toolbox, the DLL itself or the installation of files on computers. In the InterOPERA project, although the use two different EMT software tools was originally intended to demonstrate the concept of tool-independence, it also proved useful in facilitating the comparison and identification of issues.

It is recommended that a generic import toolbox be used instead of a vendor-specific import toolbox, as the latter is based on the vendor's own interpretations and expectations, which may not be clearly documented. While the benefits are recognised, a strict and unified interpretation of the format is necessary to avoid errors when a generic import toolbox is used.

Therefore, improvements were developed in the generic import toolboxes used in InterOPERA to fulfil the vendors' expectations. For example, improvements have been made to the order of functions included in the import toolbox, limitations associated with names (e.g., length), input and output types and formats

have been removed, and options have been added for interpolation if the DLL time step is smaller than the simulation time step and for an automatic time step that adapts to the simulation time step.

It is worth pointing out that the import toolbox developed by RTE and TU Delft is available as open-source software online [5]. This toolbox facilitates the dissemination of this methodology among systems operators, system integrators, and vendors beyond the project, and when built in import tool was not available in specific simulation tools. For other EMT simulation tools, the import functionality is natively integrated.

4. Technical outcomes in real-time

This section elaborates on the lessons learned during HIL testing with real-time simulation (RTS) and physical C&P replicas, and the difficulties in moving from single-vendor to multi-vendor environment.

4.1. Requirements for the single-vendor testing

In the InterOPERA project, several requirements have been defined to ensure the efficient RTS testing in MTMV grids. In addition to the model, these requirements include Human-Machine Interface (HMI), Transient Fault Recorder (TFR), synchronization, and documentation.

From the model perspective, the time step plays a crucial role for MTMV RTS. Since the C&P cubicles of the vendors are designed to work with a specific timestep, the main timestep(s) for interaction tests should be agreed upon. Otherwise, the performance of the model with the minimum main timestep would be affected. This challenge is successfully resolved in the InterOPERA project by limiting the main timestep to 50 μ s and 60 μ s for a specific simulator type. Furthermore, in a case where the main timestep was eminently far from these values, the vendor successfully implemented the model in a sub timestep environment in response to the labs' request. Hence, it can be simply adjusted to operate with these main timesteps with high fidelity. However, the challenge lies in the fact that the definitions of time step, main step and sub step depend on the simulator's brand. Different values may need to be used for a different brand with their own solving approach. To obtain consistent and comparable results in this case, extra work is needed to find a time step that is compatible with both the replica and the simulator. For example, it may be necessary to optimise the model to reduce the computational burden or improve the solver on this second simulator brand, as illustrated in [6], in order to find an adequate time step.

More generally, InterOPERA requested non-proprietary, well-documented interfaces with the simulator to interface the replicas with different simulator brands. This requirement is crucial to ensure the tool independency and facilitating the long-term use of the replicas. Thanks to this requirement, it has been demonstrated that the same replica could be connected to two different simulator brands, potentially after requesting the necessary interface development from the simulator manufacturer.

In addition, several requirements have been defined for HMI and TFR to corroborate an accurate MTMV testing process and data extraction/analysis. For the prior, automatic sequencing is preferred, e.g., the breakers open/close during (de)energization sequences with the minimum user intervention. Automatic sequencing is very important especially in a MV system with different HMI. The TFR has been set to record the agreed signal list for short and long durations. Therefore, both transient (e.g., DC and AC faults) and steady-state-based tests (e.g., ramping up the converter) are fully covered by the TFR with a sufficient sampling rate, thanks to the defined requirements. Another important requirement for the TFR is the capability to trigger it from the RTS. Hereby, the TFR of all vendors is triggered at the same time. This is a crucial feature in a MT system. Naturally, this requires the synchronization of all vendors' replicas through a Global Navigation Satellite System, considered in InterOPERA.

The results of the RTS will be analysed through the TFR records as well as the event and alarm logs. The lab and vendor can thereby simply track the testing process and replica's reaction by these logs, e.g., blocking the converter after a fault event. Regarding the TFR, the extraction and analysis of the recorded data would be eminently time-consuming in the MTMV environment. After conducting the test(s), the data of all vendors should be collected, considering their TFR approach. Then, these data should be plotted, depending on the vendor solution. In InterOPERA, both data collection and plotting processes differ from one vendor to another, making them time-consuming.

Finally, the vendors upgrade the TFR and the HMI through the established remote access. This connection not only saves the vendors' time and resources (i.e., by eliminating the need for travel to the labs) but also accelerates the fixing of issues identified by the labs. Keeping the model/replica requirements in mind, a few are requested from the vendors to facilitate the efficient building of the MTMV test grid. To this end,

vendors are requested to present documentation for the model details, replica inventory, and factory acceptance test, as well as train the labs' experts. The experiences gained in InterOPERA highlight the importance of these documents and training for both labs and vendors in concluding the adequacy of the model/replica for MTMV testing.

The next step in the InterOPERA is to integrate these models into an MTMV environment, known as a demonstration. Thanks to the well-defined requirements and tight collaboration between vendors and labs, it is expected that this transition will be accomplished efficiently. Thus, the largest MTMV HVDC testing will soon commence at both labs.

4.2. Steps for the MV integration and testing

After completing the single-vendor RTS, the integration of the three-terminal MV HVDC grid (demonstrator) should start. The smooth process of building such connection is depicted in Figure 3 and follows five steps:

1. Building a point-to-point system, including two onshore Converter Stations (CSs);
2. Replacing one onshore converter station with an offshore one, and integrating two Offshore Wind Parks (OWPs);
3. Integrating standalone DCSS;
4. Integrating the DCGC to exchange the setpoints, control modes, and open/close commands of the breakers;
5. Connecting the third converter to build the three-terminal system.

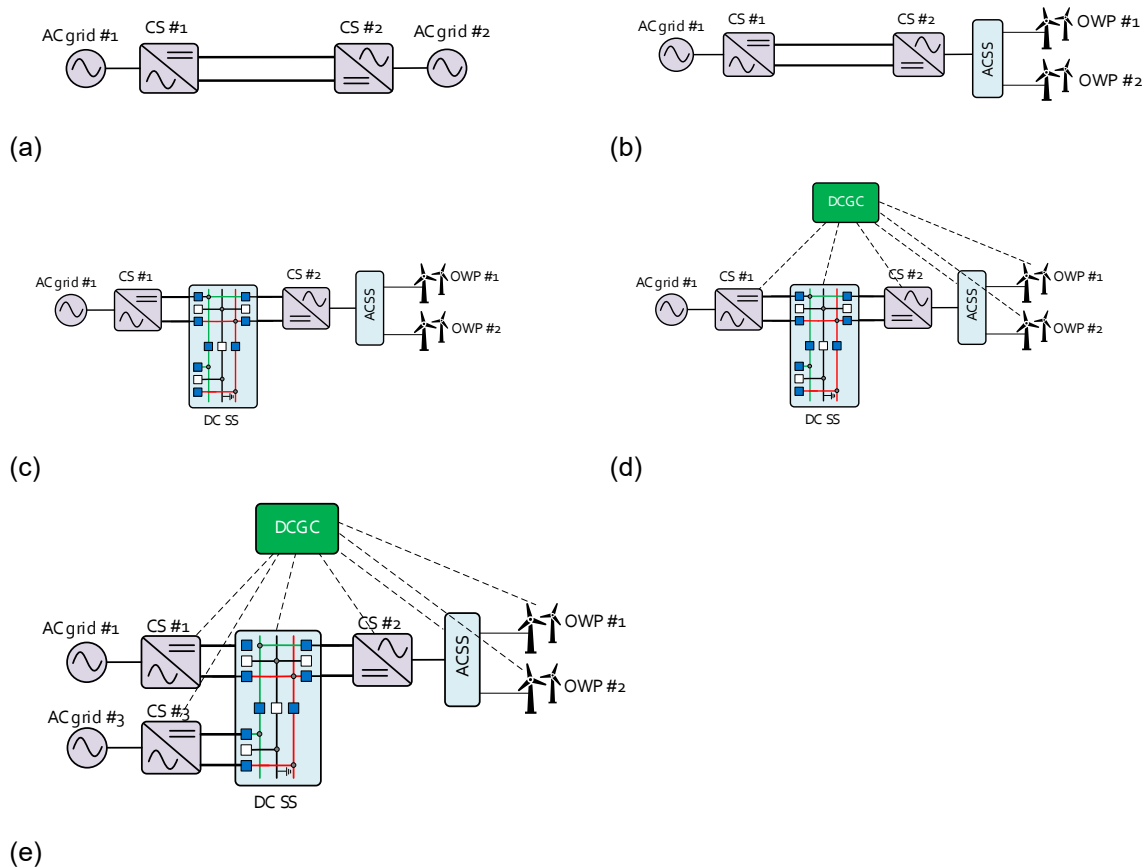


Figure 3 - Steps for integration in the MVMT system: (a) Step 1: Building a point-to-point test system with two onshore converter stations, (b) Point-to-point connection with OWPs, (c) Addition of the standalone DCSS, (d) Integration with the DCGC, and finally, (e) fully connected three-terminal HVDC system.

It is finally worth noting that this planning might deviate, depending on the delivery of the vendors in the InterOPERA project.

5. Conclusion

As part of the InterOPERA project, conducting tests with template models and replicas in multiple offline and real-time simulation environments provided valuable insights into the integration process and the key requirements.

First of all, the time-consuming process of the platform preparation and the models/replicas integration requires skilled system integrators. This must be anticipated in the planning stage to prevent delays during project execution.

The importance of documentation in all aspects was highlighted: model documentation, as well as documentation of model/replica updates and issues. It also emphasised the value of conducting initial single-vendor screening tests to quickly detect major or blocking issues, and of using a test environment prepared by the system integrator to gain better insights.

From a technical point of view, one of the key requirements for successfully integrating models in a multi-vendor environment for offline interaction studies is preparing the C&P part based on the IEEE/CIGRE DLL principle, with the expected functionalities. Thanks to this project, this methodology is expected to become more reliable. The model must also be compatible with pre-defined time steps and test automation. It must be structured in such a way that it can be easily integrated into a different test environment with interfaces for the other models. Finally, the model must provide access to all relevant parameters and signals for tests, reports, debugging and analysis.

For HIL testing, the challenges lie in the ability to interface with several real-time simulators via well-documented, non-proprietary interfaces as well as finding time steps that are appropriate for all the replicas and the real-time simulators. The HMI and TFR are also key elements in facilitating the tests and preparing/analysing the reports, and their correct implementation must be carefully considered.

According to the lessons learned from the integration process in offline and real-time platforms, the labs are now looking forward to conducting the interaction studies for the largest HVDC project worldwide.

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DISCLAIMER



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