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1 EXCUTIVE SUMMARY

This document delivers the main conclusions of the feasibility assessment of using control and protection replicas in HIL laboratory testing for de-risking the NSWPH concept. The questions and concerns raised by the NSWPH consortium have been addressed in detail, and recommendations in operating the HIL facility and rolling out a multi-vendor modularly developed HVDC-OWF project have also been provided based on the experience of RTE and RTE international.

This document starts off by identifying the risks in the design and operation of an HVDC-OWF project involving multi-vendor PED systems and developed over a long time-span. This is followed by an empirical de-risking methodology with focus on the recommended adequate tools, methods and models for different project development phases. Experience and internal studies conducted at RTE are shared with the NSWPH consortium in order to demonstrate the adverse impact of the identified risks and the importance of following the recommended methodology to de-risk the design and ensure stable system operation.

It then embarks on the discussion of the approach of using the HIL setup with real-time simulation and C&P replicas, highlighting particular considerations that should be taken into account with respect to the application (i.e., HVDC, OWF) and purpose (i.e., study, maintenance). The advantages and limitations of such an approach to de-risking the design and operation of the NSWPH project are supported, once again, using practical experience and knowledge base of RTE and RTE international.

Moreover, the financial, infrastructural, and human resource aspects of operating HIL laboratory facilities have been addressed, offering further insight into the project roll-out in terms of resource preparation and management.

Finally, the questions and comments received from the NSWPH consortium upon their review of revision R0 have been responded to and provided in Section Q&A.

It should be noted that the solutions, propositions, recommendations, and advice are presented strictly based on our experience and the technological status quo that is relevant solely to the currently available technical development and solutions. It is possible that certain implementation constraints will be relaxed, and enhanced solutions will become available with future technical advancement, which would entail further studies thus is out of the scope of this document.

It is believed that this report of feasibility assessment can help the NSWPH consortium with their decisions on whether or not to use the HIL setup with C&P replicas in interoperability studies and how to efficiently and effectively carry out all necessary testing and study activities using the HIL lab facilities with proper resources.

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3 DEFINITIONS AND ABBREVIATIONS

AC	Alternating Current
C&P	Control and Protection
DAE	Differential-Algebraic Equations
DC	Direct Current
EMT	Electromagnetic Transients
FAT	Factory Acceptance Test
HIL	Hardware-in-the-Loop
HV	High Voltage
HVDC	High Voltage Direct Current
MIIF	Multi-infeed Interaction Factor
MMC	Modular Multi-level Converter
OWF	Offshore Wind Farm
OWG	Offshore Wind Generator
PCC	Point of Common Coupling
PED	Power Electronics Device
RMS	Root Mean Square
SSTI	Sub-synchronous Torsional Interaction
TFR	Transient Fault Recorder
THD	Total Harmonic Distortion
TOV	Temporary Overvoltage
TUV	Temporary Undervoltage
UIF	Unit Interaction Factor
VSC	Voltage Source Converter
WPP	Wind Power Plant
WG	Wind Generator
WTG	Wind Turbine Generator

4 INTRODUCTION

To meet the Paris Climate Goals and considering that offshore wind energy is one of the key building blocks for the green transition of Europe, the European Commission published the EU Offshore Renewable Energy Strategy in November 2020, aiming to develop 300 GW of offshore wind complemented by 40 GW of other offshore energy technology by 2050. Established in 2017 and incentivized by the 2050 offshore wind energy capacity target set by the European Commission, the North Sea Wind Power Hub (NSWPH) consortium has been actively engaged in seeking a solution to accelerating energy transition in Europe by working towards the realization of the first offshore wind power hub project in the early 2030s.

The NSWPH consortium envisages to adopt the hub-and-spoke concept for the offshore wind power hub development, with the interconnected hubs spanning across country frontiers and integrating different energy sectors and carriers, as is illustrated in Figure 4-1 [1].

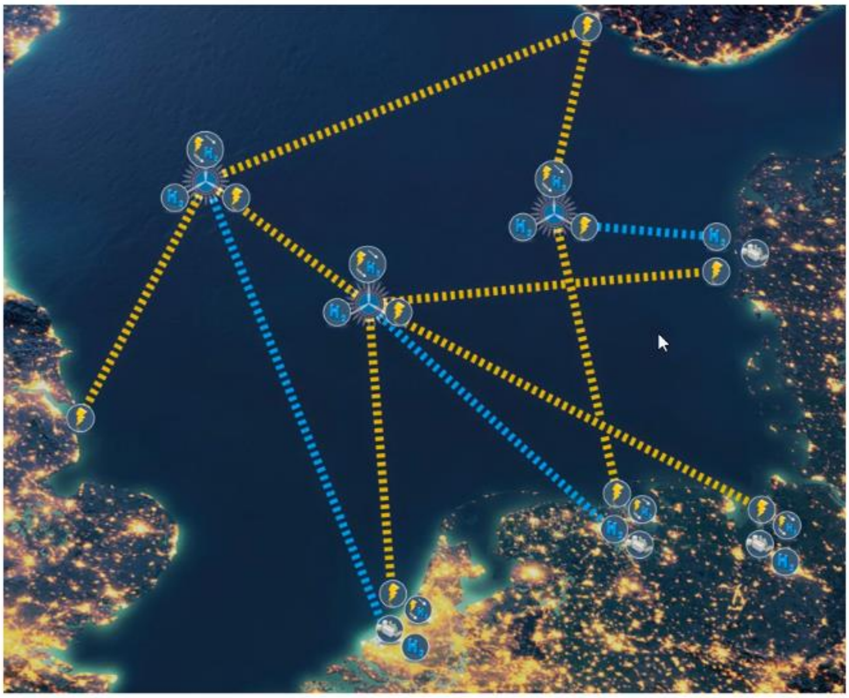


Figure 4-1 – The modular hub-and-spoke concept for NSWPH.

To this end, several pre-feasibility studies have been conducted internally with the intention of exploring different technological options and identifying potential technical challenges. Since this ambitious project would involve offshore wind and HVDC technology from different manufacturers and its development would be carried out gradually and modularly in several phases over a long time-span, questions are raised with regard to the particular technical challenges in this backdrop, especially in how to effectively de-risk the design of the NSWPH project to ensure stable grid operation. In particular, the use of the hardware-in-the-loop (HIL) setup with control and protection (C&P) replicas from different HVDC and OWF vendors in the de-risking process draws a great deal of interest from stakeholders of the NSWPH consortium, and they are seeking to investigate whether the HIL setup with C&p replicas would be necessary for the de-risking process. Thanks to their extensive experience acquired in working with C&P replicas in past and on-going projects involving multi-vendor applications as well as their active contribution to various Cigré working groups on this topic, RTE international was contracted to draw up this feasibility report of de-risking the design and operation of the NSWPH project using the HIL setup with real-time simulation and the C&P replicas.

This document starts off by identifying the potential risks in the design and operation of such a multi-vendor, multi-technology project, taking into consideration its characteristics of gradual and modular development due to future grid planning and expansion. It then introduces a detailed methodology as well as associated adequate tools currently in force within RTE and RTE international to assess the risks and ensure stable and optimal grid operation, supported by practical experience in the form of case studies gained in past multi-vendor HVDC-OWF projects.

An elaborated description of the application of the HIL setup with the C&P replicas in real-time simulation to de-risk the NSWPH project is provided in the following chapter, with focus on the technical considerations in using the C&P replicas for different applications (i.e., HVDC, OWF) and purposes (i.e., study, maintenance). The advantages (and sometimes necessity) of such an approach are, once again, supported by practical experience of RTE and RTE international from past and on-going projects.

As operating the HIL lab facilities in the studies and testing of the NSWPH project is a demanding task that requires additional investment in equipment, infrastructure, human resources, organization, and coordination, at the request of the NSWPH consortium, RTE and RTE international also share their experience and provide recommendations regarding the aforementioned aspects. In this chapter, the experience and recommendations from RTE and RTE international are best adapted to the specifics of the NSWPH project, with the hope that all relevant activities and milestones can be rolled out in a timely manner.

It is noted that the ten items in the scope of work proposed by the NSWPH consortium are fully covered in this document and are restructured for coherence. In particular:

- Items 1 and 2 are covered in Chapter 5.
- Items 3 and 4 are covered in Chapter 6, with the absolute necessity of using the C&P replicas demonstrated in Sections 6.1.6.1 and 6.2.
- Items 5 and 6 are covered in Chapters 6 and 7. Specifically, different technological options and purposes for C&P replicas are presented in Sections 6.1.3, 6.1.4, and 6.2.4. Due to NDA constraints in past and on-going projects in which RTE and RTE international are engaged, actual cost related to the procurement of real-time simulators and C&P replicas cannot be disclosed, as was agreed upon with the NSWPH consortium. Instead, cost related to the procurement of real-time simulator for the NSWPH can be scaled up and estimated in Section 7.1, and considerations for the C&P replica specifications are also provided in Section 7.2 as a supplementary contribution of this document. It is difficult to generalize the cost related to the operation of the HIL laboratory (i.e., infrastructure and human resources) as it entails aspects beyond the scope of this document, we believe Sections 7.3 and 7.4 could shed some light on this matter and help the NSWPH consortium better prepare for operating the HIL lab facilities.
- Items 7 and 8 are elaborated in Chapter 7, especially in Section 7.3.
- Items 9 is scattered throughout the document and is related to any aspect elaborated in this document but not mentioned in the scope of work proposed by the NSWPH consortium, whereas Section 7.4 is tailored to Item 10, with milestones and principal activities in an on-going multi-vendor project serving as a guideline for the roll-out of the NSWPH project.

5 RISKS ASSESSMENT OF THE NSWPH CONCEPT

In order to ensure the proper design and stable operation of the first hub-and-spoke project in the early 2030s, it is necessary to understand and identify the potential risks in the multi-vendor, multi-technology NSWPH concept that is intended to be developed gradually and modularly with respect to future decision-making and grid expansion. The operational risks in the NSWPH concept are, firstly, identified and explained in this chapter, where cross-system control coordination and interaction would raise great challenges in the design and operation of the NSWPH project. A methodology accompanied by adequate study tools adopted by RTE and RTE international in de-risking the design and operation of multi-vendor HVDC-OWF projects is presented, including a list of recommended dynamic studies that should be performed at different development stages of the NSWPH project. This is followed by case studies from the experience of RTE and RTE international in successfully identifying and resolving issues that occurred on site with the help of the proposed methodology.

5.1 Operational risks in a multi-vendor, multi-technology HVDC-OWF system

The installed HVDC-OWF systems in Europe to date are all based on the point-to-point connection with symmetrical monopole HVDC configuration. As an example, a symmetrical monopole VSC-HVDC link connected to an OWF is illustrated in Figure 5-1.

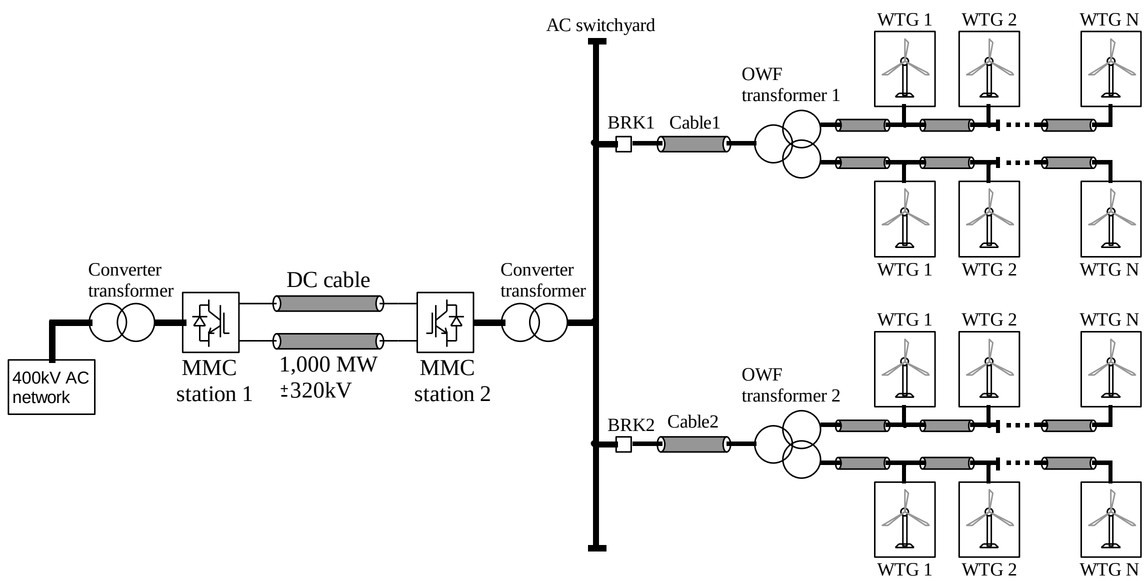


Figure 5-1 – Overview of an HVDC-OWF system

The NSWPH consortium envisions to realize the first hub-and-spoke project in 2030 with multi-infeed, multi-vendor and multi-technology systems for both HVDC and OWF. The onerous technical requirements in the complexity of the Control and Protection (C&P) systems involved as well as the gradual and modular development nature of the project raise great challenges in the following two aspects:

- Lack of sufficient offshore grid code
- Cross-system control coordination and interaction

These two challenges are intertwined with one another for reasons to become evident hereinafter. Despite the fact that both would have a significant impact on the design and operation of a power electronic device (PED) based system, interaction phenomena, as the final manifestation, are more common in a system involving multi-vendor and multi-technology PEDs such as the NSWPH concept. They are generally difficult to identify and analyze, thus require particular attention.

5.1.1 Lack of sufficient offshore grid code

Multi-vendor and multi-technology OWF and HVDC systems could be located at the same offshore hub or interconnected at several offshore hubs. Grid code compliance is currently defined as an onshore interface measure. However, within designs involving multiple offshore systems, such as in the NSWPH concept, the role each system plays in a given function is important. Therefore, it is important for such a function to be clearly defined and the expected performance of each offshore system to be stipulated as it is not sufficient to ensure stable grid operation with all offshore systems complying merely with onshore grid code. Several regulations and documents have been published with the intention of extending the Network Codes and specifying requirements for offshore HVDC and wind park connections, such as [2], [3]. Nevertheless, these regulations and documents remain rather general and lack sufficient details for industrial applications with similar levels of complexity as the NSWPH project. Therefore, the lack of sufficient offshore grid code makes it difficult to correctly stipulate control functions to achieve satisfactory offshore system performance, leading to potential interaction issues between various systems, which will be further explained hereinafter.

5.1.2 Cross-system control coordination and interaction

The guarantee of the multi-vendor interoperability of the NSWPH concept faces challenges of adverse interactions between different PEDs from both HVDC and OWF systems, network passive components and/or conventional onshore power plants, for both the AC and DC grids.

An interaction is a reciprocal action exerted by a system on one or several other systems. Interaction between components is not necessarily harmful to the network and the system. Therefore, it is important to distinguish interactions with positive effects from those resulting in negative consequences. Positive interaction leads to the improvement of network stability, whereas a negative interaction (or negatively damped interaction) causes deterioration of system performance.

PED can excite a series of unexpected negative interactions on the grid with their fast controls governed by smaller time constants as compared to conventional synchronous generation-based power systems. Moreover, due to their fast-switching capabilities, PED can distort the line voltage by injecting additional harmonic voltages and currents into the grid. The complete installation of a PED, therefore, should not be considered as a passive system knowing that the control mechanisms are capable of amplifying rather than attenuating disturbances such that the system becomes locally unstable if not properly tuned. These local instabilities, either onshore or offshore, could trigger the trip of PED (HVDC stations or large OWFs), leading to power imbalances which could further jeopardize the global frequency stability.

Two possible hub configurations have been considered by the NSWPH consortium, as is illustrated in Figure 5-2. In the two proposed configurations, the OWF hubs can be interconnected by either HVAC or multi-terminal HVDC systems, giving rise to possible adverse interactions in both the AC and DC grids.

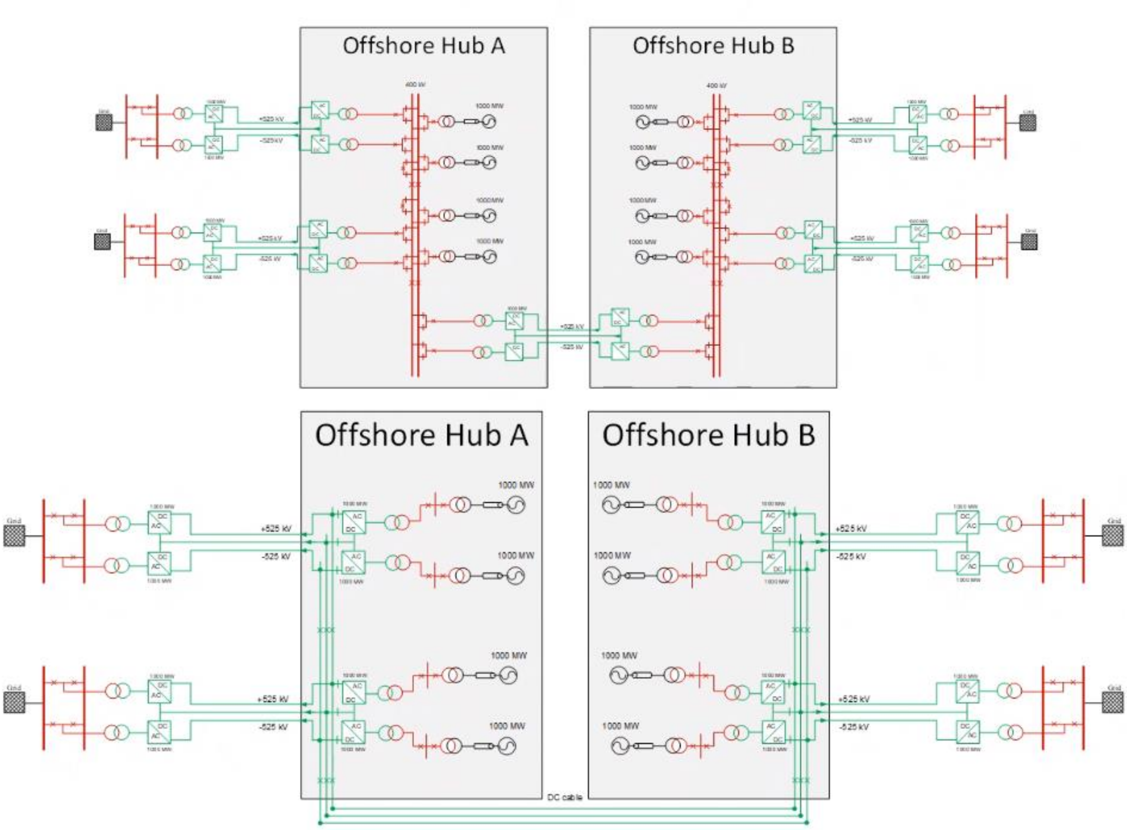


Figure 5-2 – Possible hub configurations (above: HVAC coupled hub; below: multi-terminal HVDC hub).

Table 5-1 provides an overview of potential interaction phenomena that may arise between at least two main PEDs in an AC grid. Additionally, adequate tools that should be used for different studies are included in the table as well. It is noted that this table is based on the ongoing Cigré WG B4-81 activities, following the initial work conducted in [4].

Table 5-1 – Categories of interaction phenomena between power park modules (PPMs) based on Cigré WG B4-81.

Multi-Infeed and Interaction Study Interaction between : at least two main power electronic devices (HVDC, FACTS, Renewables, etc.)					
Control loop interaction		**Interaction due to non-linear functions**		**Harmonic and Resonance interaction**	
Near steady-state (slow control)	**Dynamic (fast controls)**	**AC fault performance**	**Transient stress and other non-linear interaction**	**Sub-synchronous resonance**	**Harmonic emission and resonance**
• AC filter hunting • Voltage control conflicts • P/V stability	• Power oscillation • Control loop interaction • Sub-synchronous control interaction • Voltage stability	• Commutation failure • Voltage distortion • Phase imbalance • Fault recovery • Protection performance	• Load rejection • Voltage phase shift • Network switching • Transformer saturation • Insulation coordination	• Sub-synchronous torsional interaction	• Resonance effects • Harmonic emission • Harmonic instability • Core saturation instability
• 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	• Harmonic analysis • EMT time domain • Small-signal analysis

The different types of interaction listed in Table 5-1 are described as follows:

➢ Control loop interactions

Interactions between control loops are commonly studied for power system stability. The dynamic behavior of a power electronics component is chiefly dictated by the control system. Therefore, interactions can take place between control loops due to the control gain values of the control loop (e.g., PID control, droop control, etc.). This type of phenomenon includes two sub-types, which are slow and fast control dynamics, as is highlighted in Table 5-1.

- Interaction due to non-linear functions

During severe disturbances (e.g., faults, outage, etc.), the non-linear functions (protections, fault ride through, limiters, transformer saturations, etc.) dictate the behavior of the PED system. In these cases, EMT transient simulations should be conducted for AC and DC faults, transformers and converters energizations, start-up sequences, connection/ disconnection of large reactive/active loads, etc.

- Harmonic and resonance interactions

These interactions include high frequency harmonics emitted and resonances that can take place between several PEDs. The harmonic emissions and resonances are not limited to the voltage level of the connected equipment and can propagate into neighboring networks.

Harmonics and resonances in a system may reduce the power efficiency and result in insulation degradation of the system components if not limited properly. Furthermore, high harmonics that propagate to power electronic components through the AC grid can cause overheat in the equipment and communication circuits by interferences, leading to system malfunction. Two different high frequency phenomena can be distinguished (Figure 5-3):

- Harmonic emissions associated with semiconductor switches, thus continuously transmitted by the system, which may affect power quality. These harmonics can add or subtract depending on the interactions that occur between the two components.
- Harmonic resonances mainly related to the control system, filters, delays, etc. High frequency resonances have been reported in HVDC-VSC links such as INELFE, Borwin 1 and Luxi B2B projects [5].

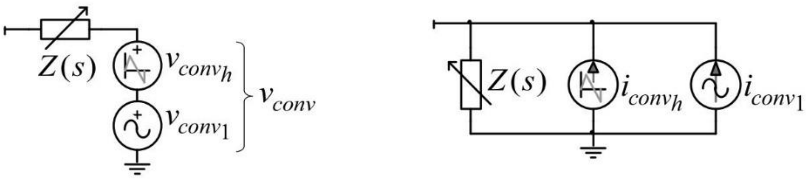


Figure 5-3 – Converter equivalent circuit for frequency response studies

Interactions due to power electronics devices have been encountered in the world. In particular, harmonic interactions studies between wind farms and transmission grid on an existing system are described in [6], which demonstrates that detailed models of wind farms equipment are required to accurately assess the phenomena. In [7], interactions between a wind farm and a compensator series are documented. In [8], problems of harmonic interactions between an HVDC link and wind farms are reported. To evaluate the risk of interactions between these new facility-based power electronics, studies have been conducted in [9] between HVDC-VSC and STATCOM equipment. A description of different types of interaction phenomena that may occur in power electronics devices is provided in [10] in which an analytical approach, based on the MIIF criteria, is presented for the investigation the risk of interactions between power electronics devices. The purpose of the work presented in [11] is to understand whether a VSC operating as an inverter for Type-IV wind turbine and PV application could form SSR with the grid, especially a weak grid with or without series compensation. In [14], the authors analyze the consequences of aggregation on the critical modes of system resonance. It is found that the dynamic aggregation does produce significantly different values of damping to several modes, and these simplifications will lead to important consequences in the interaction studies with the transmission grid.

As for the second possible hub configuration where OWF hubs are coupled via multi-terminal HVDC interconnections, it is still a rather novel concept on the European market.

Multi-terminal, multi-vendor HVDC interconnections have reportedly been in operation in China (Nan'ao [15] and Zhoushan). Nonetheless, the implementation of such a configuration in Europe still faces great obstacles due to IP issues with different HVDC converter manufacturers. Whether multi-terminal HVDC configurations are initially envisaged to interconnect certain hubs in the NSWPH project, or they are introduced at a later stage of project development due to the need of DC grid expansion (gradual and modular project development), the fact that different vendors could be contracted to deliver the converter technology with each vendor having no access to the technology of the others would indicate potential interaction phenomena even on the DC grid.

In collaboration with world-leading HVDC manufacturers, major European TSOs and renowned academics, RTE led the Best Paths DEMO#2 R&D project funded by the European Union's Seventh Framework Programme for Research, Technological Development and Demonstration [16] dedicated to the investigation of interoperability issues in multi-terminal, multi-vendor HVDC-VSC systems and the proposition of mitigation measures and recommendations. The project was carried in two stages using the offline and real-time simulation approach, respectively, in each stage. Several DC grid configurations (Figure 5-6) and hundreds of scenarios, comprised of various AC grid configurations, converter technologies and control modes, network electrical parameters and dynamic events, were studied. Believed to originate from the same root causes as is summarized in Table 5-1 (i.e., due to control loops, nonlinear functions as well as harmonic and resonance), the following interaction (or interoperability) issues were witnessed:

- Oscillatory behavior
- Differences in converter ratings
- Differences in converter dynamics
- Abnormal protection actions (i.e., abnormal converter tripping and blocking, etc.)

The following example is given to further explain the oscillatory behavior due to interoperability issues. Assuming a scenario with an active power ramp from 0 to 1000 MW in a single-vendor point-to-point connection. The DC voltage variations are illustrated in Figure 5-4.

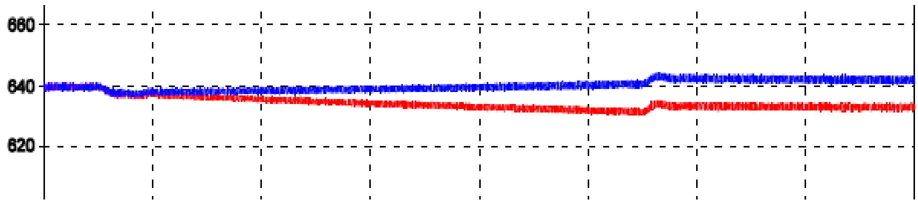
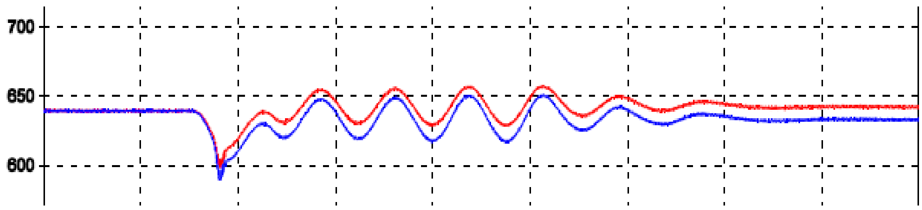


Figure 5-4 – Example of reference DC voltage during a step in active power on a point-to-point link (single-vendor)The observed DC voltage behavior corresponds to the specifications and is thus expected. However, if both converter stations are from different vendors, the same simulated scenario could render a DC voltage behavior as is illustrated in Figure 5-5.



- Figure 5-5: Oscillations observed on the DC voltage during a step in active power on a point-to-point link (multivendor configuration), illustrating some interoperability issue

It can be observed that the DC voltage oscillates for a certain period of time following the active power ramp before being stabilized, which is not expected according to the specifications for each individual converter station, indicating a system performance degradation. The performance degradation in a multi-vendor system, as compared to the case where a single vendor provides the technology for the entire system, is called an interoperability issue. Recommendations for the NSWPH concept on the implementation of multi-vendor, multi-terminal HVDC configuration as well as gradual and modular grid expansion derived from the Best Paths DEMO#2 project will be provided hereinafter.

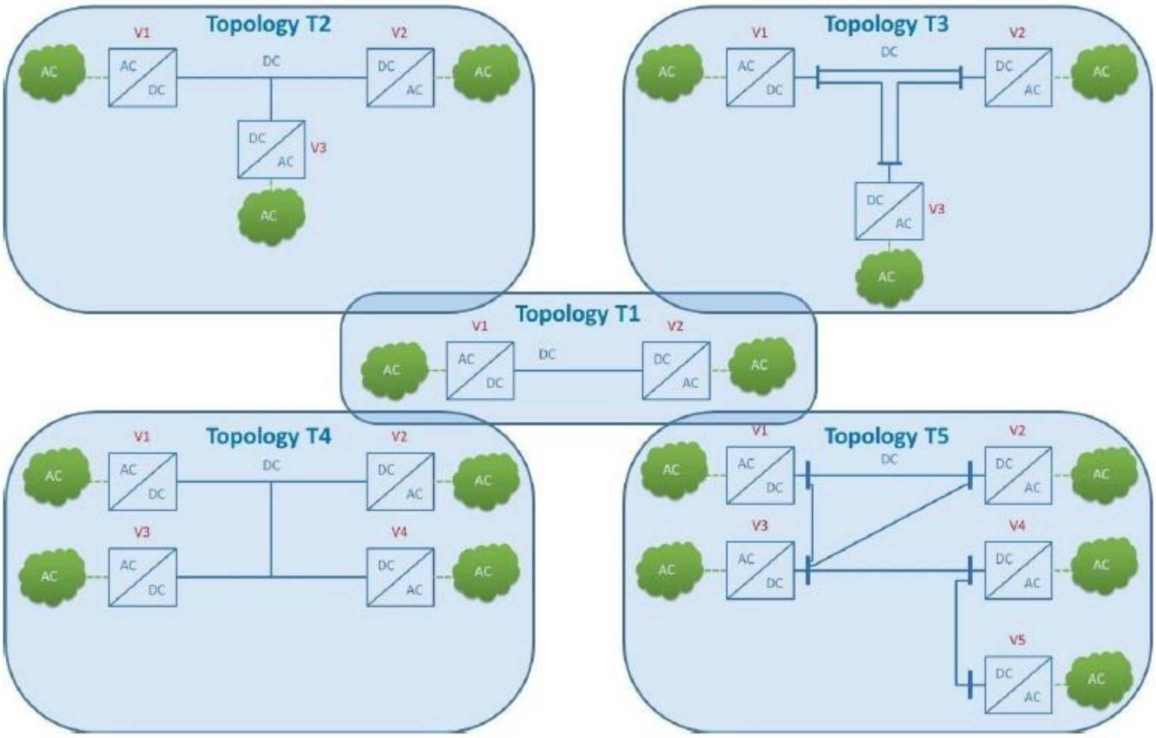


Figure 5-6 – DC grid topologies studied in the first stage of the Best Paths DEMO#2 project [16].

Although a relatively mature empirical methodology developed from collective effort between the industry and academia is available for analyzing and mitigating adverse interaction phenomena in a complex power system dominated by PED-based devices, difficulties may still arise due to the following reasons:

- High complexity of C&P system of each device and requirement of its accurate representation.
- Confidentiality and intellectual property issues related to the C&P algorithms of each vendor.
- Utilization of different software tools with multiple software versions, compilers and different numerical integration time-steps.
- Accuracy of simulation parameters/data of the device model provided by the vendor.
- Maintenance of the device model through the lifetime of the project.

Considering the potential risks discussed above in the NSWPH concept involving multi-vendor technologies with a nature of gradual and modular development, a general methodology that should be adopted in order to de-risk the design and operation of the systems is provided in the following section.

5.2 Recommended de-risking methodology for the NSWPH concept

As was discussed in the previous section, the NSWPH concept is envisaged to unfold gradually and modularly in the next decade with the goal of realizing the first hub in the early 2030s. Given the fact that this project entails multi-infeed, multi-vendor, and multi-technology systems, several types of potential risks have been identified in the previous section, which are lack of offshore grid code, and, more importantly, cross-system control coordination and interaction.

In order to de-risk the design and operation of the NSWPH project and to achieve optimal performance while minimizing system downtime due to unexpected events, dynamic simulation studies using adequate tools should be conducted at different development stages of the project, given that reliable and interoperable models are available. Therefore, firstly, this section introduces the main software tools and methods that can be used to assess and de-risk the NSWPH project. It is then followed by a detailed description of various types of EMT models generally available for dynamic studies of PED-based systems together with their advantages and limitations. Finally, recommendations for dynamic studies that should be performed with appropriate tools and models at different development phases of HVDC-OWF projects are presented, based on Cigré Working Group B4.70 [4].

5.2.1 Time-domain RMS- and EMT-type simulations

Figure 5-7 presents an overview of different types of dynamic studies commonly conducted by power system engineers and researchers for HVDC and OWF applications, which are, respectively, load-flow studies, RMS studies, and EMT studies. It can be observed that merely a single "snapshot" on a time domain scale can be achieved with load-flow studies, whereas slow dynamics in the range of a few seconds can be represented in RMS studies. EMT studies, on the other hand, offer detailed transient dynamic analysis within the microseconds or milliseconds time scale. Therefore, since PEDs have faster dynamics and more complex behavior that cannot be captured or properly analyzed with RMS-type tools, EMT studies have become increasingly crucial for the design and operation of systems with PED-based HVDC and OWF components.

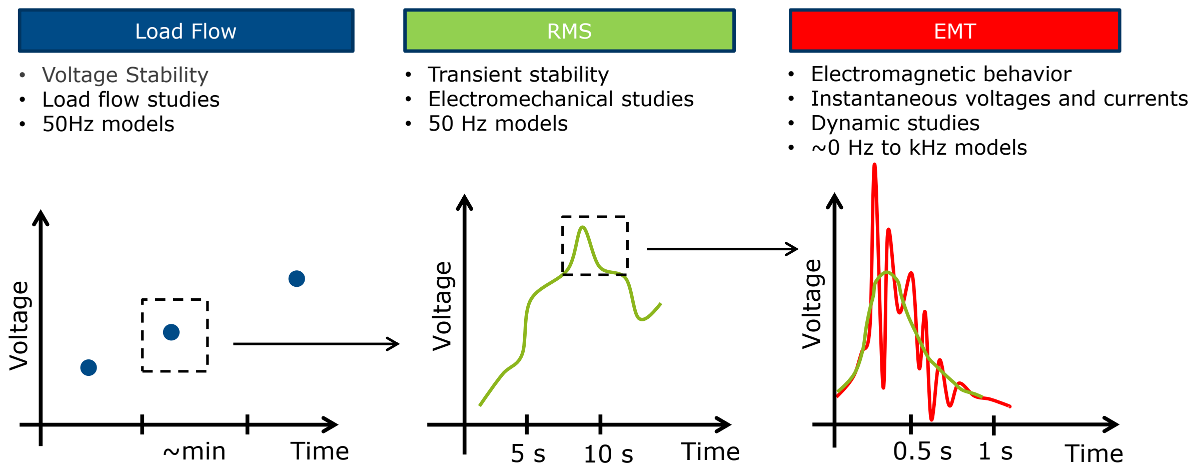


Figure 5-7 – Overview of the types of dynamic studies for HVDC and OWF applications

EMT studies are applicable to a wide range of frequencies thus require a sufficiently detailed representation of each component (e.g., HV equipment, C&P systems, converters, etc.). The simulations are performed in time domain with the objective of computing the instantaneous waveforms of state variables at an arbitrary point in the simulated network. EMT programs are used to accurately represent fast transients. Therefore, they are well suited to simulate devices such as PEDs. In comparison to RMS studies, the main drawback is the computation time which is longer as device modeling is much more detailed and simulation time step is smaller. Several software developments are ongoing to reduce the simulation time, such as combination of RMS and EMT tools, solver optimization, parallel processing, etc.

Additionally, EMT real time simulation offers a complementary solution besides offline EMT and RMS simulation due to the relatively slower simulation time in the latter. The main purposes of real time simulation are, therefore, to achieve faster EMT simulation and the possibility to connect physical external devices to perform hardware-in-the-loop (HIL) or power hardware-in-the-loop simulation (PHIL). To cope with such faster computation and connection of physical devices, simplifications in the EMT model and dedicated simulator with more powerful processors are needed. This is usually achieved by acquiring and the installing a dedicated simulation platform rather than performing offline simulation on the classical PC. Further details regarding real-time simulations will be provided in the next chapter.

5.2.2 Small-signal analysis in EMT simulations

Small-signal stability is the ability of a system to reach a stable operating point after a small disturbance. An electrical circuit can be described by a set of differential-algebraic equations (DAE), which are usually nonlinear. However, considering small variations around a steady state operating point, the system can be linearized using the Taylor series, and consequently be described by state-space equations or by a transfer function. Once the analytical system equations are deduced, several analytical tools exist to assess and analyse the stability of the system [17] such as the computation of eigenvalues, eigenvectors, mode shapes, participation factors, etc. However, the analytical approach has several drawbacks, which are:

- The system is non-linear and needs to be linearized to extract the analytical equations. Such an extraction would require simplifications and assumptions, leading to a reduction of model accuracy. Therefore, the validity of the model should be continuously validated against the non-linear system (such as EMT-type model) to ensure good behavioral coherence.
- For a complex system, such as multiple HVDC links and OWFs, the extraction of the analytical model becomes complex and the analysis process difficult due to the fast-increasing number of variables.
- The analytical approach requires detailed knowledge of the control system including all relevant control loops, filters, delays, etc. Therefore, full access to the control details and exact structure of each system is needed. However, such information is generally hidden (or black-boxed) due to confidentiality issues and IP protection. In such cases, the derivation of the analytical equation becomes impossible.

Considering the drawbacks listed above, the analytical approach is suitable mainly for HVDC manufacturers. From the perspective of a TSO, the use of analytical approach to perform small-signal analysis is limited. Such an approach is generally based on generic, simple, and open models, thus mainly for the purpose of R&D to explore generic potential interaction phenomena and/or help with skill and expertise development of engineers.

To overcome the above-mentioned difficulties and to ensure accuracy and confidence in the results, EMT tools are becoming more and more appealing as an alternative or a complementary solution to perform small-signal analyses.

To deduce the frequency response of power electronic devices (including the control loop impact), the small-signal perturbation technique can be used [18]. This technique consists of injecting a small perturbation at each frequency in the considered EMT circuit in a time-domain simulation. Subsequently, for each injected frequency, the required variables are computed using, for example, frequency domain analysis. Figure 5-8 illustrates the typical flow chart to conduct the frequency domain study. More details on the implementation in EMT tools can be found in [19].

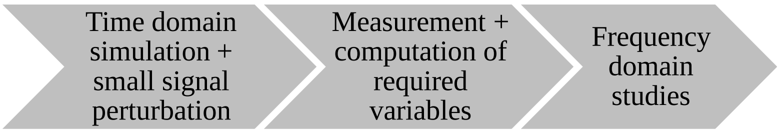


Figure 5-8 – Flowchart for frequency domain study using EMT simulation

It is noted that depending on the studied case and frequency range of interest, the variables of interest (the input or excited variables and the output or observed variables) might also be different. In [20], three different types of perturbation are used to extract different frequency response results. To further elaborate on using the EMT approach to conduct small-signal analyses, the following subsection presents an example of control stability study for a system with HVDC using this approach.

5.2.2.1 Control stability study

The common approach for control stability study is to apply a current perturbation method, as illustrated in Figure 5-9. Since the injected harmonic currents are of only a few amps, compared to the fundamental frequency current, the controller and protection system will not be disturbed and will operate normally.

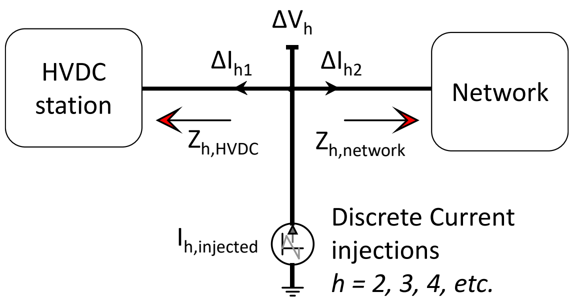


Figure 5-9 – Example circuit to linearize a network and a VSC including controllers

The injected harmonic currents $I_{h\_injection}$ are split into ΔI_{h1} and ΔI_{h2} (see equation (5-1)), and the induced harmonic voltages are observed at the PCC as a consequence of the injected harmonics $I_{h\_injection}$. By applying Ohm's law, the harmonic impedance of the HVDC station Z_{h_HVDC} can be simply calculated from equation (5-2).

$$i_{h\_injection} = \Delta I_{h1} + \Delta I_{h2} \tag{5-1}$$

$$Z_{h\_hvdc} = \frac{\Delta V_h}{\Delta I_{h2}} \tag{5-2}$$

By varying the frequency of the injected pertubation and repeating the computation of equation (5-2), the impedance in frequency response can be deduced.

Figure 5-10 – Harmonic stability: time domain to frequency domain stratagem

This numerical approach allows to reach a compromise between VSC models, which are usually built in time-domain, and harmonic studies, which are commonly performed in frequency domain.

Using the EMT approach in small-signal analyses alleviates the drawbacks of the analytical linearization approach by representing the detailed control system in the converter model without compromising its complexity. Therefore, it is more accurate and takes into account the non-linearity of the control system. Moreover, this approach allows the use of black-boxed devices that preserve the IP rights of manufacturers while sharing the functionalities of their control models, which is a suitable solution for TSOs. The main drawback of this approach with respect to the analytical method, is the computation time needed to extract the frequency response by means of time domain simulation. Depending on the frequency range of interest, generally a few to several tens of seconds need to be simulated in a EMT tool to obtain the results.

5.2.2.2 Harmonic emissions

To assess harmonic stability and avoid potential adverse interactions in a system with multiple PEDs, it is necessary to determine the level of harmonic distortion at the PCC (Point of Common Coupling) of each power electronic based device. To this end, two aspects need to be considered:

- Converter-generated harmonic emission.
- Pre-existing (background) harmonics, including their possible amplification by the converter.

In the calculation of the overall harmonic distortion, the network and converter harmonic sources can generally be considered as independent from each other. This assumption allows separate analysis of both effects, using different models and tools, and is valid for most purposes. It is also noted that this is a general approach that is applicable for most studies, independent of network configurations. However, for the offshore AC grid, the pre-existing harmonics would come from the wind generators instead of the network.

In the following discussion, the network is represented as an ideal harmonic voltage source along with its impedance $Z_{Net}(f)$. The same harmonic impedance is used for the calculations of both the emissions and the amplification of the pre-existing AC network harmonics. Appropriate assumptions regarding the magnitude of pre-existing harmonic voltages and the values of AC network impedance that should be used in such calculations are a complex issue and are discussed in [21], [22].

- Converter-generated harmonics

The impact of the converter harmonic contribution to the overall harmonic distortion at the PCC can be analysed, as is presented in Figure 5-11.

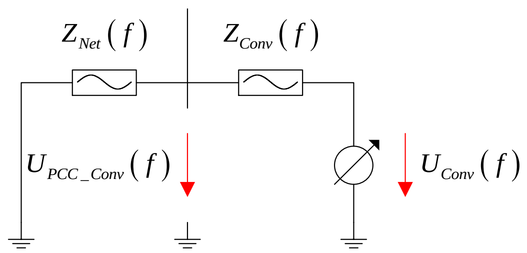


Figure 5-11 – Harmonic contribution by the converter

In Figure 5-11, the converter is represented as an ideal harmonic voltage source $U_{Conv}(f)$. In a typical design study, the converter impedance $Z_{Conv}(f)$ is defined by the manufacturer and the network impedance $Z_{net}(f)$ of the relevant frequency range shall be provided by the network operator. The network impedance may have a wide range of possible values depending on configuration and load levels. A suitable calculation algorithm, therefore, is required to determine the worst-case scenario from specified network impedance loci, i.e., the impedance that maximizes the distortion at the PCC for each individual frequency.

The harmonic distortion at the PCC is then calculated by:

$$|U_{PCC\_Conv}(f)| = \left|\frac{Z_{Net}(f)}{Z_{Net}(f) + Z_{Conv}(f)}\right| . |U_{Conv}(f)| \tag{5-3}$$

- Pre-existing harmonics

The impact of pre-existing (background harmonics) on the total harmonic distortion at the PCC can be analyzed using the model shown in Figure 5-12.

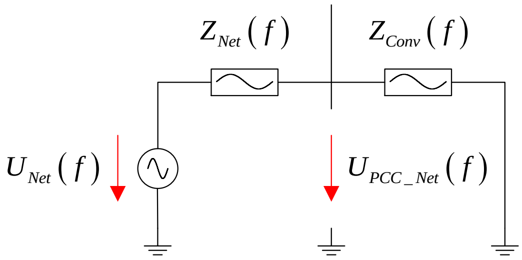


Figure 5-12 – Amplification of background harmonics

The harmonic voltage distortion at the PCC due to pre-existing harmonics can then be defined by:

$$|U_{PCC\_Net}(f)| = \left|\frac{Z_{Conv}(f)}{Z_{Net}(f) + Z_{Conv}(f)}\right| . |U_{Net}(f)| \tag{5-4}$$

- Combination of converter-generated and pre-existing harmonics

There is no fixed relationship between the phase angles of the converter-generated harmonics and the pre-existing harmonics. Therefore, an assessment of harmonic performance at the PCC needs to consider the summation of the two, taking into account their random phase relationship. An aggregate harmonic distortion may be calculated by adding the harmonic voltages at the PCC from converter generation and those from modification of the pre-existing harmonics, using methods based on the relevant standards, e.g., the "General Summation Law" presented in IEC 61000 3-6 [24], as expressed in equation (5-5).

$$U_{h_{PCC}}(f) = \sqrt[\alpha]{\sum_i U_{hi}^{\alpha}} = \left(|U_{PCC\_Conv}(f)|^{\alpha} + |U_{PCC\_Net}(f)|^{\alpha}\right)^{\frac{1}{\alpha}} \tag{5-5}$$

where the suggested indicative values of the exponent α are frequency-dependent, as is shown in Table 5-2.

Table 5-2 – Indicative summation exponents [24]

Harmonic order	α
$h<5$	1
$5 \le h \le 10$	1.4
$h>10$	2

Other methods can also be applied depending on project specified and/or grid code requirements. Harmonic studies are usually conducted using in-house tools, DigSilent PowerFactory or EMTP software.

5.2.3 EMT models for dynamic studies

EMT model development for PED systems in a gradually and modularly developed multi-vendor, multi-technology project is a crucial process to ensure interoperability. To clarify, the definition of "model" refers to the entirety of relevant control mechanisms, protections functions, specifications and performance requirements defined in the study including all necessary scripting and referenced power system elements. In addition, it would require interfaces, necessary measurements, filtering, and any other external code to achieve satisfactory performance for the intended purposes.

On the system level, the PED model should be suitable for dynamic performance studies with adequate representation of control and protection (C&P) functionalities. They are typically implemented as:

- full software schemes comprised of measurement elements, control loops, protection algorithms, and switching devices based on:
    - either offline simulation tools with black-boxed or open-access C&P system;
    - or real-time simulation models with black-boxed or open-access C&P system.
- hybrid schemes consisting of hardware replica of C&P system and software model of switching devices implemented using real-time simulation tools.

At different phases of project development, utilities generally conduct PED integration studies to evaluate, predict, and analyze certain issues. Several types of PED models are utilized in these studies depending on the project phase and their availability to the utility. These models can be categorized mainly into two types: generic and manufacturer black-boxed models, which will be discussed in the following subsections.

5.2.3.1 Generic models

A generic model is defined as a model that is developed based on a general concept. A generic model can be re-used in a wide range of projects with relatively minor reconfiguration or modification. However, they must include adequate functionalities to render satisfactory behavior for the intended study. For instance, fast front waveform responses of the control system could only be achieved if the generic model includes associated measurement elements in a realistic way on top of the relevant control loops, and different fault ride-through analyses could only be performed if the model includes both fast and slow acting protections, etc.

For HVDC-OWF applications, five types of generic models are available: model based on standards/pre-standards, models from software library, in-house generic models, academic models, and manufacturer generic model.

Although generic models can render satisfactory behavior for certain dynamic events and small disturbances, their usage is limited to extend to a wider range of phenomena in the cases of non-linear transients or high disturbances.

Generic models can be either black-boxed, open-boxed or semi black-boxed. However, several parameters are usually accessible to the end user such that they can tune and understand the general PED structure. A generic model usually includes only the principal C&P functionalities that are relevant to the considered study and does not necessarily represent the actual PED configuration in a real project.

- Model based on standards/pre-standards

Models based on standards/pre-standards are developed by international working groups (WGs) that often include experts from industries, academics, consultancies, and utilities. Therefore, such generic models are generally accepted by the international community and all data and information provided are publicly available. It also facilitates information sharing and communication between different stakeholders.

The IEC standard 61400-27 [32] is generally used in the industry for WTGs. Despite being sufficiently detailed for RMS tools, its specifications for EMT tools, which are yet to be published, are lacking. Nonetheless, several WTG models applicable to EMT tools have been published by WGs such as IEEE Task Force [33].

As for HVDC models, an EMT generic model that is also applicable to RMS tools is provided by a Cigré WG in [25]. Additional information regarding C&P system is detailed by another Cigré WG in [4]. Furthermore, ongoing work on developing improved EMT generic models is carried out by other WGs such as JWG B4-82.

The models based on standards/pre-standards are adequate for network-focused studies (both onshore and offshore) in terms of HVDC and OWF performances. However, they become less accurate for applications beyond this scope.

- Open-access model

Due to the high complexity of PEDs, universities and research institutes have developed open-access models based on PED theoretical functionalities in order to help engineers better understand the theoretical phenomena that may arise and shed insight on certain practical issues encountered. Several publications from academia are available online and in the literature, such as the generic model developed by Strathclyde University in collaboration with HVDC Centre [34] and that developed in the EU funded R&D project BEST PATHS as a collective effort between the academia and industrial partners [35].

- Model from software library

Generic models are also available in different commercial software packages. For instance, most commercial EMT tools (EMTP-RV, PSCAD, Simulink, etc.) provide HVDC and WTG generic models. Depending on the specific commercial software and its version, such models are usually developed based on available standards/pre-standards and/or in partnerships with the academia and/or industry.

These models can be useful in EMT planning studies to explore areas where standards may be required or features that no standard covers in the intended area of analysis.

- In-house generic model based on specification

Certain utilities, consultancies and manufacturers have the expertise to develop their own in-house generic models. One of the advantages of this approach is that the developed model can be easily customized in different studies according to their specific requirements. However, a strong expertise from expert engineers and other human resources are required in the development of such in-house generic models and the maintenance of these models during the life cycle of a project.

These models are based on experience and can render expected behavior in more detail or represent a simplification or a translation of a vendor model/ a set of vendor models supplied. However, their usage might be limited in cases involving new vendor technology or new phenomena which previously were not part of the focus of model validation process.

- Manufacturer model from previous project

A manufacturer model from previous projects can also be used in future projects, which is a common practice adopted by manufacturers at the early stage of a project. It is also possible for utilities and consultancies to use manufacturer models from previous projects in the current project within the legal framework.

The accuracy of such a generic model depends on project specifications and PED versions. If the specifications of the current project and PED version are the same as or close to those in the previous projects, such a model would undoubtedly render a more realistic behavior corresponding to the specifications of the current project. This is the case where this generic model is considered as the most accurate in comparison to all the previously described generic models. This model would still remain useful even if the specifications of the current project and/or PED version are different from the previous ones. In such cases, however, a prudent evaluation of the model behavior would become necessary.

5.2.3.2 Manufacturer black-boxed model

Unlike the generic model, the manufacturer black-boxed model refers to a specific model used in a specific project. To protect the IP rights of the manufacturer, a black-boxed model, which is not fully accessible, is usually provided by the manufacturer to the utilities for a project. This model usually includes the exact data and configurations of the power circuit of the project as well as the exact C&P system involved for offline EMT simulations. Some simplifications in the C&P system might be adopted (e.g., functions in the start-up/shut-down sequences, etc. in order to accelerate offline EMT simulations). In particular, for the use in RMS tools, the manufacturer black-boxed model includes only the relevant C&P systems for network stability studies as all C&P functions, especially those involving fast control loops, cannot be implemented in an RMS tool; for the use in EMT tools, this black-boxed model would include an exact or a similar copy of all C&P functions that are relevant for EMT simulations with simplifications implemented on slow control functions such as run-back functions, AC emulation, POD, etc. In addition, relevant protection functions are included in the EMT model.

In general, two types of black-boxed models can be distinguished:

- A complete black-boxed (or encrypted) model

The end-user only has access to the main control parameters, such as references of active power, reactive power, AC voltage, frequency, etc. as well as droop values and upper/lower limits. No further detailed information on the C&P systems and the HV equipment (or power circuit structure) is accessible. This type of complete black-boxed models is usually provided by the manufacturers by default when no further details on model requirements have been explicitly specified in the project.

- Customized black-boxed model

Depending on project requirements and utility specifications, another type of black-boxed model, namely the customized black-boxed model, can be obtained from the manufacturer. In a customized black-boxed model of an HVDC-MMC converter station, as is illustrated in Figure 5-13, the power circuit of HV equipment such as transformers, cables, generators, filters, converters, etc. is accessible whereas areas touching sensitive IP issues, e.g., internal control and protection systems, are black-boxed. This type of model can be obtained in the cases where the utility, already having access to all the HV equipment data, owns the PED system. Additionally, the C&P system can be fully or partially black-boxed in a customized black-boxed model based on project requirements and the agreement between the utility and the manufacturer. For an HVDC-MMC system, as an example, the interface between the encrypted and open data lies at the MMC valves. As is illustrated in Figure 5-14, either all valve information including the capacitor voltage and current of each SM is accessible as in Model 2, or the valve is black-boxed as in Model 3.

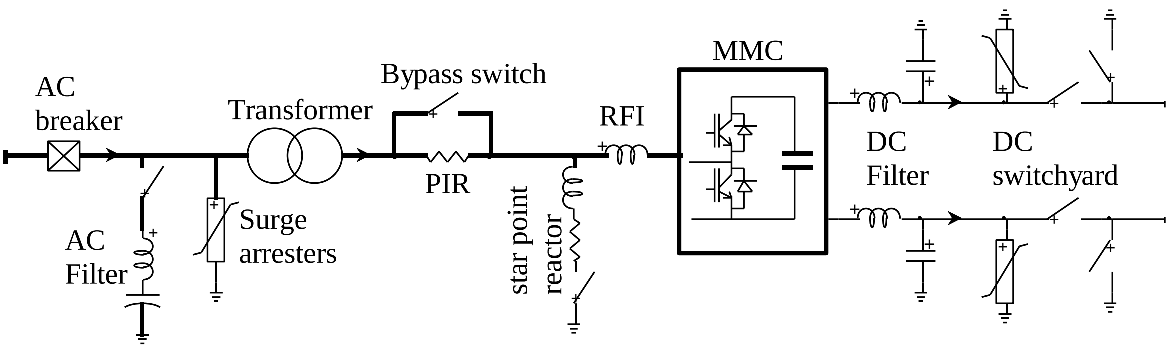


Figure 5-13 – General layout of an HVDC-MMC converter station

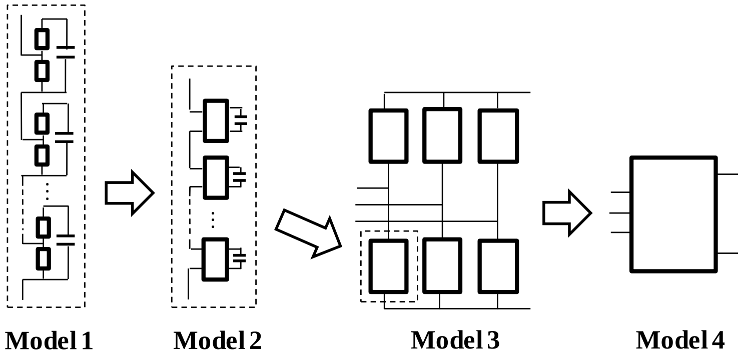


Figure 5-14 – MMC model evolution in the order of decreasing complexity [36]

5.2.3.3 Advantages and limitations of offline EMT models

The two types of models discussed in the previous sections are usually used by utilities and manufacturers in offline EMT dynamic interoperability studies. Their advantages and limitations are described as follows:

Generic models

Advantages:

- Compared to the manufacturer black-boxed models, solution time with a generic model is usually faster as it is less complex.
- Compared to the manufacturer black-boxed models, the end-user usually has more access to the internal structure and parameters of a generic model thanks to its relaxed IP right constraints, which indicates that the generic model is more accessible, more flexible, and easier to manipulate.

Limitations:

- A generic model is less accurate due to the fact that it does not represent the real system. Therefore, the end-user would need in-depth technical knowledge and experience of the system to evaluate the results correctly and carefully before drawing any conclusion.

Manufacturer black-boxed model

Advantages:

- A manufacturer black-boxed model comes from the manufacturer who builds the system. Therefore, it should accurately represent the system behavior and give confidence to the end-user in the results.
- Compared to the generic model, the manufacturer black-boxed model offers little access to its internal structure, parameters and configurations, which spares the end-user the need of in-depth technical knowledge of the system in order to manage the model.

Limitations:

- Solution time using the manufacturer black-boxed model is usually longer compared to with the generic model because many more components are included and are modelled in detail in the former.
- Depending on the software version, it can be difficult to manage the manufacturer black-boxed model in the long run during the project life cycle (10 to 20 years) due to its low accessibility and flexibility. Additionally, the manufacturer black-boxed model usually has specific requirements for the adopted numerical simulation time-step (e.g., only a narrow range of fixed time-steps are allowed) to ensure a satisfactory model behavior, which poses significant constraints in interaction studies for a system with multi-vendor PEDs as in the case of the NSWPH project.
- During the entire life cycle of an HVDC-OWF project, the C&P systems are continually updated on site. However, the manufacturer black-boxed model which is usually not designed to be used during the entire life cycle of the on-site

installation, would become less accurate and reliable with time, and even incompatible with new EMT software versions due to EMT software upgrade and development.
- The manufacturer black-boxed model is valid principally for specific studies advised by the manufacturer and required in the project specifications. Its accuracy and validity may be questionable in extended system studies that were not planned in the design stage. This is due to the simplification and even omission of certain functions in the manufacturer black-boxed models.

Apart from the disadvantages of the generic and manufacturer black-boxed models listed above and considering the specifics of the NSWPH project, offline EMT PED models also have the following drawbacks:

- The C&P system modelling in offline models is usually simplified with non-relevant or less-relevant functions and parts excluded due to the high complexity of the on-site HVDC-OWF C&P system, trading off accuracy to a certain extent against simulation efficiency.
- The majority of parameters are pre-selected during the C&P system design stage in offline models without coordination between them. Therefore, the integration of the complete system requires continual parameter optimization, thus constant updating and validation every time a change is made during the entire design stage of the project, which is a time-consuming task in the management of the offline model as the IP sensitive components are usually encripted and the source code may not be available, thus poses considerable constraints in C&P system interaction studies of a system involving multi-vendor and multi-technology PEDs [37].
- Due to the much longer simulation time required for a dynamic event, the offline models are not suitable for events involving slow variations that last from tens of minutes up to several hours such as those involving reactive power control devices (AC filter switching, AC voltage control, synchronous condensor and STATCOM) [37].

Real-time simulation using C&P replicas, with its exact (or almost exact) representation of the actuall C&P system implemented on site and its ability of capturing system behavior in real-time following a dynamic event, would provide a valuable complementary solution in the above-mentioned aspects where only using offline models is insufficient or impossible. The HIL set-up with real-time simulation using C&P replicas for an HVDC-OWF project such as NSWPH will be elaborated in the following section.

5.2.4 Evaluation of interoperability at different project phases

Following the previous discussions, the assessment activities for interoperability of the NSWPH project with multi-vendor HVDC and OWF systems can be categorized chronologically with respect to project development stages, as is illustrated in Figure 5-15.

For each phase of an HVDC-OWF project, several studies should be performed to detect potential interaction risks and evaluate interoperability in a multi-vendor PED system, using different types of software tools. A detailed description of dynamic studies to be performed at different project development phases can be found in [4].

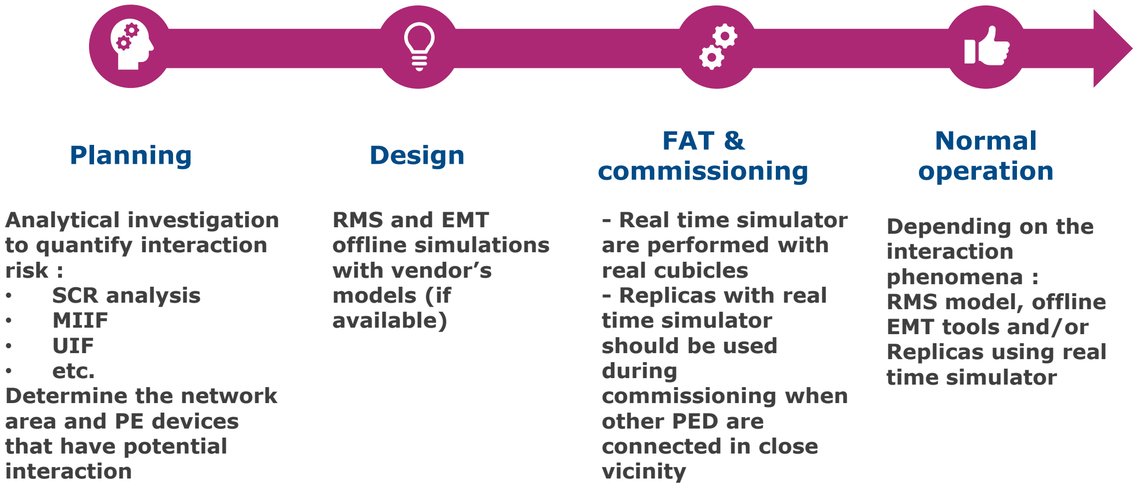


Figure 5-15: Assessment of interoperability during different phases of a multi-vendor HVDC-OWF project.

- Planning stage

During the planning stage, for the case of PEDs (HVDC and PPMs), the analytical investigation offers a simple and rapid approach to determine the network locations where potential interactions with other grid users might occur. The UIF and MIIF approaches are the main methodologies adopted by the TSO as a screening to detect risks of SSTI (sub-synchronous torsional interaction) with adjacent generators, and of any other control interaction between PEDs in the surrounding area. Additionally, if the project has an innovative nature due to special needs or if state-of-the-art technology is involved, it is also beneficial for the TSO to perform supplementary dynamic studies (e.g., RMS and EMT type simulations), as well.

- Design stage

During the design stage, RMS- and EMT-type offline tools are used with the vendor models to investigate the predominant risks of interaction. The scope of the studies can vary depending on the project specifications. Such interaction studies are conducted by the TSO, as well as by the vendors and/or by a third party.

- FAT & Commissioning stage

During the Factory Acceptance Test (FAT), the control tuning (of the real control system) shall already be set and is, therefore, validated using real-time (RT) simulations. Additional interaction studies may be conducted with the help of real cubicles to validate the interaction studies performed during the design stage. During the commissioning phase, if deemed necessary, interaction study assessments are conducted to support the commissioning of the PED system, which may help to avoid on-site delays.

- Operation stage

The TSO is responsible for the stability and security of its own network. Therefore, they shall perform studies to evaluate the impact of any newly installed grid user in the network and the that of any network modifications, which entails the use of accurate models. The complete list of potential circumstances in which studies are required can be long. The following non-exhaustive list is provided as a reference:

- Post-incident analyses
- Impact and interaction with classical AC protections
- Development of the AC grid topology
- Dynamic behavior studies (leading to operational limitations, e.g., ramp rate, partial load rejection, islanding)
- Fault studies
- Rate of change of frequency (RoCoF) studies to evaluate the need for synthetic inertia provided by PGMs

- Interaction studies between grid users
- Harmonics and resonance studies
- System defense and system restoration studies including black-start studies
- Sub-synchronous interaction studies (including synchronous and/or non-synchronous power generating modules)
- Line and transformer energization studies
- Transformer magnetization studies including sympathetic inrush current
- Control coordination with other equipment studies
- Extension of any HVDC system
- For HVDC stations: refurbishment of high voltage equipment or modification of the converter station topology (new filter, change of transformer, new DC cable)
- Refurbishment of the grid control and protection system

Three types of tools are commonly used during operation, which are RMS, offline and real-time simulation, with their application depending on the studied scope. It is common to use two different tools to perform a study in order to validate and cross-check the results. For instance, when performing RMS studies for slow dynamics (such as power oscillation), real-time simulation can also be used as a complementary tool to validate the model behavior and the obtained mitigation measure. In certain cases, generic models are also used, which helps to understand the specific behavior and to acquire in-depth knowledge of the system.

5.3 Case studies (lessons learnt by RTE)

The objective of this section is to share the experience of RTE and RTE international with the NSWPH consortium by presenting previously performed internal studies as well as issues encountered at various stages of real projects, demonstrating:

- The risks of control parameter sensitivity and lack of common offshore grid code on system performance, as was explained in Section 5.1.
- The importance of following the methodology presented in Section 5.2 to evaluate potential risks of interaction and to de-risk the design and operation processes in a system involving HVDC and OWF.

Considering the multi-infeed, multi-vendor, and multi-technology characteristics of the NSWPH project, the presented case studies include the following setups: multi-vendor WTGs (Case Study 5.3.1), multi-technology HVDC links (Case Study 5.3.2), and HVDC+OWF (Case Study 5.3.3). In particular, Case Study 5.3.1 demonstrates the impact of sensitivity of control parameter tuning inside WTGs from different vendors on the overall system performance due to lack of common offshore grid code, potentially leading to interaction issues if these WTGs are interconnected on the same offshore grid and also posing constraints on the HVDC design, whereas the importance of following the methodology presented in Section 5.2 to evaluate potential risks of interaction and to de-risk the design and operation processes in a system involving multi-vendor, multi-technology HVDC and OWF can be understood from the other case studies.

5.3.1 Control parameter sensitivity on system performance

The considered case study is based on the Cigré TB604 benchmark model [25] and the work conducted by RTE international for the COMPOSITE project of Testing of HVDC-connected Offshore Wind Farms [22] in the UK, as is presented in Figure 5-16. It consists of an MMC-based HVDC link in symmetrical configuration and an aggregated OWF system.

The HVDC link has a rated power of 1GW, rated DC voltages of ±320 kV and a DC cable of 200 km (modelled using the frequency-dependent line/cable model). Since generic system studies are of concern, the MMC Model #3 is used and is considered adequate. Submodule capacitor stored energy is 33 kJ/MVA, arm reactors is 15% and transformer reactor is 18%. The remaining electrical parameters of the converter station can be found in [25]. The generic onshore and offshore converter control structures implement the RTE in-house generic control models, with the onshore converter station operating in PQ mode, including the negative sequence current control for unbalanced AC faults whose details can be found in [27], to control DC voltage and the offshore converter station in VF mode to regulate offshore frequency and AC voltage [28].

Four types of WTG models are used and compared in this case study to evaluate the impact of WTG on the HVDC performance. They are:

- WTG Generic 1: It is the RTE in-house generic model based on specifications. This model is used as the base case.
- WTG Vendor A, Vendor B1 and Vendor B2: Three manufacturer black-boxed models from previous projects. The sole difference between Vendor B1 and B2 lies in the reactive current support strategy during AC faults, with only Vendor B2 injecting reactive currents during AC faults. A power plant controller is used to set the reactive power reference of OWF to zero. These three models are used to evaluate the impact of WTG models from different vendors on the HVDC performance.

Regarding the onshore 400 kV network, an equivalent synchronous machine (SM) including its governor/turbine IEEEG3 and its exciter SEXS is considered. The SM has an equivalent short-circuit level of 10 GVA.

It should be noted that all four WTG models are compliant with the onshore grid code of RTE, which shares similar operating principles to that of the UK in regard to fault-ride-through requirements. It will be seen hereinafter that compliance with the onshore grid code does not guarantee the same compliance for the offshore network, which would lead to potential risks of interaction following a disturbance, as was discussed previously.

All simulations are performed using EMTP-RV [26].

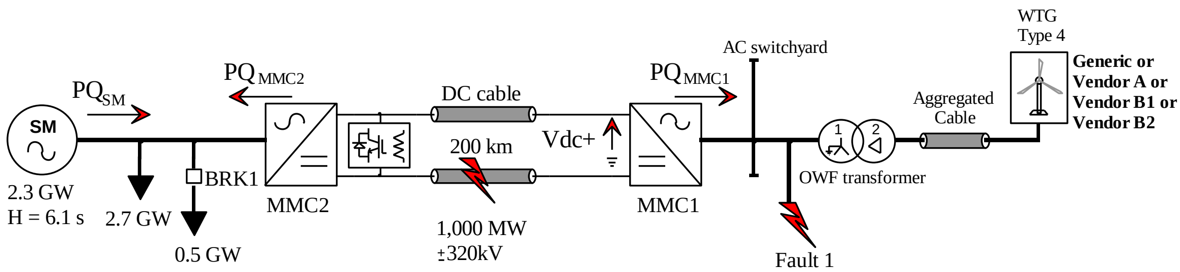
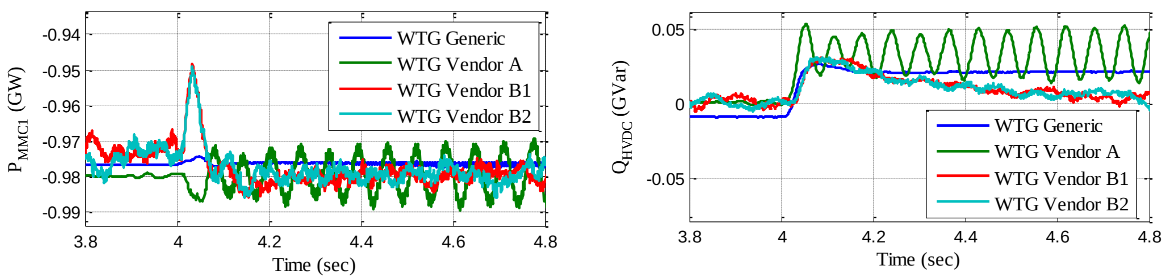


Figure 5-16 – Single-line diagram of the HVDC-OWF test system

5.3.1.1 Offshore AC voltage step change

In this test, a step change of 5% is applied on the AC voltage reference at offshore station MMC1. The test is to show satisfactory performance of the considered HVDC generic model and the overall expected behavior of the offshore system. The same test is applied using the four WTG models and results are presented in Figure 5-17 for comparison of the following variables: active/reactive power and AC voltage measurement.



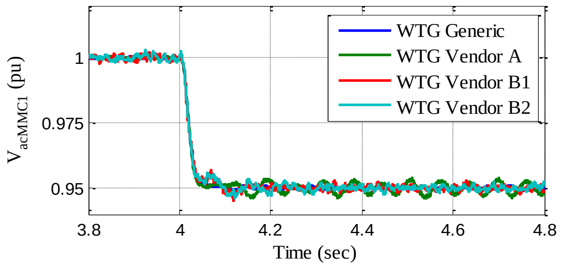


Figure 5-17 – Vac offshore step change

It is observed that Vendor B1 and B2 remain stable following the disturbance with the offshore reactive power returning to zero thanks to the power plant controller, while a 15 Hz undamped oscillation can be observed on the offshore active and reactive power of Vendor A.

In a real HVDC-OWF project, the performance of HVDC link with WTG Vendor A would be considered unacceptable, and either the HVDC or WTG control or both would need to be improved to achieve stable operation. This test case demonstrates the importance of control coordination between HVDC and OWF and that unexpected behavior might arise on an OWF despite compliance of the WTG with the onshore grid code. This could further lead to risks of interaction and instability if multi-vendor WTGs exist on the same offshore platform. Additionally, it raises the importance of using accurate and detailed offshore WTG models in early studies and ensuring control coordination between the HVDC and OWFs in the design phase of the project.

5.3.1.2 Offshore frequency step change

A frequency step change of 0.4 Hz is applied on the frequency reference at offshore station MMC1, with the offshore active/ reactive power and frequency for all four models presented in Figure 5-18.

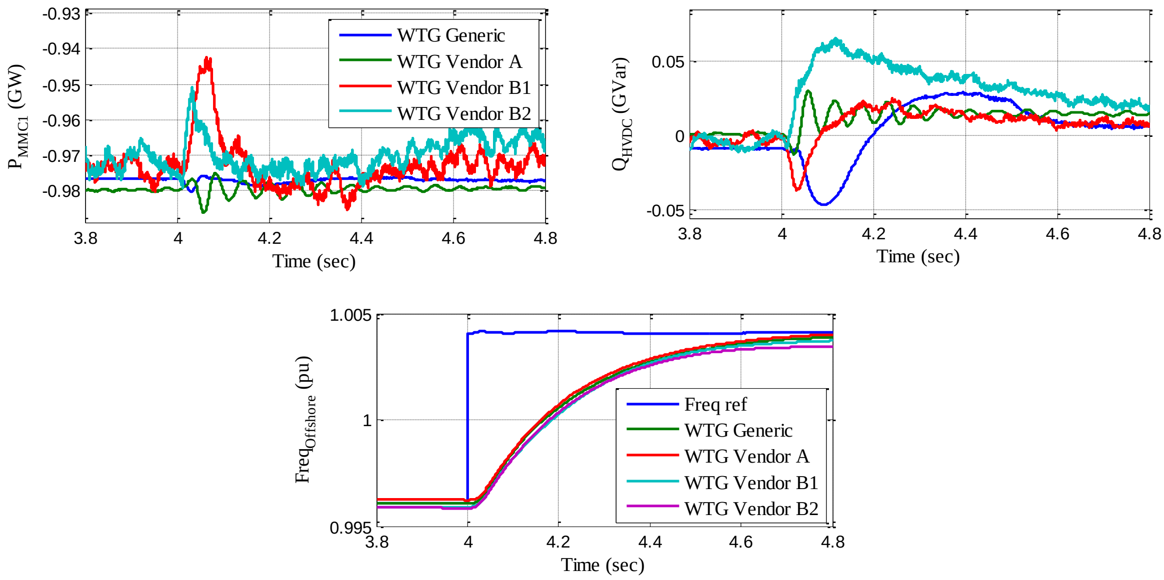


Figure 5-18 – Offshore frequency step change

It can be observed that the overall system remains stable despite a slight variation in the active and reactive power following the disturbance. However, the first reaction in the dynamic response of active and reactive power is different for all four models. Although the behavior of all four models does not have a major impact on the HVDC performance in this test case, attention should be given to the different behavior of active and reactive power dynamic response as possible risks of interaction might arise, resulting in unexpected consequences.

5.3.1.3 Offshore AC fault

In this test, a three-phase AC fault with 5% residual voltage and a duration of 200 ms is applied on the offshore AC switchyard (See Fault 1 in Figure 5-16). The comparison of different electrical quantities on the offshore AC switchyard for all the four WTG models are presented in Figure 5-19.

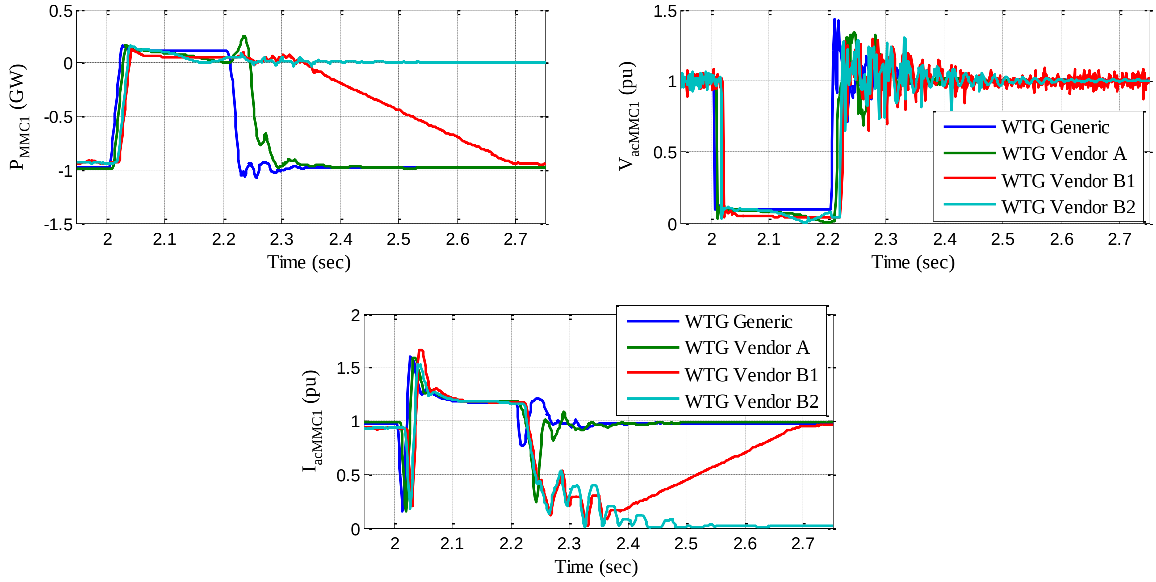


Figure 5-19 – Offshore AC fault

It is observed that the three manufacturer black-boxed models behave differently during fault recovery. In particular, the active power of Vendor A recovers in a similar manner as the base case (WTG Generic 1) and that of Vendor B1 is ramped back to the pre-fault value within approximately 400 ms whereas Vendor B2 trips due to overvoltage protection.

It is interesting to note that, in comparison with the base case, the three manufacturer black-boxed systems render inconsistent performances in regard to different levels of disturbances. Specifically, one system (e.g., WTG Vendor A) that shows unexpected behavior following a small disturbance (e.g., AC voltage step change) might render satisfactory performance after a large disturbance (e.g., AC fault), and vice versa. This is because different control functions are involved with respect to different dynamic disturbances, and it demonstrates the sensitivity and high nonlinearity of the overall system. Therefore, it is imperative that functional specifications of HVDC and OWF controls should be defined and designed to ensure operation stability in a wide range of dynamic events such as step change, AC faults, energization, etc.

Moreover, the tripping of WTG Vendor B2 implies a non-compliance with the grid code despite the fact that all models comply with the RTE onshore grid code, which indicates Vendor B2 would not trip during such an event if it were connected to an AC grid. This, once again, demonstrates that potential operation risks could exist in an offshore network involving multi-vendor, and possibly multi-technology PED systems due to the insufficiency in onshore grid code compliance.

5.3.1.4 DC pole-to-ground fault

A permanent DC pole-to-ground fault is applied at the center of the negative pole cable in this test, as is shown in Figure 5-16. Different electrical quantities at the offshore station MMC1 for all WTG models are shown in Figure 5-20.

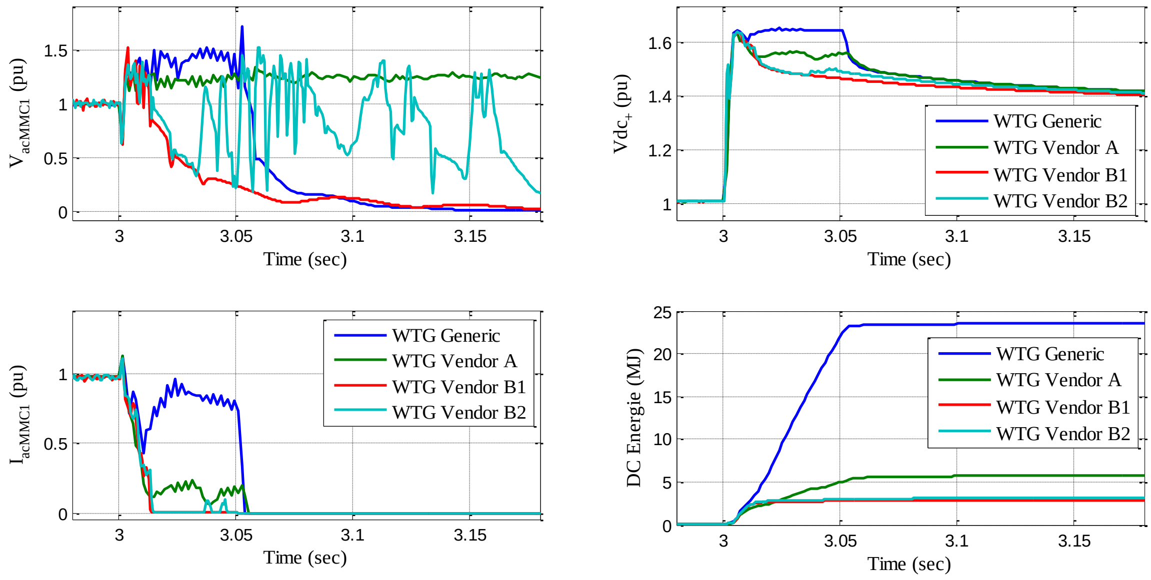


Figure 5-20 – DC pole-to-ground fault

Approximately one 1 ms after fault ignition (t=3sec), MMC blocks, leading to a temporary AC overvoltage (1.53 pu) and temporary DC overvoltage on the healthy DC cable (1.65 pu) until AC breakers open two cycles later. The energy of the DC pole-to-ground arrester at the converter station reaches 23 MJ when considering the WTG generic model. Such a transient has an obvious impact on DC cable design as well as on the converter station and OWF system. Several conclusions can be drawn from this test:

- Regarding the AC voltage, Vendor B1 and Vendor B2 WTG models show similar behavior during the first 50ms after fault ignition. Subsequently, the AC voltage in vendor B1 reduces to zero, whereas visible resonances appear at the AC switchyard for Vendor B2. However, for Vendor A, a temporary AC overvoltage reaches 1.27 pu and persists during 200 ms after fault inception.
- From the perspective of DC overvoltage, the WTG Generic model has the longest lasting overvoltage as compared to other vendor-specific models.
- As for the DC energy absorbed by the surge arrester, the WTG Generic model exhibits the highest and worst-case energy absorption when compared to the other three vendor-specific models.

These results demonstrate that HVDC converter equipment design can be affected by the OWF control system. Therefore, for transient stress studies during design phase, accurate WTG models should be carefully chosen. Moreover, in this test case, AC voltage behavior of Vendor B2 is not acceptable. It should, therefore, be clearly stated in the specification to avoid such behavior if identified at the design stage or corrected if the project is in operation.

Overall, the following lessons are learnt from the tests presented above:

- Compliance of WTGs from different manufacturers with onshore grid code does not guarantee satisfactory behavior and system performance following dynamic events due to control sensitivity, coordination and lack of sufficient offshore grid code, further leading to potential risks of interaction if multi-vendor and multi-technology PED systems are interconnected (HVDC and OWF).
- The control coordination between HVDC and each OWF would have a significant impact on the HVDC performance and design, which poses constraints in the design phase of a project involving HVDC and multi-vendor, multi-technology OWF applications.

- It is crucial to obtain accurate and detailed models for the HVDC and the WTGs from different vendors in early design studies to de-risk the design and operation processes.

5.3.2 AC temporary overvoltage after fault recovery – planning stage study

This subsection presents results of AC temporary overvoltage studies after fault recovery in the planning stage of a new HVDC-MMC project connected at the same busbar with an existing HVDC-LCC link, as is illustrated in Figure 5-21. This configuration is similar to the ELECLINK HVDC link that is scheduled to be commissioned in 2021 connected in close proximity to the IFA2000 link which consists of two 1000 MW HVDC-LCC links in bipolar configuration interconnecting Les Mandarins (France) and Sellindge (UK). Therefore, the manufacturer EMT model of the IFA2000 link (with only one link of 1000 MW) and the generic in-house HVDC-MMC model are used in this planning study.

The study is performed parametrically in EMTP-RV, considering variations of certain parameters that may have an impact on the overall system performance. These parameters are summarized in Table 5-3. A short-circuit level of 5 GVA and a three-phase-to-ground fault incident on the interconnecting busbar are considered in this study. Different from the ELECLINK and IFA2000 configuration, the converter stations of the two HVDC links in this test are decoupled at the other end in order to simplify the analysis, as is shown in Figure 5-21. The total number of simulations performed in this test is 120.

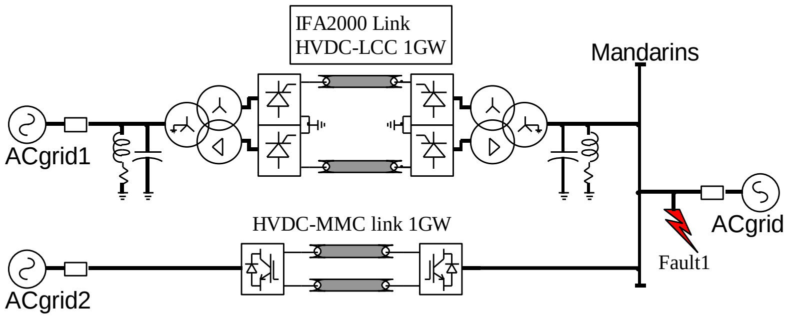


Figure 5-21 – Single-line diagram of a new HVDC-MMC link connected next to an existing HVDC-LCC link

Table 5-3 – Parameter variations in the presence of HVDC-LCC Link

Parameters	Number of configurations
Impact of HVDC-LCC link	HVDC-LCC link included with active power transits of ± 1000 MW HVDC-LCC link excluded
P/Q setpoints of the HVDC-VSC link	± 1000 MW, ± 800 MW, 0 MW -300 MVar
Fault resistance	0, 10, 30 and 50 Ω
Settling time of the VSC Inner control	7 and 10 ms

The RMS phase-to-phase overvoltages at the PCC, considering parameter variations, are presented in Figure 5-22 and Figure 5-23. In particular, the time-domain voltage waveforms for all 120 simulated cases are shown in Figure 5-22 where the black bold curves represent the overvoltages without the HVDC-LCC link whereas the remaining thin curves are those with the HVDC-LCC link, and the maximum RMS peak values recorded for each of the 120 simulations are presented in Figure 5-23, with the first 80 cases including the HVDC-LCC link and the remaining 40 cases without.

It can be observed that oscillations in the voltage waveforms after fault recovery are less damped and the duration of overvoltage is generally longer in the cases with the HVDC-LCC link (see Figure 5-22); from Figure 5-23, it can also be noticed that the maximum TOVs are higher when the HVDC-LCC link is included, with the maximum peak overvoltage reaching 1.53 pu, as compared to the cases without the HVDC-LCC link where maximum overvoltage peak is approximately 1.34 pu.

It can, therefore, be concluded that the TOV peak and duration would increase on a new HVDC-MMC link connected at the same busbar with an existing HVDC-LCC link, with the principal underlying reasons being a reduced short-circuit ratio, increase in reactive power support during the fault and control interaction between the two HVDC links.

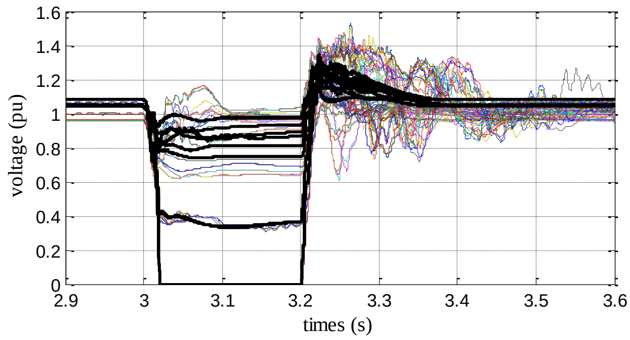


Figure 5-22 – RMSLL AC overvoltage at PCC results - impact of HVDC-LCC link

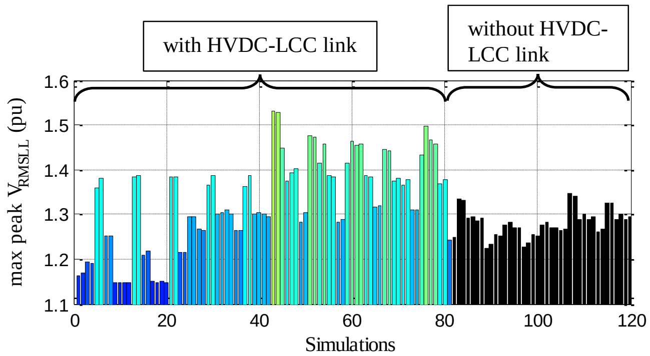


Figure 5-23 – Maximum TOV peak - impact of HVDC-LCC link

A lesson learnt from this study is that such planning stage studies are crucial in estimating the temporary overvoltage that can arise on a new HVDC link connected in proximity to an existing one and can help with the specification and design of the new HVDC link through evaluation of potential risks of interaction between the two links. This is especially important for the NSWPH project, considering its nature of gradual and modular development. Further details can be found in [51].

5.3.3 Offshore harmonic instability – planning stage study

One of the planning stage studies performed for the FAB link project is presented in this subsection. The planned project consists of two symmetrical monopole HVDC-MMC links between France and the UK, with a total rated power of 2*700 MW and a DC voltage of ±320 kV. On one of the links, a tee connection is planned to host a third converter station at Alderney Island. The offshore station is planned to be connected to a tidal farm power plant at a rated power up to 600 MW.

The offshore network configuration is illustrated in Figure 5-24. Seven feeders are connected to the main converter transformers. Each feeder is rated at 100 MW and a cable connection of 5 km is assumed between the transformer and the tidal farm. The semi-aggregated park model is considered adequate for this planning study. Since the tidal farm is composed of a VSC back-to-back converter similar to a wind power plant (WPP) Type 4 technology, a manufacturer black-boxed model of a WPP Type 4 is, therefore, used. This assumption for the planning study is valid as the dynamic behavior is similar. The offshore converter station uses a generic in-house MMC model with U/F control.

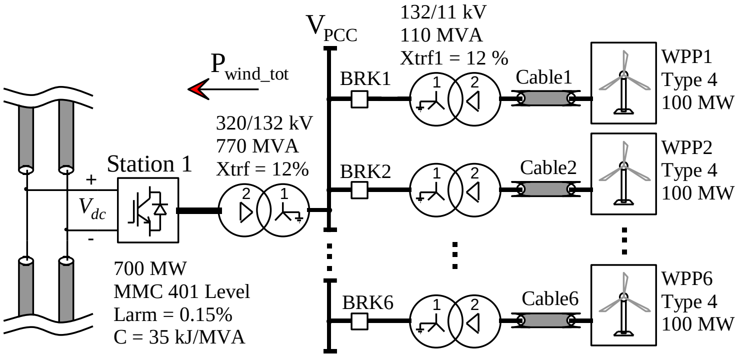


Figure 5-24 – Network configuration of the offshore station [29]

5.3.3.1 Time domain simulation

A test case of EMT time-domain simulation is conducted, where the wind farm feeders are disconnected successively with a delay of 0.5 s. Therefore, the total active power is reduced by 100 MW after the disconnection of each feeder. The total active power and AC voltage at the offshore PCC are presented in Figure 5-25.

A high frequency resonance occurs at $t = 3.5s$ on the AC voltage at the opening of BRK3, as can be observed in Figure 5-26 of the amplified interval. The frequency of this resonance is approximately 830 Hz.

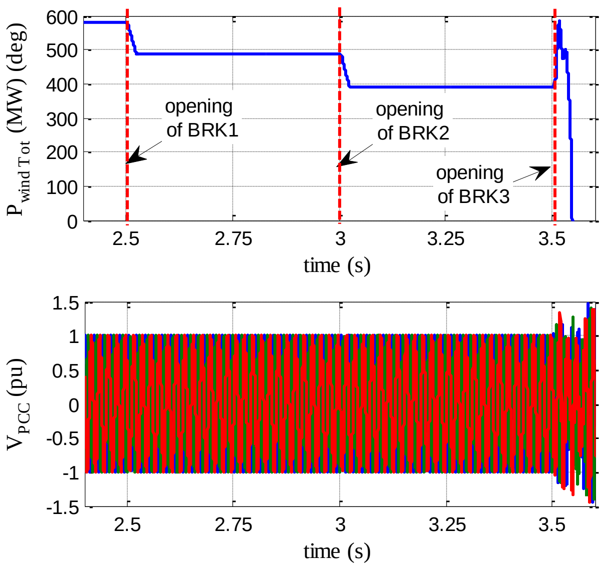


Figure 5-25 – Time domain waveform of wind farm feeder disconnection

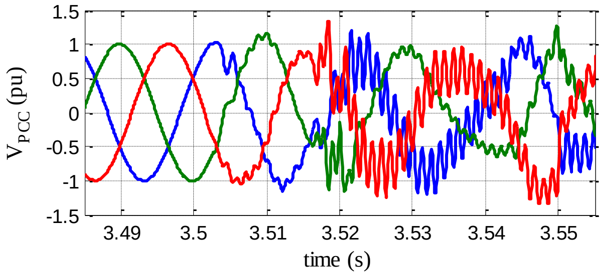


Figure 5-26 – Zoomed waveform of AC voltage (V_{PCC}) at BRK3 opening

5.3.3.2 Small-signal stability analysis

Following the time-domain studies, a small-signal stability analysis is performed to evaluate harmonic stability of the system, using the impedance-based approach as was explained in Section 5.2.2. The circuit diagram implementing the EMT-type current injection method with a frequency scan to deduce the frequency responses for this analysis is shown in Figure 5-27. The magnitude and phase angle of the impedance of the converter station $Z_{HVDC}(s)$ and the wind farm $Z_{WPP}(s)$ (before and after BRK3 opening) are plotted in frequency domain, as is presented in Figure 5-28.

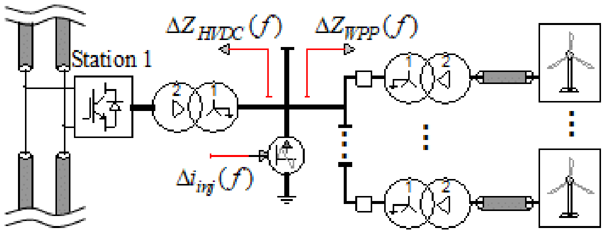


Figure 5-27 – Circuit diagram of the offshore station for the small-signal stability analysis

It is worth mentioning that the intersection points between the $Z_{HVDC}(f)$ and $Z_{WPP}(f)$ magnitude curves determine the frequency values at which the phase margin should be computed [30]. From Figure 5-28, it is observed that only one intersection point exists between $Z_{HVDC}(f)$ and $Z_{WPP}(f)$ around 800 Hz with a phase margin close to 180° prior to the opening of BRK3; nonetheless, two intersection points appear after BRK3 opens at 520 Hz and 833 Hz, respectively, with the phase margin for both frequencies higher than 180°. This explains the resonance phenomenon observed in Figure 5-25 and Figure 5-26. Additionally, it is noticed that $Z_{WPP}(f)$ has a negative resistance (< -90^0) in the range of the two frequencies whereas the angle of $Z_{HVDC}(f)$ does not exhibit any negative resistive behavior in the considered frequency range. Therefore, it can be concluded that the main system causing harmonic instability in this test case is the WPP controllers rather than the control loop of the converter station.

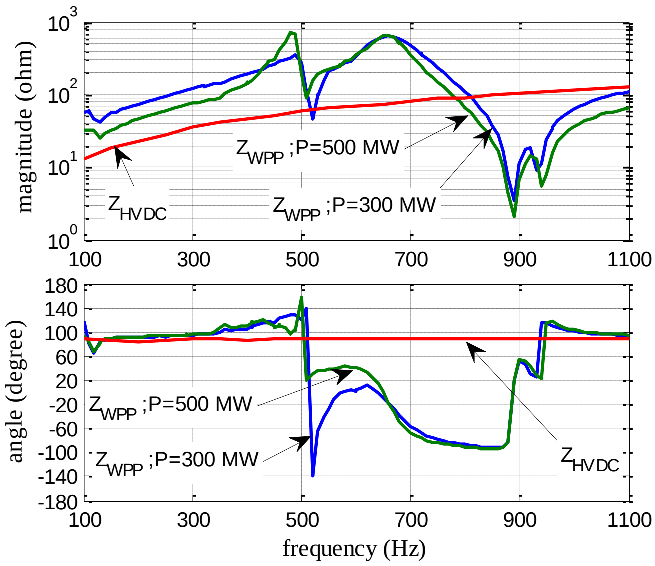


Figure 5-28 – Frequency response of converter station and WPP

From this test case, it is learnt that the WTG plays an important role in overall system stability. Furthermore, it is necessary to follow the methodology introduced in Section 5.2.4 to evaluate risks of potential stability issues and to de-risk the design and operation processes at an early stage of the project with adequate WTG EMT models as well as harmonic impedance data.

5.4 Summary

The main conclusions in this chapter are summarized in this section as follows:

The multi-vendor, multi-technology NSWPH concept that will be developed gradually and modularly faces great technical challenges due to the lack of sufficient offshore grid code and cross-system control coordination and interaction both on the AC and DC grids.

EMT studies shall be needed to analyze and evaluate the complex behavior and fast dynamics of PED-based devices that are present in HVDC and OWF systems thanks to their wideband nature and detailed representation of circuit components, which is crucial for interoperability assessment in the multi-vendor NSWPH project.

Small-signal analysis in the EMT environment is necessary to assess control stability issues in a multi-vendor PED-based system. It not only takes into account the non-linearity of the control systems while alleviating certain drawbacks of the analytical approach, but it helps to protect the IP rights of each vendor, as well.

The empirical methodology consisting of studies that should be performed using adequate tools at different development stages of the project shall need to be followed in order to fully and confidently assess interoperability issues in the NSWPH project.

6 DE-RISKING THE NSWPH PROJECT USING HIL SETUP

In continuation of the discussions presented in the previous chapter and considering the limitations of offline EMT PED models, this chapter proceeds to discuss the approach of using HIL setup with real-time simulation and the C&P replicas for interoperability studies in the NSWPH project, with focus on the considerations of using the C&P replicas for different applications (i.e., HVDC and OWF) and purposes (i.e., study and maintenance). The benefits and, under many circumstances, the necessity of using HIL real-time simulation with C&P replicas to de-risk the design and operation of the NSWPH project with multi-vendor, multi-technology HVDC and OWF applications will be explained in full detail. It is necessary to point out that both offline EMT models and the HIL setup with real-time simulation and C&P replicas should be considered as complementary tools to each other, and both approaches would be indispensable to ensure proper design and stable grid operation of the NSWPH project. This is a lesson learnt from the involvement of RTE international in the Johan Sverdrup project (the first European multi-vendor parallel-connected HVDC system in grid forming operation), as will be further elucidated in Section 6.2.3.

6.1 Real-time simulation with C&P replicas

Unlike the two types of offline models (i.e., generic and manufacturer black-boxed models) described in the previous chapter, the approach introduced in this subsection entails the need of real-time simulators and replicas of the control and protection systems.

6.1.1 HIL setup

The hardware-in-the-loop (HIL) setup is a method that is used to test and develop complex physical C&P systems. A HIL setup includes the following components:

- Real-time simulator to emulate the power system network
- Physical C&P system cubicles
- IO interfaces between the plant simulation and the C&P system under test

This approach serves as a reference model for the validation of C&P functions thanks to the involvement of physical C&P cubicles. These physical C&P cubicles can be either the actual cubicles installed on site or replicas of those cubicles which are to be described in the following subsections.

6.1.2 Actual C&P cubicles

During the design stage of an HVDC-OWF project, the HIL setup is used to test the actual physical C&P cubicles before on-site shipment and commissioning. These real-time simulation tests are usually performed by the manufacturers at the real-time laboratory at their locale. The objectives of the HIL setup and the tests are to:

- Validate performance requirements of the C&P system
- Ensure compliance with the grid code
- Perform supplementary tests that cannot be performed with offline EMT tools
- Complete Factory Acceptance Test (FAT) together with clients
- Validate and test the remote-control interface between the HVDC or OWF and dispatcher
- Ensure that the protection system is well coordinated
- Ensure the correspondence between the actual transient behavior and that simulated using offline EMT tools
- Prepare for on-site commissioning tests

6.1.3 C&P replicas for HVDC applications

A C&P replica is a copy of the actual control and protection system for the converter stations installed on site. An overview of a HIL setup with C&P replicas is presented in Figure 6-1. With the use of actual C&P systems, many limitations of offline models identified in previous subsections can be resolved, which makes the HIL setup with C&P replicas the go-to approach adopted by many utilities around the world (China, Canada, South Korea, India, Brazil, France, the UK, etc.) to de-risk HVDC projects. It is noted that the discussions of C&P replicas presented in this subsection are based on HVDC applications. Considerations for the C&P replica setup for wind farm connections will be presented in Section 6.1.4.

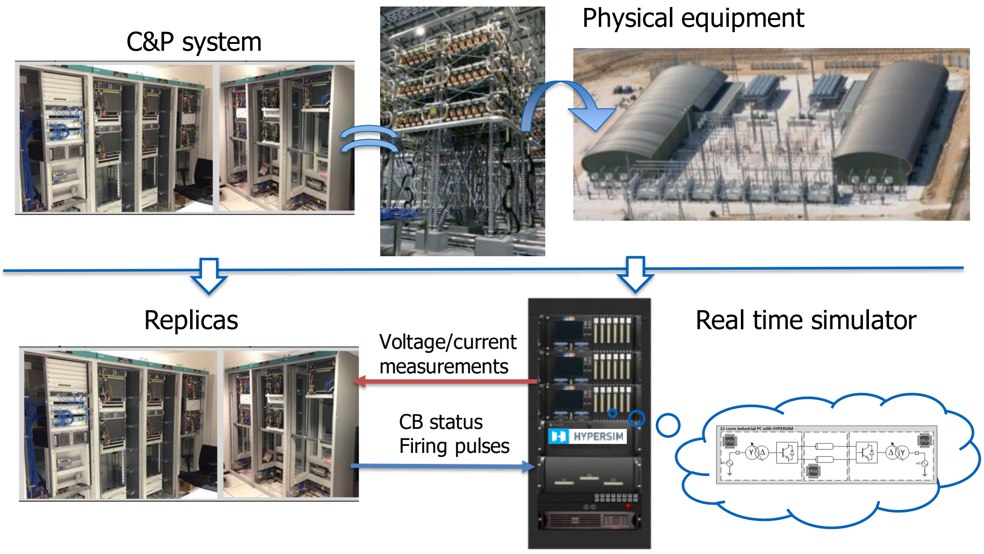


Figure 6-1 – HIL setup overview

Not only can the replicas be used to analyze the electrical behavior of the system, but they can also support maintenance activities related to the C&P cubicles. C&P replica are usually a partial copy of the real system installed on site, but not a complete copy of the entire C&P system on site. Some reduction and simplifications are always required because C&P

replicas are not interfaced with the physical equipment (e.g., valves, control cooling system, communication system, etc.). Different types of reductions can be proposed by HVDC/FACTS vendors to fulfill customer needs. This is why RTE is used to classifying C&P replicas in two types: study replica and maintenance replica.

Study replica

The study replica is dedicated to functional verification, dynamic system performance and protection studies for HVDC projects. It includes a set of cubicles related to network studies and the main C&P functions that would have an impact on the behavior of the system as well as the operator workstation. In addition, the study replica could include AC protection relays together with amplifiers integrated into the real-time simulation platform, Transient Fault Recorders (TFR) for plots and analysis purposes, and functionalities of Valve Base Electronics or Module Management System depending on the converter technology and project requirements. Since redundancy is not considered, the study replica often involves fewer cubicles compared to the maintenance replica.

A non-exhaustive list of studies that can be performed with the study replica is presented as follows [37]:

- Integration and operation of the HVDC link with the AC system (e.g., energization, step change of active and reactive power, step change of power references, transient disturbances due to fault and recovery, transient stability, temporary overvoltages, start-up and shut-down sequences, etc.)
- Adjusting C&P algorithms and tuning of C&P parameters
- Network and HVDC contingency playback and analysis
- AC and DC fault analysis and the consequential C&P behavior
- Black-start studies
- Interaction studies of different electrical installations (e.g., between different PEDs, between the AC network development and the HVDC converter station, etc.)
- Dynamic transient studies in a multi-vendor and multi-technology system
- C&P system update testing and validation before on-site implementation
- Operator training

However, the study replica is usually not used to perform functional and protection studies of electrical station services at medium/low voltages and auxiliary systems (e.g., water cooling system, HVA/C, fire detection, etc.) because these are not included in the real-time simulation environment [37].

Maintenance replica

The maintenance replica consists of a set of C&P cubicles to the greatest extent identical to the actual cubicles installed at the converter stations, which include the complete installation of C&P cubicles, Transient Fault Recorder (TFR), communication system including interstation communication as well as operator station. Unlike the study replica, the maintenance replica also includes the redundancy of the C&P equipment (for system switchover tests) and the same interfaces to the real-time simulation platform, as the actual on-site implementation. Therefore, apart from functional and dynamic performance and protection studies (that can be performed with the study replica), the maintenance replica can also be used to prepare for on-site maintenance operations during the entire life cycle of the project, train C&P hardware and software maintenance personnel, test and validate redundant system update before on-site implementation during the project life cycle, etc.

In addition, depending on the project requirement, the maintenance replica could also include AC/DC filter protection, converter transformer protection, converter cooling system, AC/DC switchyard control and auxiliary controls, hybrid optical measurement, zero-flux measurement, interface between converter control and the real-time simulation platform, etc. [37].

Similar to the study replica, the maintenance replica is usually not used to perform functional and protection studies of electrical station services at medium/low voltages and auxiliary systems (e.g., water cooling system, HVA/C, fire detection, etc.) because these are not included in the real-time simulation environment [37].

Due to the higher number of cubicles required in the maintenance replica, a higher cost can thus be expected. Therefore, the techno-economic aspects of the project need to be evaluated and analyzed prior to deciding whether a study replica would be sufficient or a maintenance replica would be necessary. Furthermore, discussions among stakeholders would be required to find the optimal solution. It is also important to note that the maintenance replica can be used to perform the same studies as the study replica, which is the reason why RTE decided to purchase only maintenance replicas that are used for both applications (maintenance and grid studies)

6.1.4 C&P replica setup considerations for wind farm connections

The HIL setup with C&P replicas has been used by utilities across the globe to conduct dynamic system design and performance studies for HVDC applications for several decades because:

- the C&P system of HVDC converters has a significant impact on grid operation, which is well-known and well-documented;
- the C&P system of HVDC converters is relatively physically centralized.

In the meantime, the converter vendors are used to performing HIL real-time dynamic studies using the C&P replicas for each project, which also encourages the use of such an approach for HVDC applications.

However, this is currently not the case for WTG vendors due to the following reasons:

- the impact of the C&P system of WTGs on grid operation has only been gaining attention recently ([5]-[7]);
- the C&P system of WTGs is relatively more distributed, with one set for each WTG inside a farm.

In addition, the WTG vendors currently do not adopt the practice of performing HIL real-time dynamic studies using the C&P replicas for each project. Instead, they would do so for each generation of WTG technology. Therefore, unlike for HVDC applications, the use of HIL real-time simulation with C&P replicas for OWF connection is technically less mature nowadays. The solutions proposed in this subsection should only be considered as technical suggestions for the NSWPH project, which would require further investigation and validation among different stakeholders and WTG vendors.

The C&P replica for wind farm connections are different from those for HVDC applications, thus requiring additional considerations. Different components of a wind farm connected to a transmission grid modelled in an offline EMT tool is illustrated hierarchically in Figure 6-2, where several control systems included in the C&P replica can be identified:

- Wind turbine controller for one wind generator (#2)
- Converter and grid controller for one wind generator (#3)
- Wind farm controller (#1)
- Controllers of any SVC or STATCOM that are part of the connection

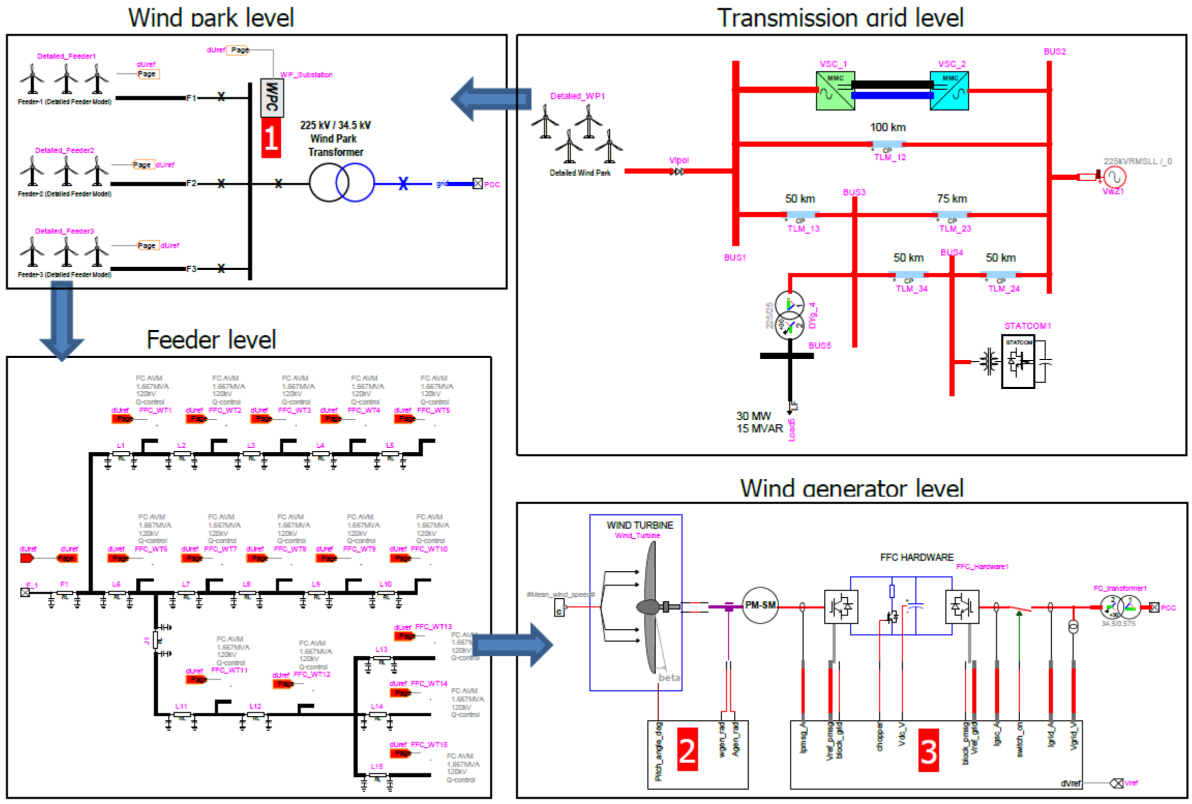


Figure 6-2 – Wind farm EMT offline model connected to a transmission grid – illustrative example

It is noted that the C&P replica for wind farm connections usually corresponds to the C&P system of a single wind generator, technical solutions need to be found to study the behavior of the entire wind farm. Among all the possible solutions, two solutions are described in this subsection.

Solution 1 (detailed) – detailed model for the wind farm and the transmission grid

In this solution method, all feeders, wind generators and the transmission grid shown in Figure 6-2 are simulated in real-time. The physical wind farm controller is connected to the wind park model, also running in real-time. A single wind generator model is controlled by the physical replica (wind turbine controller + converter controller) whereas all the other wind generator models are controlled by simulated controller models that are tuned to represent the respective installation. These simulated controller models, which can be generic, should be validated against the wind turbine and converter controller replica. C&P replicas of other PED based equipment (HVDC, FACTS) can also be connected. The setup for this solution is presented in Figure 6-3.

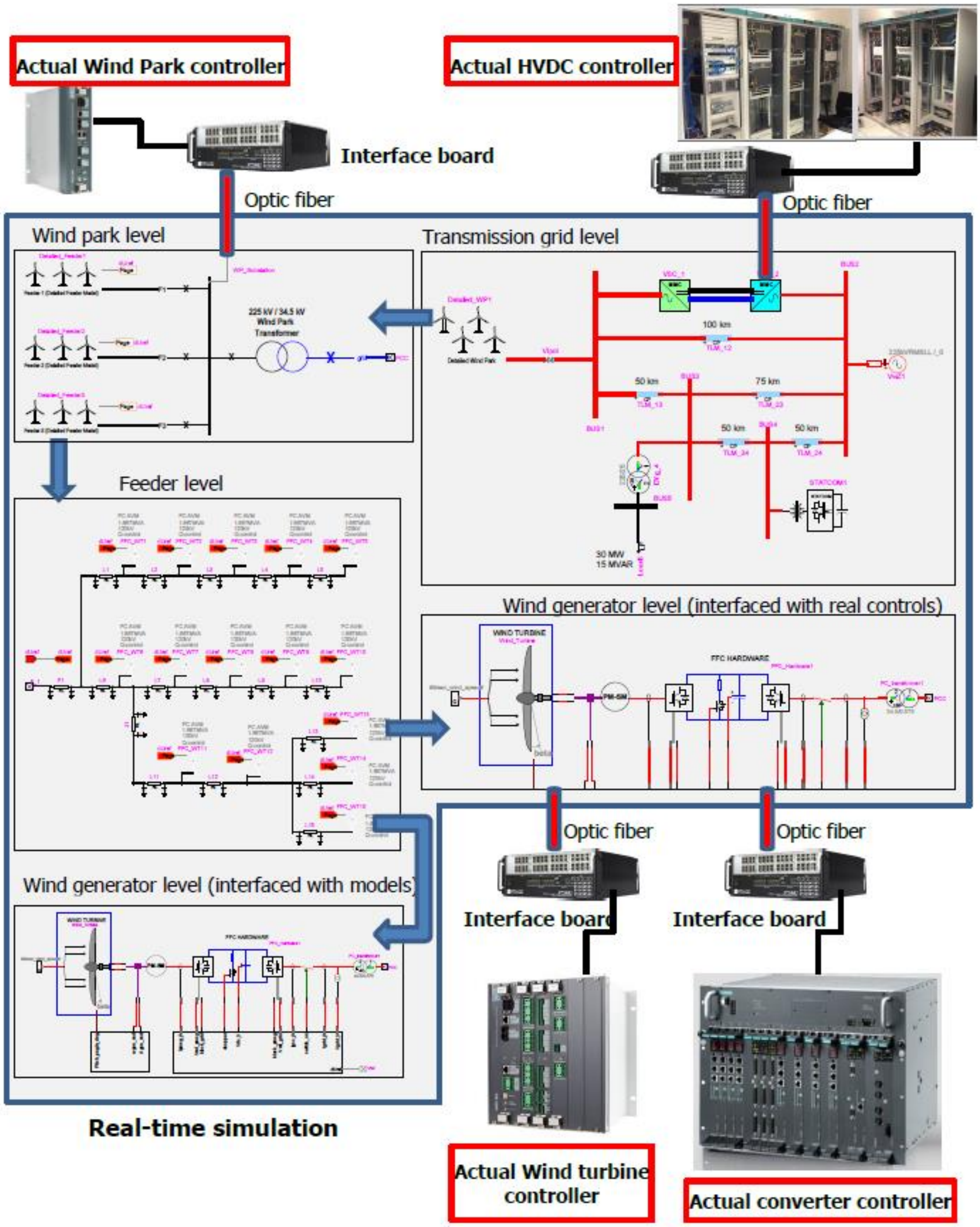


Figure 6-3 – Detailed real-time wind farm model connected to a transmission grid and C&P replicas

Solution 2 (aggregated) – aggregated model for the wind farm

In this solution, all feeders and wind generators are aggregated and simulated in real-time together with the transmission grid which is modelled in detail. The physical wind farm controller is connected to the wind farm model and is also running in real-time. The aggregated wind generator model is controlled by the physical C&P replica (wind turbine controller + converter controller). C&P replicas of other PED-based equipment (HVDC, FACTS) can also be connected in the same simulation. The setup for this solution is presented in Figure 6-4.

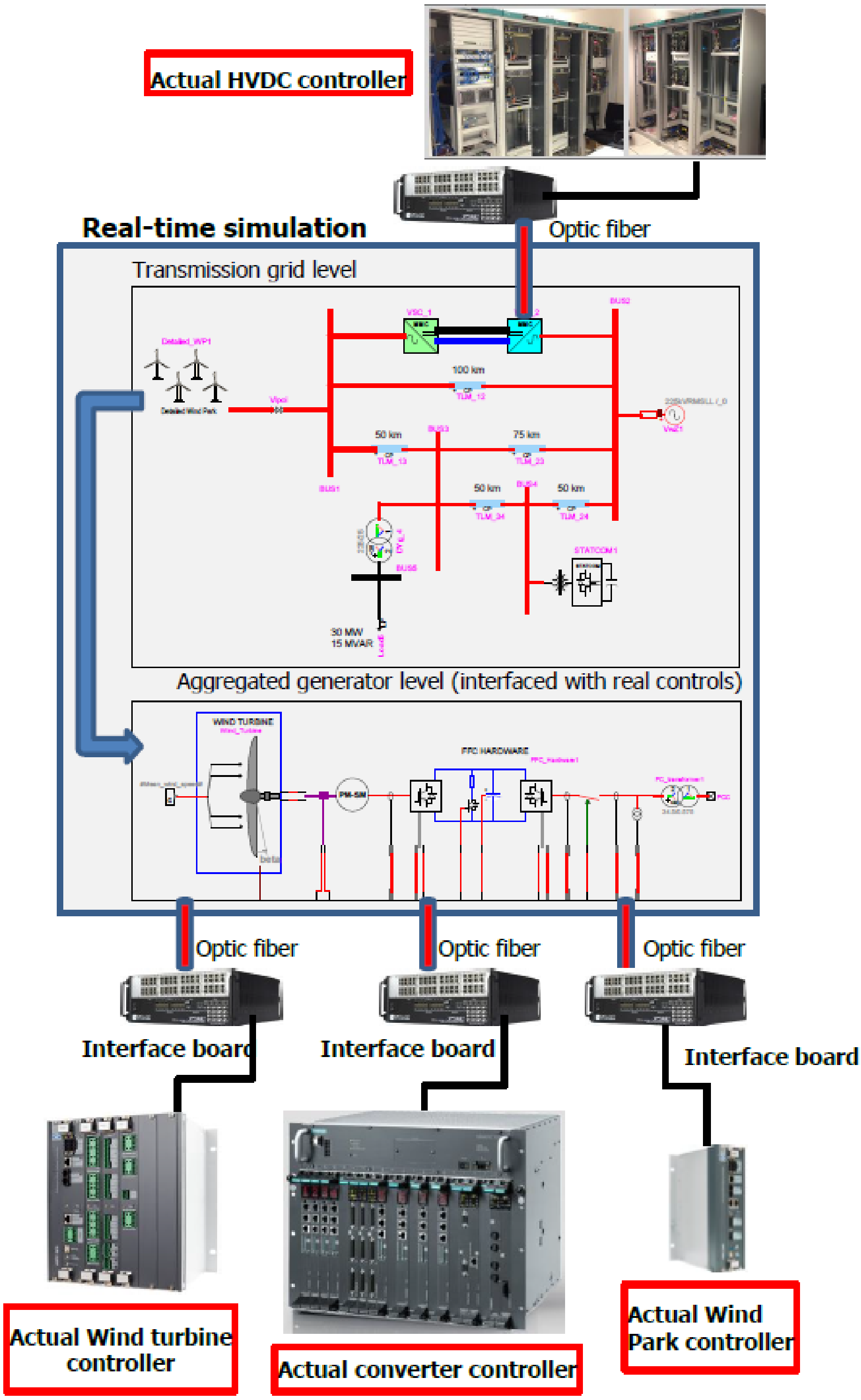


Figure 6-4 – Aggregated real-time wind farm model connected to a transmission grid and C&P replicas

It is worth mentioning that both setups depend on the project specifics and technical requirements that shall be discussed among stakeholders and with manufacturers.

6.1.5 Real-time simulator requirements

Besides the C&P replicas, a HIL setup also includes a real-time simulation platform consisting of a real-time simulator and IO interfaces communicating with the C&P replicas, which is discussed in this subsection.

6.1.5.1 Real-time EMT models

Similar to offline models, real-time EMT models should include all necessary electrical components in a system to be studied. At the early stage of project development, a Thevenin equivalent voltage source representing a range of short-circuit levels is generally sufficient to model the onshore AC network, especially in the testing of the interface between the real-time simulator and the C&P replicas, which is usually performed at the commissioning of replicas for study purposes. However, further studies might require a detailed onshore AC network representation depending on project requirements. In general, all HV electrical components in a network can be modelled using the standard components available in the library of the real-time simulator. Customized models of PED-based equipment may be involved in certain projects. In such cases, the task of modelling these PEDs is the responsibility of the PED manufacturer possibly in collaboration with the real-time simulator vendor. Supplementary libraries, codes, and documents specific to the customized model should be provided to the end-user in order to perform studies and analyses.

Moreover, the need to respect real-time constraints in a real-time simulation could indicate model simplification. In particular, simplification on the modelling of nonlinear components such as surge arresters and transformers might counteract the accuracy brought by using the C&P replicas in fault analysis, resulting in transient behavior different from that observed in offline simulation or on site. Therefore, a prudent evaluation of all aspects is needed before drawing conclusions purely based on the performance of the C&P replicas. In such cases, a cross-check with the same study performed on an offline EMT tool and with recordings of real event on site would help with the analysis and decision-making. Some examples can be found in [48].

Further details and considerations for real-time modelling of AC and PED-based electrical components can be found in [37].

6.1.5.2 IO interfaces

Two solutions are available to interface the C&P replicas with the real-time simulator, which are standard interface and digital interface [37]. Depending on the technology of the real-time simulator and the C&P manufacturer, one of the two interfaces can be chosen, or both can be collectively implemented.

Standard interface

The standard interface is usually implemented with copper wiring using IO interface boards of the real-time simulator. No special development is required for this type of interface. The requirements for the resolution and dynamic range of analog inputs should correspond to the specifications of the C&P system. However, the delays using this interface could pose certain constraints in the operation of the HVDC link or OWF. Therefore, a careful evaluation considering the specifics of the project needs to be carried out prior to the choice of interfaces.

In general, four types of IO signals are involved in the standard interface. They are:

- AI: analog input (typically ±10V)
- AO: analog output (typically ±10V)
- DI: digital input (typically 24V)
- DO: digital output (typically 24V)

Depending on the project, the standard interface usually requires a significant number of IO signals, which would have an impact on the cost of the real-time simulator and other relevant hardware.

Digital interface

The digital interface is usually implemented with a digital bus using optic fibers. It drastically reduces the amount of wiring between the C&P replicas and the real-time simulator. However, certain development on the communication protocols needs to be carried out in the real-time simulator, which is mostly not a daunting task thanks to the experience of the real-time simulator supplier and the C&P replica manufacturer. Depending on the technology involved and specifics of the project, three types of digital interfaces can be used [37]:

- Digital interface based on standard protocol (e.g., IEC 61850, MODBUS, etc.). These interfaces are typically used for low-speed applications such as status change of circuit breakers, disconnector and tap changers.
- Digital interface based on specific protocols to achieve fast communication in order to meet real-time simulation requirements.
- Digital interface based on FPGA to achieve very fast communication. This interface is usually used in VSC real-time models. No universal standard has been developed for this type of interface to date, which would call for a joint development between the real-time simulator supplier and the C&P replica manufacturer based on project requirements.

6.1.6 Advantages and limitations of real-time simulation with C&P replicas

Following the discussion on the HIL setup, C&P replica considerations for both HVDC applications and OWF connections as well as real-time simulator requirements presented in previous subsections, the advantages and limitations of real-time simulation using C&P replicas are explained in this subsection.

6.1.6.1 Advantages of real-time simulation with C&P replicas

- **Accurate representation of the actual C&P system**

The modelling of detailed C&P systems for EMT offline studies demands considerable effort because the actual controls may be implemented on multiple platforms (e.g., CPU, DSP, FPGA, etc.). As a result, simplifications are often adopted in order to reduce modelling complexity and speed up offline EMT simulation (usually performed on a single CPU), which adversely would hinder the offline EMT models in providing reliable results. Real-time simulation with C&P replicas, on the other hand, offers an accurate representation of the C&P systems implemented on site without simplifications or assumptions in the control systems. In the frequency range of a concerned study, it can produce the most accurate results and allow a confident evaluation of the system behavior. The use of real-time simulation with C&P replicas is crucial in de-risking a project involving multi-vendor and multi-technology HVDC-OWF applications such as NSWPH as it played a key role in identifying and resolving the interaction issues in existing installations around the world discussed in Section 5.1.2.

- **More accessibility and flexibility than the manufacturer black-boxed model**

The C&P system is based on algorithms protected by the IP rights of the manufacturer. Therefore, its detailed internal structure, parameters and internal C&P signals are not accessible to the end-user in an offline EMT model. However, the C&P functions can be more visible in the C&P replicas, offering the end-user the possibility of tuning and manipulating certain parameters under the agreement of the manufacturers and obtaining a deeper insight in the observed behavior.

In addition, the higher accessibility and flexibility of C&P replicas could also facilitate operator training.

- **A solution to long-term optimal operation and maintenance**

The C&P systems are continually updated during the entire life cycle of the project (e.g., control strategies, parameter changes, etc.). These updates and changes will have an impact on the system performance. Since offline EMT models are not designed to be used for the entire life cycle of the installation and updating them every time a change or a modification is made is time-consuming, they are usually not updated accordingly thus cannot reflect the functionalities and changes newly implemented on site. It is also not possible to fully validate the offline EMT model updates even if they are contractually required. On the contrary, real-time simulation with C&P replicas provides a more flexible and manageable solution in tracking C&P software updates and validating the updates before on-site implementation.

Furthermore, due to software version and computer operating system upgrades within a span of several years, the offline EMT models that are functional today might not be compatible with future software versions or operating systems. However, this is not an issue with the solution using C&P replicas in that:

- all models running in real-time are accessible (parameter and data) and can be transferred to another simulation tool if needed;
- the C&P replicas remain identical to the system installed on site (hardware and software). Spare parts can be ordered with a high level of reliability when necessary.

- **Indispensable for certain studies**

Real-time simulation with C&P replicas makes it possible to perform certain studies that cannot be performed using offline EMT models such as actual start-up and shut-down procedures, black-start sequences, etc. because the functions involved in these procedures are not included in the offline EMT models. In addition, as was already discussed in Section 5.2.3.3, offline EMT models are not always suitable for events involving very slow variations that last from tens of minutes up to several hours due to the much longer simulation time required for such events, which can be impeditive for the project development. Real time-simulation with C&P replicas does not have such an issue of simulation time constraint as it runs in real-time.

- **Valuable support for the HVDC maintenance and operation team**

As was mentioned in Section 6.1.3, the maintenance replica consists of a set of C&P cubicles to the greatest extent identical to the actual cubicles installed at the converter stations as well as the redundancy of the C&P equipment and various interfaces to external environments identical to the on-site implementation. This would considerably facilitate training of maintenance personnel and support the HVDC maintenance and operation teams in that:

- The maintenance replica offers real HVDC HMIs which allows realistic system operation.
- The maintenance replica comes with all associated tools (i.e., TFR, system analyzer, event/alarm list, etc.) as on-site implementation.
- The high identicality to the on-site system allows the maintenance team to prepare for maintenance operations and to analyze hardware issues.

Since the warranty period for C&P and valve maintenance is usually 5 years, having a professionally trained team dedicated to maintenance activities would be a great asset to a TSO, with the help of the maintenance replica.

- **A solution to analyze multi-infeed, multi-vendor, multi-technology systems**

The most commonly used EMT simulation tools are based on fixed time-step solvers. The offline C&P models provided by manufacturers are valid only for a small range of numerical simulation time-steps, depending on the C&P philosophy and the sampling rate requirements. For instance, EMT models for 2-level VSC converters typically require a simulation time-step between 1μs and 10μs. Average-value converter models or HVDC-MMC converter models can operate with time-steps between 20μs et 50μs. Validity of offline C&P models is usually guaranteed only for the specified range of simulation time-steps, which is a strong limitation for offline simulations of systems invoving multi-vendor and multi-technology PEDs. This is especially true when it is necessary to study interactions between an OWF and HVDC / FACTS equipment, as is the case of the NSWPH project.

Real-time simulation with C&P replicas, however, provides an efficient solution to this issue for the following reasons:

- Each C&P software runs on its dedicated hardware with its appropriate simulation time-step
- Real-time simulations can run on different platforms (e.g., CPU, FPGA, etc.) to meet specific sampling rate requirements.

Furthermore, real-time simulation with C&P replicas also offers a platform to host other hardware such as DC/AC protections and wide-area control devices to validate and perform coordination study among multi-vendors and multi-technology systems.

- **A key to speeding up commissioning and increasing long-term availability**

Apart from all the advantages of real-time simulation with C&P replicas discussed previously, it is also worth mentioning that this approach is a mandatory tool in order to respect the time schedule of on-site commissioning and increase long-term system availability for OWF connections based on the experience of RTE and RTE international in HVDC/FACTS systems. Similarly, availability gain can also be expected in the adjacent HVDC and FACTS equipment. Needless to say, the prospect of increasing system availability using real-time simulation with C&P replicas would indicate significant economic benefits for projects involving industries with considerable annual turnovers.

6.1.6.2 Limitations of real-time simulation with C&P replicas

- **Additional investment in human resources and infrastructure**

It is easy to realize that the approach of using real-time simulation with C&P replicas, despite its advantages in de-risking the design, operation and maintenance of a multi-vendor and multi-technology system, would imply a more costly investment from the project owner in terms of human resources and infrastructure. The aspect of human resources consists mainly in engineers and/or operators as well as training activities with respect to the HIL setup (real-time simulation environment and C&P replicas), while investment in infrastructure would involve the purchase and maintenance of the HIL setup, constructing and operating laboratory facilities designated for real-time simulation studies with C&P replicas. The investment aspect will be further elaborated in the next chapter.

- **Less accurate power circuit model due to real-time constraints**

As was mentioned in Section 6.1.5, despite the fact that the C&P replicas provide an accurate representation of the actual C&P system on site, certain power circuit components models in real-time simulators could be less accurate compared to those in offline EMT tools due to the simplification adopted in order to respect real-time constraints. In particular, offline EMT models usually render more accurate transient behavior for frequencies above several kHz. In such cases, it is, therefore, necessary to cross-check with the same study performed on an offline EMT tool in order to further boost confidence in result analysis and decision-making.

- **Less efficient compared to offline EMT simulation under certain circumstances**

Real-time simulation with C&P replicas possesses great advantages over offline EMT simulation in terms of simulation time for events involving extremely slow dynamics, as was mentioned previously. Contrary to what one might believe, it can, however, prove to be less efficient compared to offline EMT simulations in certain situations. One example from the Johan Sverdrup project shows that a great number of tests using the HIL setup with C&P replicas for interoperability studies could lead to system alarms, unexpected failures and trippings that would require physical intervention from the operators and engineers to bring the system back to normal operation. It is possible to automize these procedures. However, it would call for the agreement and effort from the vendors to modify part of the C&P system. In particular, over 10000 simulations were performed on PSCAD with fewer resources in less than two years for the Johan Sverdrup project, whereas approximately only 3000 tests were planned to be conducted with real-time simulation within two and a half years of studies, considering the above-mentioned constraints. This is also a limitation in the HIL setup approach, as compared to offline EMT simulation, in the sensitivity analysis at later stages until commissioning of the project because thousands of test scenarios would need to be run automatically in parallel without user intervention.

For better clarity, Table 6-1 summarizes the comparison between the HIL setup with C&P replicas and offline EMT simulations for the aspects that are crucial in interoperability assessment for a multi-vendor PED-based system. It is noted that the aspects being compared are strictly technical, excluding infrastructural and human resource considerations which are discussed in the next chapter, as well as implementation possibility for various project stakeholders considering their respective resources (which is out of the scope of this document). In addition, aspects that are only relevant to a single approach are not included for comparison.

Table 6-1 – Comparison between the HIL setup with C&P replicas and offline EMT simulations for the aspects that are crucial in multi-vendor interoperability assessment.

	HIL setup with C&P replicas	**Offline EMT simulations**
Representation of actual on-site C&P system	Accurate because real hardware and identical software are used	Less accurate with simplifications and approximations
Representation of power circuit components	Less accurate for certain nonlinear devices and frequencies above several kHz. May require additional component (interface lines) and/or less accurate models of switching devices (Fixed impedance based solution)	Accurate Model can be adapted to the accuracy requirement
C&P accessibility and flexibility	More accessible and flexible to use. High level control systems may be accessible on the replica and not black box.	Less accessible and flexible to use. Usually C&P functions are usually black boxed.
Following on-site system updates	Tracking software update is easier because same software than on site.	Difficulty and uncertainty in tracking and implementing updates especially after commissioning
Regarding multi-vendor EMT models	Easy to accommodate time-step differences because each C&P systems run on their own hardware	Difficulty in accommodating time-step differences (leading to potential accuracy issues)
Operational cost	Costly investment in infrastructure, hardware, and human resources	Less costly, require standard computers and specialized skills.
Studies of system operation, involving operator intervention or slow-varying dynamics	Feasible	Not feasible
Automatic run of large numbers of sensitivity studies in parallel	Not feasible due to the need of operator intervention. It could be feasible if the C&P software running in replica is modified. Running several scenarios in parallel is not possible.	Feasible.

It is easy to observe that both approaches have mutually complementary advantages and limitations in the aspects that are crucial for interoperability assessment in the multi-vendor NSWPH project. Considering the technical status quo, it is, therefore, recommended to use both approaches in complement to one another in the dynamic studies of the NSWPH project to adequately assess potential interoperability issues and to confidently de-risk the design and operation of the project, which is further demonstrated in the case studies hereinafter. It is important to mention that this analysis is based on RTEi experience on the present technologies available. It will most probably evolve in the future with enhanced offline simulation tools and models.

6.2 Case studies (lessons learnt by RTE)

The objective of this section is to share with the NSWPH consortium the experience of RTE in using real-time simulation with C&P replicas from previous and current projects, demonstrating the advantages (and necessity) of this approach in forensic studies after certain issues occurred in the system, and de-risking activities in a system involving multi-vendor, multi-technology PEDs.

Specifically, two case studies from the INELFE projects are presented, where the use of real-time simulation with C&P replicas was essential for the identification of the root cause of the observed phenomena on site and the implementation of corresponding mitigation techniques (Sections 6.2.1 and 6.2.2). These two case studies are followed by an example of the on-going Johan Sverdrup project (Section 6.2.3) in which the HIL setup plays an indispensable role due to offline simulation and project constraints in de-risking the design and implementation studies of a system consisting of two HVDC links from different manufacturers. Moreover, HIL-supported HVDC maintenance activities at RTE are introduced in Section 6.2.4, demonstrating one of the major applications of C&P replicas for a TSO. Last but not least, an accuracy issue in terms of artificial resonance in real-time simulation caused by the modelling approach implemented in semiconductor switches due to real-time constraints is presented in Section6.2.5, further highlighting the fact that both offline EMT and real-time simulation approaches would indispensable in interoperability studies for the NSWPH project and they should be used in complementary to one another.

6.2.1 INELFE harmonic instability study

A resonance phenomenon occurred on the INELFE HVDC link on September 22nd, 2015, following a dynamic event in the vicinity, leading to the tripping of the link. The on-site voltage measurement during the event is presented in Figure 6-5 (left). This figure shows a high frequency oscillation of approximately 1.7 kHz in an undamped overvoltage reaching 1.7 pu that lasted several seconds, prior to the tripping of the HVDC link that results in a sudden halt of power exchange.

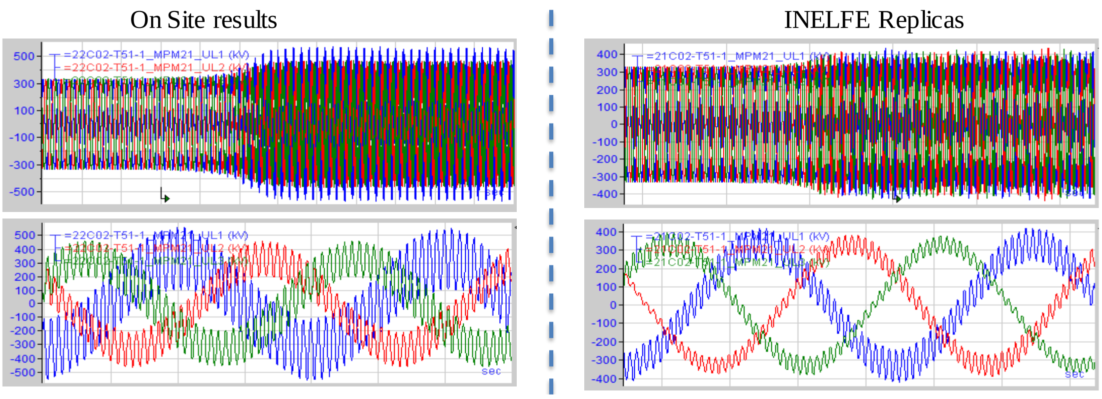


Figure 6-5 – INELFE AC voltage at PCC - high frequency oscillation

Initially, it was attempted to conduct offline EMT studies to investigate the event. However, offline EMT studies using the manufacturer black-boxed model were unable to reproduce the phenomenon observed on site due to the simplification of the C&P systems and the fact that the offline manufacturer black-boxed model was not up to date. Therefore, real-time simulation with C&P replicas were eventually opted to successfully reproduce the observed event, as is shown in Figure 6-5 (right, as compared to the on-site measurements on the left).

Once the observed phenomenon was successfully reproduced with the HIL setup, RTE was able to perform studies in order to investigate the possible network topologies that could lead to such an event, understand its root cause, and propose feasible solutions. In addition, discussions with the HVDC manufacturer were launched with a new version of the C&P software to solve this issue proposed later on. The proposed software update was first tested and validated on the real-time simulator using C&P replicas before on-site implementation. It was discovered that the observed resonance phenomenon was harmonic instability due to the fact that the converter, together with its controls, exhibits the behavior of "negative resistance" in certain frequency ranges, giving rise to undamped oscillations caused by interactions with the AC grid. Details of this control instability phenomenon can be found in [19]. However, it turned out that the new updates could effectively resolve the resonance issue at the expense of dynamic performance degradation of the HVDC link, resulting in a non-compliance with the specifications.

The investigation conducted by RTE to understand the root cause of the observed phenomenon is briefly introduced in this section, using a generic in-house EMT model to protect the IP rights of the HVDC manufacturer.

The network configuration used in this investigation is presented in Figure 6-6. It consists of an HVDC-MMC link connected to an AC network (Network 1). Network 1 includes two overhead lines of 50 km connected in parallel, an AC breaker "BRK", a shunt compensator and a Thevenin equivalent voltage source with a short-circuit power level of 20 GVA. 1000 MW of active power is transmitted from Grid 1 to Grid 2. In the studied scenario, the opening of AC breaker BRK disconnects one of the overhead lines from Station 1, leading to a modification of the AC grid impedance characteristics thus causing the observed harmonic instability phenomenon.

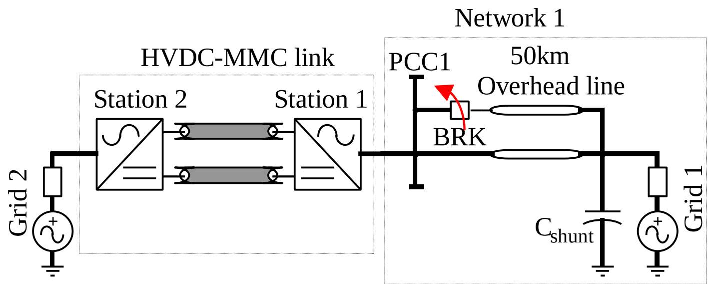


Figure 6-6 – Circuit configuration of the INELFE harmonic instability case study

A small-signal analysis described in Section 5.2.2 was performed. The frequency responses of the active impedance of Converter Station 1 $Z(f)$ and the impedance of Network 1 at PCC1 before and after the disconnection of the overhead line are presented in Figure 6-7, with their phase angles zoomed in the y-axis shown in Figure 6-8. The intersections of the amplitudes of $Z(f)$ and Network 1 impedance determine the frequency points at which the phase difference should be calculated. It can be observed that the intersection points are shifted when only one overhead line is connected to Station 1, thus changing the stability phase margin. It should be mentioned that if the phase difference becomes greater than $180°$ in certain frequency ranges, the system is said to present "negative resistive" characteristics and loses its stability, making it prone to produce undamped oscillations caused by interactions with the external network. It can be observed in Figure 6-7 and Figure 6-8 that the phase difference between $Z(f)$ and Network 1 impedance with one overhead line is greater than $180°$ at approximately 1.7 kHz, which explains the cause of the observed resonance.

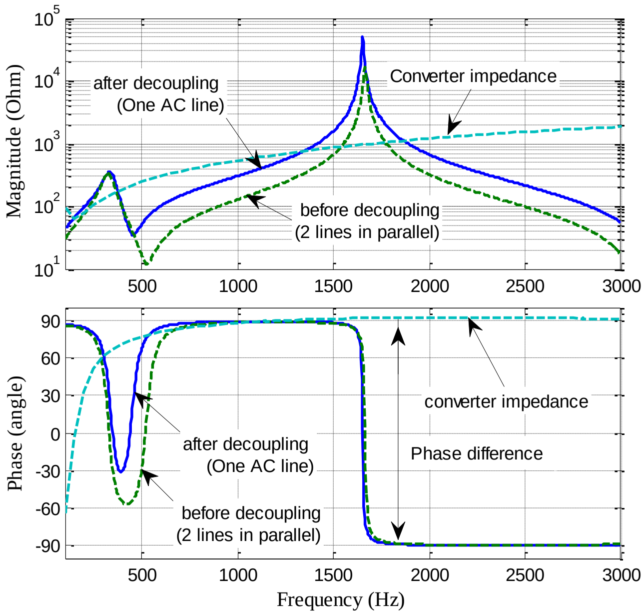


Figure 6-7 – Frequency response of Network 1 and the converter station

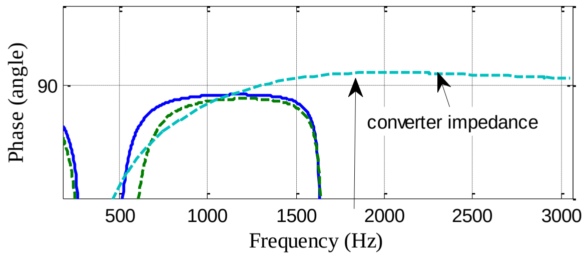


Figure 6-8 – Phase angle presented in Figure 6-7 zoomed in the y axis.

The discovered root cause was further validated in time-domain simulation. The voltage waveforms at PCC1 are presented in Figure 6-9 where a resonance frequency of 1.7 kHz can be clearly observed after the opening of breaker BRK.

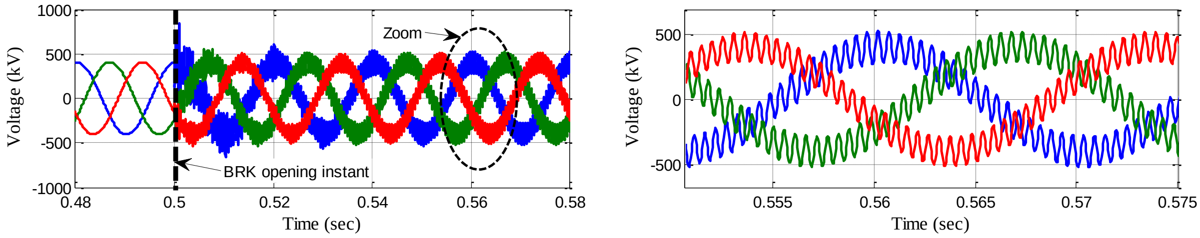


Figure 6-9 – AC voltage at PCC1 and zoomed view of an interval

Other details of this case study can be found in [12]. A few lessons can be learnt from investigating and resolving this issue:

- Accurate EMT representation of the AC grid is required for analyses of sufficiently high frequencies (e.g., using frequency-dependent models for overhead lines and adjacent HV equipment).
- It is important to provide the manufacturer with accurate network harmonic impedance during the implementation stage as the observed high-frequency phenomenon depends on several parameters such as AC line, short-circuit level, AC configuration, etc.

- Most importantly, the C&P replicas, representing the actual on-site C&P implementation, are required to analyze and resolve the issue as it was not possible to reproduce the observed phenomenon (as a first step of investigation) with the manufacturer black-boxed model due to control simplification and software version being out of date. In addition, measurement delays and filter processing implemented in the C&P system would also have a major impact on this event [19].

6.2.2 INELFE AC emulation issues

The Continental Europe (CE) synchronous system is the largest synchronous power system, supplying power to 26 countries from Spain and Portugal in the west, to Denmark in the north as well as to Turkey in the east. Several oscillation modes exist in such a complex electrical system, such as control modes related to AVR and governors and electromechanical modes related to turbine and generator inertias in which the latter, mostly poorly damped, can lead to inter-area oscillations when excited which are manifested by low-frequency (0.1 Hz – 2 Hz) power swings between distant areas and large voltage variations that could result in system instability.

An East-Centre-West inter-area oscillation event occurred on December 1st, 2016, where the Iberian Peninsula and Turkey oscillated against the centre of the system (Germany, Poland, etc.), following the mode shape illustrated in Figure 6-10. Details of this event can be found in ENTSO-E report [39], as well as [12] and [13].

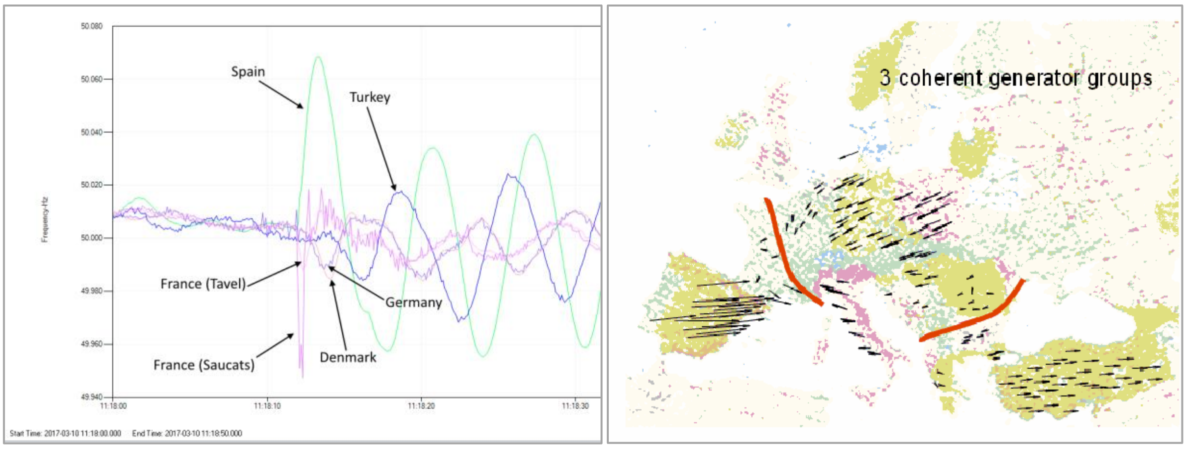


Figure 6-10 – Frequencies at different locations of CE system and mode shape in the oscillatory event on December 1st, 2016, [39]

The Spanish and French networks are interconnected by 4 overhead lines (400 kV and 225 kV) in parallel with the 2 GW INELFE HVDC link. The on-site recordings from the PMU of the oscillatory event on December 1st, 2016, are presented in Figure 6-11, in which three sequences can be distinguished:

1. Before the oscillatory event, the active and reactive power transfer between France and Spain are stable.
2. A quasi-stable oscillation at a frequency between 0.15 Hz and 0.16 Hz occurs after the opening of a 400 kV circuit breaker.
3. These oscillations are subsequently damped due to the decreased power exchange between France and Spain.

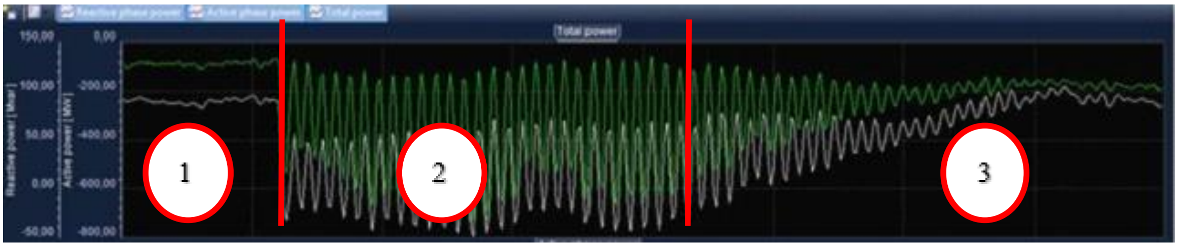


Figure 6-11 – On-site recordings of the oscillatory event on December 1st, 2016

This event was critical for the Iberian Peninsula network in that it posed great risks of blackouts. RTE and REE launched RMS and EMT studies following this event in order to reproduce this inter-area oscillation event using real-time HIL simulation and the INELFE replicas (see Figure 6-12) and investigate in possible mitigation techniques. It should be noted that this event can be reproduced using the offline EMT model theoretically. The reasons why real-time simulation with C&P replicas were involved were:

- The AC emulation function was suspected to have been simplified or excluded in the available manufacturer black-boxed model. Additionally, it was also suspected that the offline manufacturer black-boxed EMT model was not up to date due to control software updates implemented only on site, as in the previous case study.
- Certain internal control parameters in the C&P replicas were accessible to RTE based on the contract specifications with the HVDC manufacturer, which greatly facilitates testing mitigation measures and speeds up the investigation process. However, the manufacturer model provided to RTE was completely black-boxed, leaving no accessibility to its internal structures.
- The observed oscillatory phenomenon lasted tens of seconds. Therefore, real-time simulation would be a more efficient approach than using an offline EMT tool in terms of simulation time.

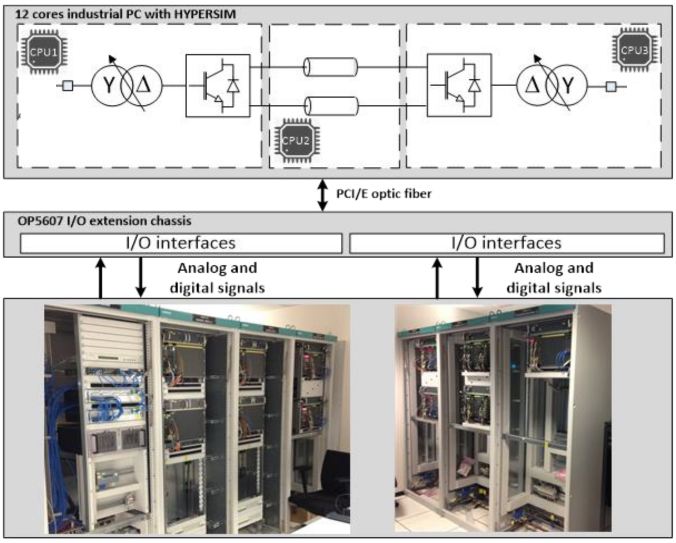


Figure 6-12 – HIL simulation of INELFE Replicas with Hypersim simulator

A test bench was developed as a first step in the investigation, considering the East-Centre-West inter-area oscillation mode and the sequence of events. It is noted that the developed test bench was not intended to model a detailed and realistic network, but to imitate the observed phenomenon which is the inter-area oscillation of approximately 0.155 Hz and the sequence of events with the intention of investigating potential solution methods as well as validating future software modifications on the INELFE control cubicles.

The observed and reported sequence of events [39] can be reproduced by the equivalent network presented in Figure 6-13, in which Zline1 and Zline2 are the two equivalent 400 kV AC line connections between France and Spain, two generic synchronous machines (H1 and H2) are modelled to reproduce the inter-area oscillation mode, and the INELFE HVDC link operates in AC Line Emulation [40]. This emulation technique was adopted for the HVDC link to emulate the behavior of an AC line with its active power flow being a function of the angle difference.

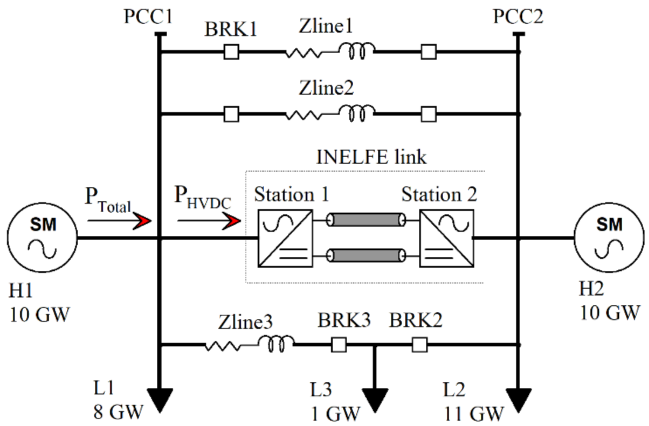


Figure 6-13 – Equivalent grid around the HVDC-INELFE link

The AC emulation function used in INELFE link is given by:

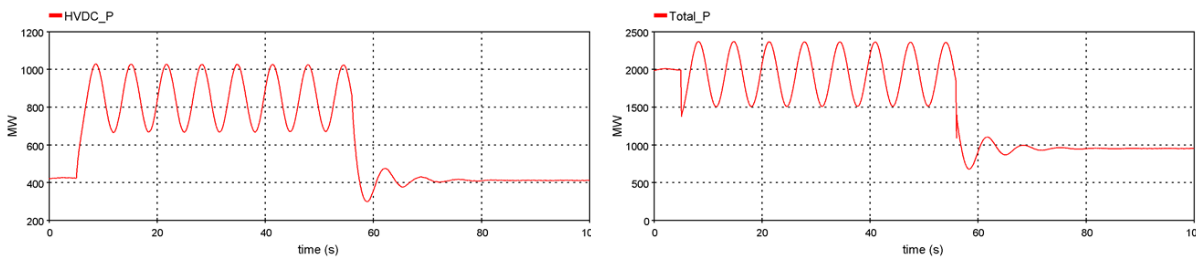
$$P_{ref}^{tot} = P_{ref}^{setpoint} + K^{HMI}(\delta_{station1} - \delta_{station2}) \tag{6-1}$$

where P_{ref}^{tot} is the total active power reference, $P_{ref}^{setpoint}$ refers to the active power reference constant setpoint, K^{HMI} is the static gain set by the operator ($MW/degree$) and $(\delta_{station1} - \delta_{station2})$ is the angle difference between the two stations. For this particular test, K^{HMI} and $P_{ref}^{setpoint}$ are set to 360 and 0, respectively. Therefore, equation (6-1) is transformed into the same form of the AC line active power transfer function, given by:

$$P_R = \frac{V_S V_R}{X}\sin(\Delta\delta) \approx \frac{V_S V_R}{X}\Delta\delta \tag{6-2}$$

where V_S and V_R are the line terminal voltages, X is its series impedance and $\Delta\delta$ is the angle difference.

Using the equivalent network configuration presented in Figure 6-13 and the INELFE replicas, the observed oscillatory event was successfully reproduced in a time-domain simulation, as is shown in Figure 6-14. In Figure 6-14, the plotted signals are (from top to bottom) the total power exchanged between PCC1 and PCC2, power transfer through the HVDC link, and the angle difference between PCC1 and PCC2.



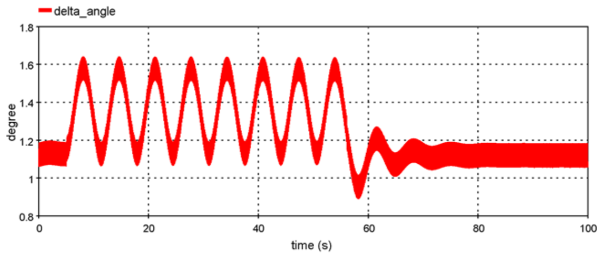


Figure 6-14 – Real-time simulation results using the INELFE replicas to reproduce the event

Three stages of the event can be observed in Figure 6-14:

- Stage #1, t<5s: All circuit breakers are closed except for BRK3 which is open. The active power exchange between PCC1 and PCC2 is 2 GW.
- Stage #2, 5s<t<55s: An oscillation of active power of approximately 0.15 Hz occurs between PCC1 and PCC2 occurs after the opening of BRK1.
- Stage #3, t>55s: Load transfer following the opening of BR2 and closing of BRK3, which leads to increased damping of the oscillations.

A new control tuning was proposed after studying the impact of the low-pass filter used in the AC line emulation. On the INELFE replicas, the above sequence of events was re-simulated in a time-domain simulation. The total power exchanged between PCC1 and PCC2, power transfer through the HVDC link as well as the angle difference with the new control tuning (tuning #2) are replotted against the results using the original tuning (tuning #1), as is presented in Figure 6-15.

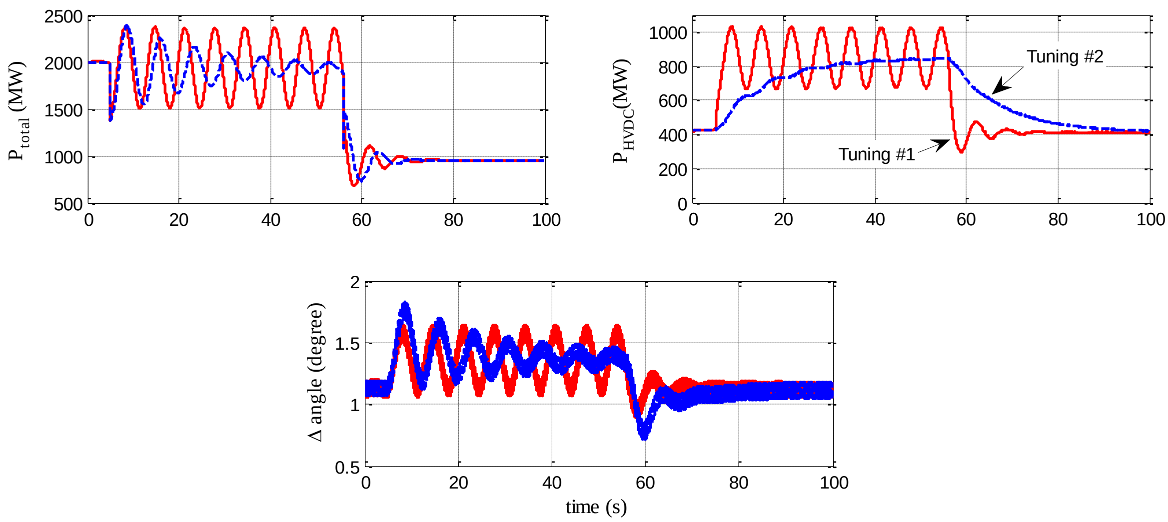


Figure 6-15 – Comparison of different control gain tunings using the INELFE replicas

It can be observed that the active power oscillations are damped using the new control tuning (tuning #2).

Additionally, small-signal studies were carried out to further investigate the control behavior during the inter-area oscillation for both tuning settings by analyzing the dynamic variation of the gain K in equation (6-1) in frequency domain. It is noted that although it can be set statically by the INELFE link operator on the HMI (e.g., 360 at 0 Hz), the parameter K is a frequency dependent variable that evolves dynamically with respect to frequency.

Setting $P_{ref}^{setpoint} = \delta_{station2} = 0$, equation (6-1) in frequency domain becomes:

$$P_{ref}^{tot}(f)/\delta_{station1}(f) = K(f) \quad (6\text{-}3)$$

It is noted that in equation (6-3), $K(0\,Hz) = K^{HMI} = 360$, which is set by the operator. To determine the frequency response of $K(f)$ with the help of the HVDC replicas, a small perturbation is injected into the HVDC link using the open loop configuration, as is illustrated in Figure 6-16. The frequency response of $K(f)$ could be obtained by computing equation (6-3) for each frequency point in a real-time simulation environment.

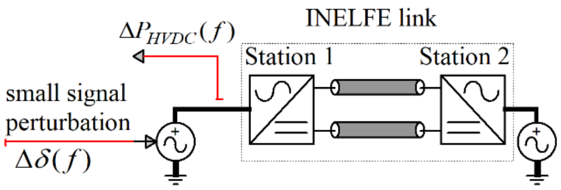


Figure 6-16 – INELFE real time simulation configuration to compute K(f)

The frequency response of $K(f)$ for both tuning settings is presented in Figure 6-17.

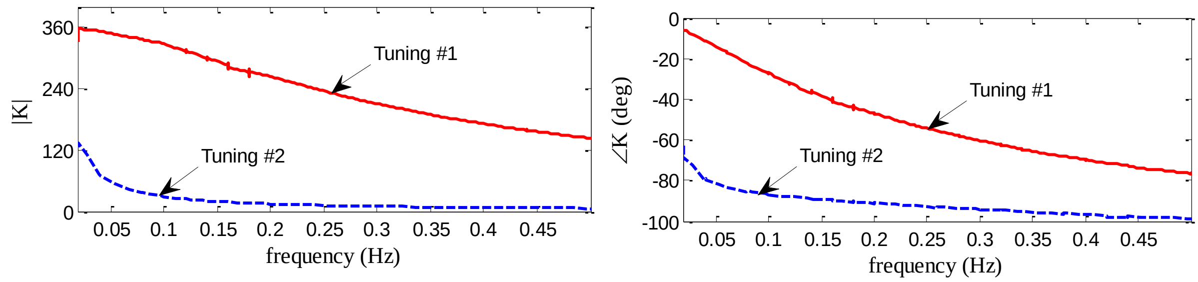


Figure 6-17 – Frequency response of K for the two different tunings

Several observations can be made in Figure 6-17:

- For tuning #1, the amplitude of K, $|K(f)|$, is close to 360 at low frequencies, corresponding to the static value K^{HMI} set by the operator. However, $|K(f)|$ decreases as the frequency increases, indicating that the AC line emulation behaviour of the HVDC is reduced (i.e., active power fluctuation of the HVDC is reduced) as the frequency increases.
- The angle of K, $\angle K(f)$, is close to zero at low frequencies (e.g., $f < 0.02\,Hz$) for tuning #1. $\angle K(f)$ decreases as the frequency increases. Despite the fact that it is not straightforward to provide a physical interpretation of $\angle K(f)$, it does contribute to system stability and the cause of the inter-area oscillations observed on December 1st, 2016, for reasons to become clear hereinafter.

As demonstrated above, the frequency response of $K(f)$ of the HVDC link can be computed using the open loop configuration presented in Figure 6-16. Similarly, the dynamic gain of the equivalent network can be obtained in frequency domain without considering the HVDC link:

$$P_{PCC1}(f)/\delta_{PCC1}(f) = K_{grid}(f) \qquad (6\text{-}4)$$

where $K_{grid}(f)$ can be interpreted as the image of the equivalent network admittance.

The stability of the closed loop system can be evaluated by calculating the phase margin from the system frequency response. To this end, it is sufficient to superimpose the two curves $K(f)$ and $K_{grid}(f)$ obtained previously, as is shown in Figure 6-18.

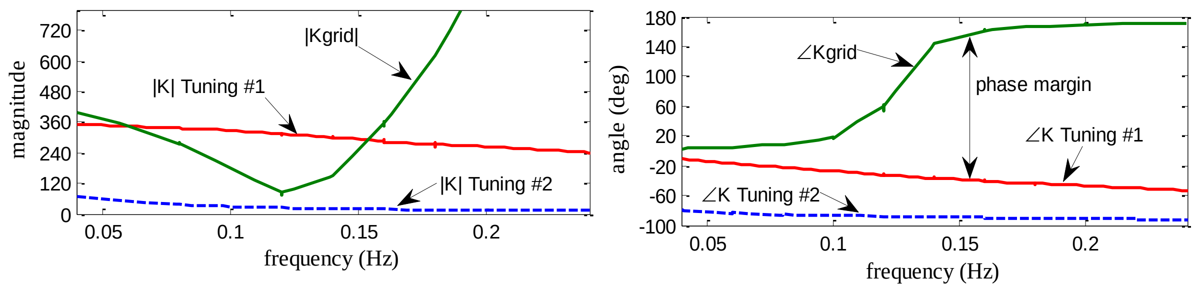


Figure 6-18 – Frequency response of K and Kgrid

The intersection points of the two amplitudes $|K(f)|$ and $|K_{grid}(f)|$ determine the resonant frequencies of the closed loop system. It is observed in Figure 6-18 that, at the second intersection point where the frequency is approximately 0.155 Hz, the phase margin is close to $180°$, indicating an undamped oscillation at this frequency. This corresponds to the reproduced power oscillations in Stage #2 (5 s< t <55 s in Figure 6-14) for the observed event on December 1^{st},2016. Nevertheless, no intersection points exist for $|K(f)|$ and $|K_{grid}(f)|$ if tuning #2 is used, which implies system operational stability thanks to the absence of resonant oscillations, further validating the mitigating measure by control gain tuning.

After the C&P modification was tested and validated on the replicas, it was successfully implemented on site by RTE and REE in January 2019 with a software update at both converter stations. Figure 6-19 presents the active power exchange through the 400 kV AC line Vic-Baixas and both HVDC links before and after the control parameter modification. As expected, a slower and smoother HVDC response can be observed.

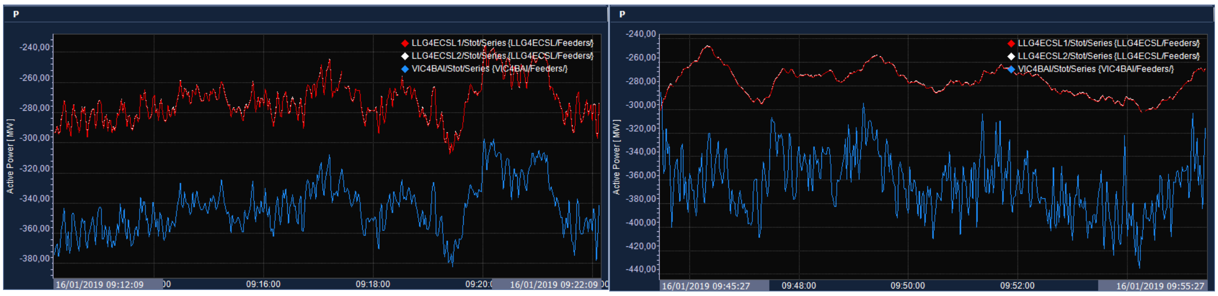


Figure 6-19 – Active power through the 400 kV AC line Vic-Baixas (blue) and both HVDC links (red/white) (left: before control tuning, right: after control tuning)

Overall, as a lesson learnt from this work, with the help of the HVDC C&P replicas and HIL setup:

- the RMS INELFE model was corrected and validated based on real-time simulation studies;
- the exact C&P parameters that should be modified can be identified;
- the control system behavior can be evaluated and analyzed in different types of studies (time-domain studies, small signal analyses, etc.);
- mitigation techniques can be validated before on-site implementation while protecting the IP rights of the vendor;
- test benchmarks for future software updates during lifecycle operation can be developed.

6.2.3 Johan Sverdrup Interaction study

Discovered in 2012 and located approximately 200 km from the west coast of Norway (city of Stavanger), The Johan Sverdrup O&G field is the largest O&G field ever discovered on the Norwegian continental shelf with an estimated resource of 1.9 – 3 billion barrels for the next 50 years. The field development includes two symmetric monopole HVDC links connected in parallel both onshore and offshore and is divided into two phases: the phase-1 HVDC contract was awarded to ABB in 2015, with the 100 MW, two-level HVDC-VSC commissioned in 2019 and is currently in operation; the phase-1 HVDC contract of a 200 MW, HVDC-MMC link was awarded to SIEMENS in 2018 and will be commissioned in 2022. For both links, the DC cable length is approximately 200 km and the DC transmission voltage is ±80 kV. The Johan Sverdrup project is set to be the largest offshore distribution grid in the world and the first European multi-vendor parallel connected HVDC systems in grid-forming operation. Further information can be found in [41]. A simplified single-line diagram of the Johan Sverdrup project is presented in Figure 6-20. It is noted that the areas enclosed in dotted lines represented various offshore O&G platforms.

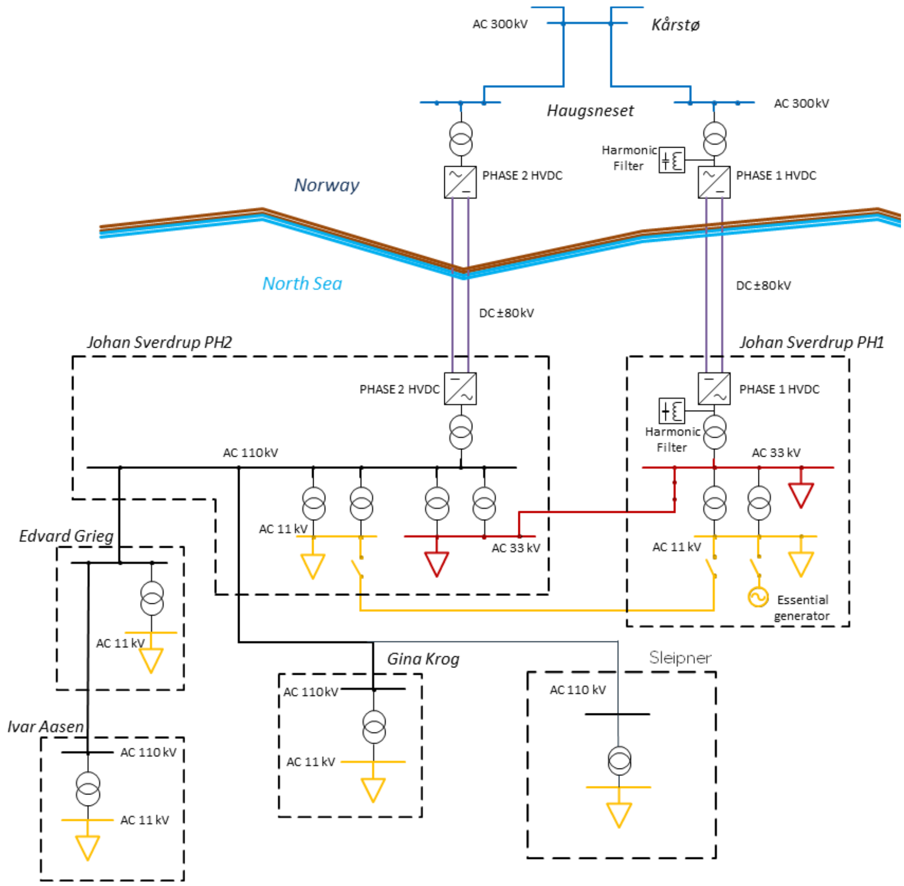


Figure 6-20 – Simplified single-line diagram of the Johan Sverdrup project

Each HVDC system was or is being developed by the respective manufacturer with the implementation of their own C&P philosophy without information exchange due to IP issues. Therefore, studies are required to ensure secure power supply for Johan Sverdrup, its neighboring offshore platforms, and other consumers under all operating conditions, which is the reason why RTE International was contracted as a third party to oversee and perform offsite offline and real-time EMT parallel operation studies with data provided by both HVDC vendors to analyze both onshore and offshore potential interaction phenomena in order to ensure interoperability of the two parallel HVDC links under steady-state, dynamic and transient operating conditions.

In addition, each of the HVDC system shares an interface with a global controller called Power Management System (PMS) with the following main functionalities:

- Control offshore load sharing between the two HVDC links based on their capacity
- Secondary offshore voltage and frequency control
- Prepare suitable conditions for the coupling and de-coupling of the two offshore HVDC converters
- Activate load shedding command under critical overload conditions

The PMS control unit is integrated in the control system of Power Distribution and Control System (PDCS) which handles all automation processes and provides monitoring and stable control of the entire Johan Sverdrup electrical power network consisting of the two embedded HVDC links to shore, generators, and distribution network at 110 kV, 33 kV, 11 kV, 6.6 kV, 0.69 kV, 0.4/0.23 kV. The PMS and PDCS are developed by Kongsberg Maritime.

As was mentioned previously, offline simulation studies are conducted to detect potential interoperability issues when both HVDC links are operating in parallel during the design stage of the phase-2 HVDC system. Based on the results from offline simulations, a set of real-time simulation studies with the HIL setup are defined to be performed prior to on-site commissioning of the second HVDC link. Furthermore, an iterative process is established to ensure an efficient and robust coordination between all stakeholders when interactions are detected and/or software updates are delivered (see Figure 6-21 and Figure 6-22).

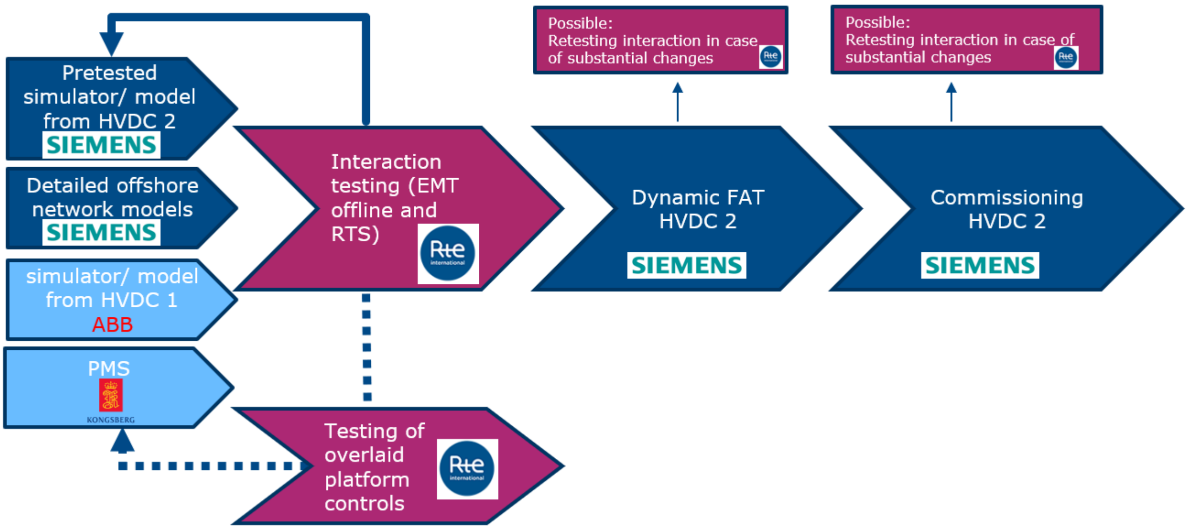


Figure 6-21 – Process for parallel operation studies and coordination between stakeholders

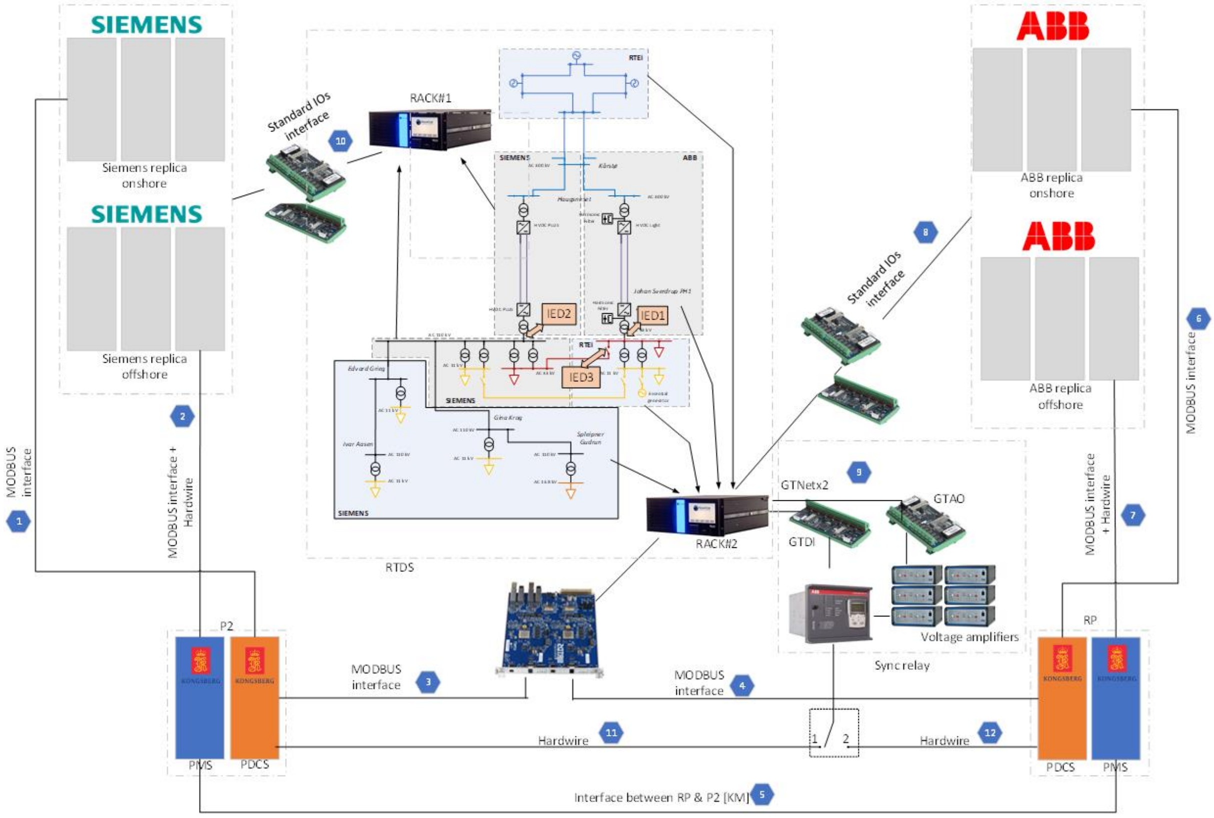


Figure 6-22 – HIL setup with replicas for interaction study of Johan Sverdrup project

In this project, the main advantages of C&P replicas are the limitations raised with offline models, which are:

- The offline EMT models provided by the 2 vendors do not run with the same time step. Solutions for multistep EMT simulations would be difficult to use because the 2 HVDC systems are tightly electrically connected. Although certain possible solutions have been investigated, potential risks of accuracy degradation and numerical instability still exist. To ensure a good study accuracy, models have been run with the smallest time step agreed by both vendors. Parallel computation of simulating the network on different cores by decoupling via transmission lines was not considered because no existing transmission line in the network would fulfil such requirements and adding an artificial line would introduce accuracy issues. Therefore, the main consequence is long simulation time.
- An iterative approach needs to be established for offline EMT simulation to investigate, analyze and mitigate a detected interaction phenomenon, which includes the following steps:
  1) integrate the updated offline PED models and/or C&P software updates into the full network EMT circuit;
  2) Perform pre-defined test cases;
  3) Generate test reports and distribute them to all parties involved;
  4) Analyze the results with manufacturers;
  5) Propose solutions when adverse interactions are detected;
  6) Manufacturers implement solutions in their detailed open model and evaluate the solutions in standalone mode at their facility;
  7) Manufacturers perform offline EMT model black-boxing and/or provide C&P software update and deliver it to the third party, then go to step 1).

  Although the duration of each iteration depends largely on the complexity of the detected interaction phenomenon and the resources available to the vendors to analyze different solutions, it proves to be rather time-consuming in most cases.

HIL real-time simulation with C&P replicas, on the other hand, allows faster problem-solving through efficiently evaluating the impact of certain control parameters or algorithms on the system performance in a number of studies. This is further facilitated by the remote access of the vendors to their C&P software in the real-time lab.

- The PMS and PDCS are involved in slow control dynamics whose durations are in the range of tens of seconds or minutes. Operator intervention is often required to complement the PMS and PDCS control actions on site. However, an offline EMT model for detailed PMS and PDCS functionalities is not available. A generic PMS model including only principal secondary control functionalities was developed by RTE international for offline studies, but it is not sufficient to guarantee stable on-site parallel operation of two HVDC links.

However, for the Johan Sverdrup project, both offline and real-time simulation approach are and will be used until on-site commissioning on site because they are complementary.

One of the main justifications to use offline and real-time simulation in tandem until the end of the project is to ensure a high level of quality control, which is why:

- Benchmarking is vital to detect any error or limitations in offline or real-time simulation.
- When results are superimposed a perfect match between offline and real-time simulation results does not exist. Experience and discussions with vendors are essential.

An example of benchmark test is provided in Figure 6-23. A 1-phase-to-ground fault with was simulated at Kårstø during 100ms, with both HVDCs operating at almost full capacity. Results obtained from offline simulation are superimposed with those from HIL real-time simulation. A detailed model of the offshore grid is used in both approaches. Settings of both HVDC systems, C&P software versions and initial conditions implemented in each model were carefully checked. Given the complexity of the system simulated, both results match quite well.

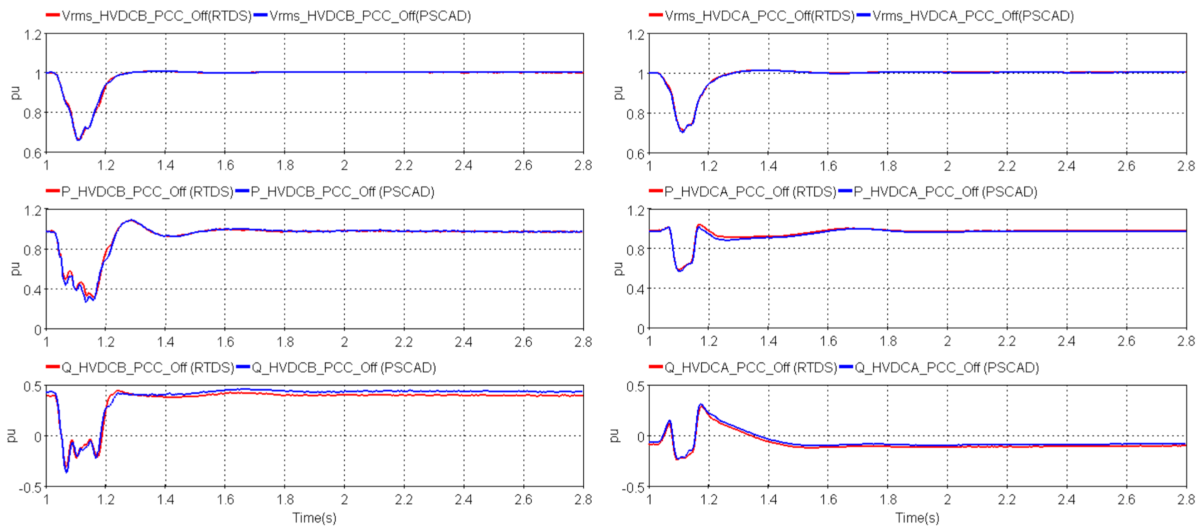


Figure 6-23 – Benchmark offline/HIL simulation

An important advantage in continuing with offline simulations at later stages/until commissioning of the project is the ability to perform sensitivity analysis by running automatically thousands of test scenarios in parallel. This is more complex to achieve with HIL simulation without any adaptation of the C&P software.

6.2.4 HIL-supported HVDC maintenance activities at RTE

As the French TSO, RTE operates and maintains the AC transmission grid from 400 kV to 63 kV voltage levels in France. Besides, it is also in charge of all the HVDC interconnections between France and neighboring countries. All the HVDC projects in different development stages in France are illustrated in Figure 6-24.

Figure 6-24 – HVDC projects in France.

As is shown in Figure 6-24, three HVDC links are currently in operation, which are:

- IFA2000: two independent bipole HVDC-LCC interconnections of 2×1000 MW between France and the UK.
- INELFE: two symmetric monopole HVDC-VSC interconnections of 2×1000 MW between France and Spain.
- IFA2: one symmetric monopole HVDC-VSC interconnection of 1000 MW between France and the UK.

Three other HVDC projects are in various stages prior to commissioning. They are:

- Savoie-Piémont: two symmetric monopole VSC-HVDC interconnections of 2×600 MW between France and Italy, currently under construction.
- Biscain Gulf: two symmetric monopole VSC-HVDC interconnections of 2×1000 MW between France and Spain, currently in tender phase.
- Celtic: one symmetric monopole HVDC-VSC interconnection of 700 MW between France and Ireland, currently in specification stage.

Apart from the above-mentioned HVDC project, another symmetric monopole HVDC-VSC interconnection of 1000 MW exists between France and the UK through the Cross Channel Tunnel, which is currently in commissioning. This is a private project and the only HVDC interconnection in France not owned and operated by RTE.

Considering the number of HVDC links that are already connected or planned to be connected to the French grid, RTE decided to take charge of all maintenance activities for these HVDC links after the C&P and valve maintenance warranty period (five years for all HVDC projects of RTE) by building an HIL lab in 2012 to host the C&P replicas. This decision was made based on the following reasons:

- ➢ It is a more economical solution even considering the procurement of C&P replicas, as compared to maintenance contracts with manufacturers. It should be noted that this is solely based on the negotiations between RTE and different manufacturers and cannot be further generalized.
- ➢ It can ensure more efficient and performant problem-solving as RTE would have full control over resource management of its maintenance team.

- Having its own team dedicated to HVDC maintenance activities would be a great addition to the asset of a TSO.

Among the two types of replicas (study replica and maintenance replica) , the maintenance replica consists of a set of C&P cubicles to the greatest extent identical to the actual cubicles installed at the converter stations as well as the redundancy of the C&P equipment and various interfaces to external environments identical to the on-site implementation. Therefore, RTE decided to only purchase maintenance replicas for all HVDC links owned and operated by RTE in order to facilitate training of maintenance personnel and support the HVDC maintenance and operation teams in that:

- The maintenance replica offers real HVDC HMIs which allows realistic system operation.
- The maintenance replica comes with all associated tools (i.e., TFR, system analyzer, event/alarm list, etc.) as on-site implementation.
- The high identicality to the on-site system allows the maintenance team to prepare for maintenance operations and to analyze hardware issues.
- Operator training can be organized with the HVDC manufacturer at the HIL lab facilities during trial operation period without impacting the real system on site.

The following C&P replica hardware has been installed to date in the HIL lab on the premises of RTE for its own applications:

- 5 sets of SVC replicas from ALSTOM Grid and SIEMENS
- 1 set of HVDC-LCC replica from ALSTOM Grid (IFA2000)
- 2 sets of HVDC-VSC replicas from SIEMENS (INELFE project)
- 1 set of HVDC-VSC replica from ABB (R&D project)
- 1 set of DCCB replica for a 3 terminal DC grid from ABB (R&D project)
- 1 set of HVDC-VSC replica from SIEMENS (ELECLINK)
- 2 set of HVDC-VSC replicas from GE (FIL)
- 1 set of HVDC-VSC replica from ABB (IFA2)

Apart from the replicas listed above, another 3 sets have also been installed for the Johan Sverdrup projects. They include:

- 1 set of HVDC-VSC replica from ABB
- 1 set of HVDC-VSC replica from SIEMENS
- 1 set of Power Dispatch Control System replica from Kongsberg Maritime

All these C&P replicas are housed inside the 2000 m² designated technical facilities, together with 16 real-time simulators (~300 CPUs) and IO cabinets (for both HYPERSYM and RTDS simulators). Ten engineers are full-time in the lab for network studies and maintenance activities.

The objective of the discussion presented in this subsection is to introduce, other than dynamic interoperability studies, the application of the C&P replicas in maintenance activities, using the current practice at RTE as an example. It is believed that the reasons behind such a decision made by RTE could help the NSWPH consortium with their decision-making if it is decided to adopt the HIL setup with real-time simulation using the C&P replicas as the de-risking approach for the NSWPH project.

6.2.5 Accuracy issues in HIL real-time simulation

Despite the ability of incorporating the C&P replicas, representing realistic control and protection behavior, into dynamic system studies, simplifications and approximations are often adopted in modelling power circuit components due to real-time constraints. An internal study has been conducted at RTE to demonstrate that some of the modelling approaches commonly used in real-time simulation tools could lead to numerical issues that are practically impossible to resolve for industrial application. In this subsection, an example of artificial resonance caused by the real-time modelling of semiconductor switches inside a modular multilevel converter (MMC) is presented.

First of all, it is understood that the modelling of MMC in EMT-type tools is a challenging task due to the large number of semiconductor switches in the converter. This constraint usually imposes numerical integration time-steps of a few µs and a large number of I/Os, leading to considerably long simulation time even for several seconds of dynamic event in offline tools. The reason behind this is that switches in EMT-type simulation tools is typically modelled as two-valued resistors whose resistance is "small" in the closed state and "large" if the switches are open. For the MMC that has a large number of semiconductor switches which are turned on and off constantly every few µs, the nodal admittance matrix of the electrical network would need to be re-factorized and updated each time any semiconductor switch changes its state, which is a time-consuming task. Obviously, such tremendous computational burden makes it impossible to adopt this approach in real-time simulation due to the real-time constraints. Therefore, as was originally proposed in [45] and [46], a fixed admittance (FA) matrix approach is often used to solve for power electronic circuits as a solution to increase computational performances in real-time simulation tools.

The key idea of the FA matrix approach is to represent the switches as a capacitor in the open state and an inductor in the closed state, thus avoiding the need for matrix decomposition and refactorization due to the change of state of semiconductor switches. Although several techniques have been proposed in the literature to improve numerical stability in this approach (e.g., with the use of a damping resistor as proposed in [47]), accuracy issues could still arise at high frequencies, resulting in disturbances that are difficult to handle. An issue encountered during the Factory Acceptance Tests (FATs) of a VSC-HVDC project in France demonstrates the accuracy limitations of the FA matrix approach at high frequencies. Details can be found in [49].

During the FAT of this project, several converter blocking tests were performed in order to evaluate the performance of the HVDC system. These tests were comprised of blocking both converters for a few hundred of ms and subsequently deblocking them to re-allow power transmission, as required in the specifications. Figure 6-25 a) presents a simplified view of the equivalent circuit of a single converter arm connected to the start point reactor. All the diodes of a single arm can be in the open state (high-impedance state) when the converter is blocked, while the submodule capacitors are charged. The equivalent circuit of this converter arm using the FA matrix approach when the converter is blocked can be illustrated as in Figure 6-25 b). It is observed that the cable and diode capacitance would form a resonance circuit together with the start point reactor.

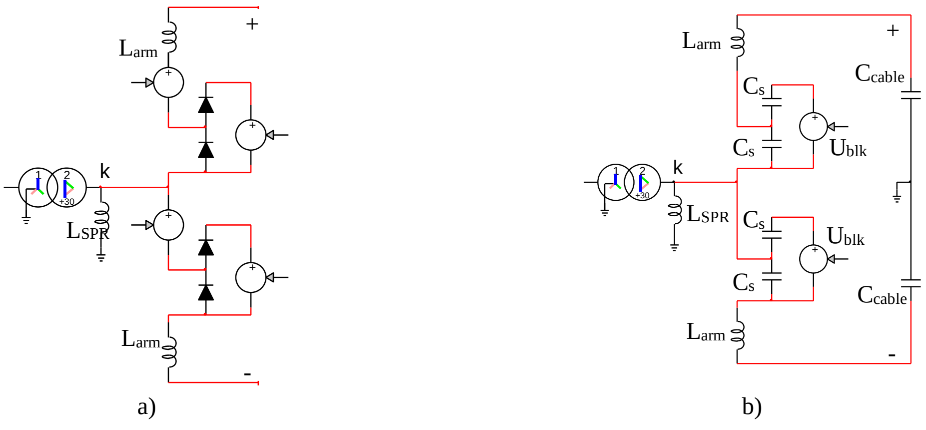


Figure 6-25 – Simplified arm modeling for HIL testing.

As the arm inductance (a few hundreds snipof mH) is assumed to be negligible compared to the start point inductance (several kH), the resonance frequency of the circuit connected to the converter transformer at node k can, therefore, be calculated as follows:

$$f_{FA} = \frac{1}{2\pi\sqrt{2L_{SPR}\left(2\frac{C_{cable}C_S}{2C_{cable}+C_S}\right)}} \tag{6-5}$$

Considering the typical inductance value of the start point reactor is approximately 6.5kH and the cable capacitance between core and sheath is around 20 μF for a +/-320 kV DC XLPE cable, the resonance frequency of this equivalent circuit with respect to the numerical integration time-step is presented in Figure 6-26.

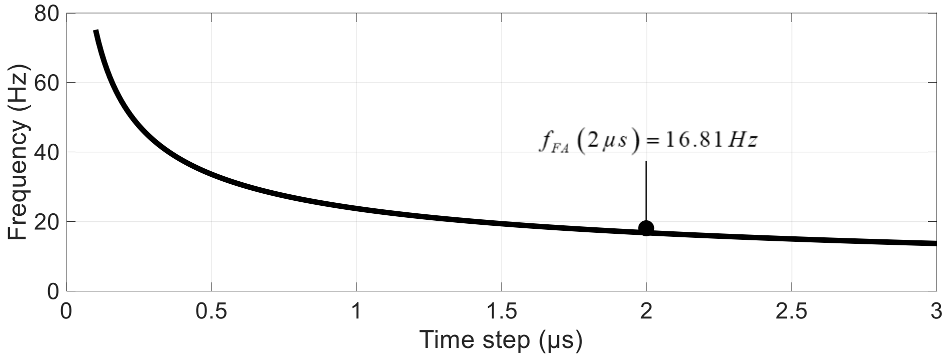


Figure 6-26 – Resonance frequency versus simulation time-step

The amplitude of this resonance is usually quite high due to the low damping of the circuit. In addition, the technique of using damping resistors proposed in [47] in series with Cs for numerical stability has virtually no impact on the resonance amplitude. The amplitude of the impedance seen at node k increases as the simulation time-step decreases, as is shown in Figure 6-27.

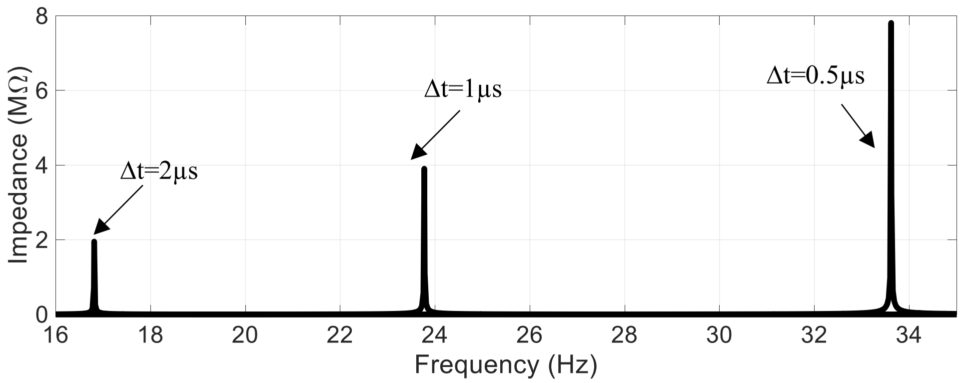


Figure 6-27 – Frequency impedance for different simulation time-steps

The monopole point-to-point HVDC link was simulated using the FA matrix approach with a numerical integration time-step of 2 μs. The simulated scenario is converter blocking at $t = 2s$ for a duration of 500 ms, following normal active power transmission of 1000 MW. The three-phase voltage at the transformer terminal of the converter side is presented in Figure 6-28. As a comparison, the three-phase voltage simulated using the detailed approach with network nodal admittance matrix refactorization every time a semiconductor switch, represented by a two-valued resistor, changes its state, is also presented in Figure 6-28. A resonance frequency of approximately 17 Hz can be clearly observed in the voltage waveforms obtained from the FA matrix approach, which led to the tripping of the HVDC due to harmonic protection.

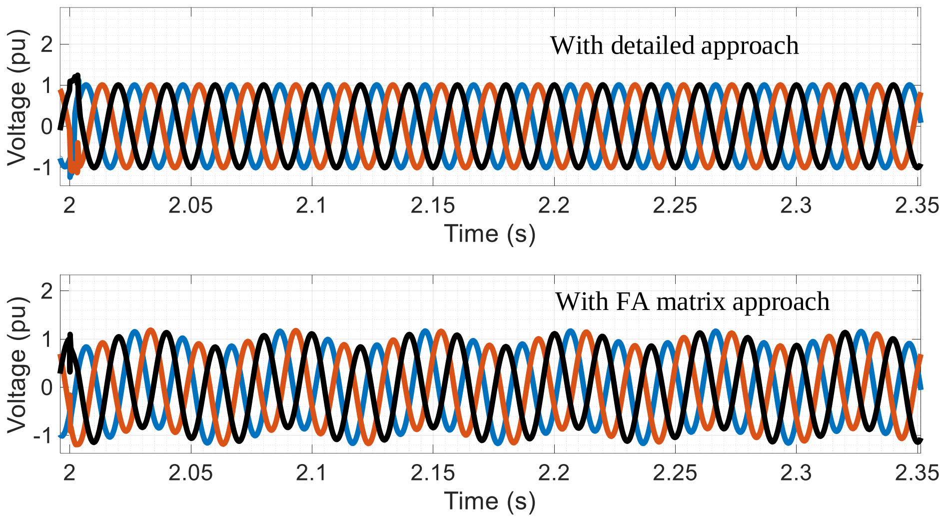


Figure 6-28 – Voltage at converter side

The same resonance frequency can also be detected in the current in the start point reactor, as compared to that obtained using the detailed approach (see Figure 6-29).

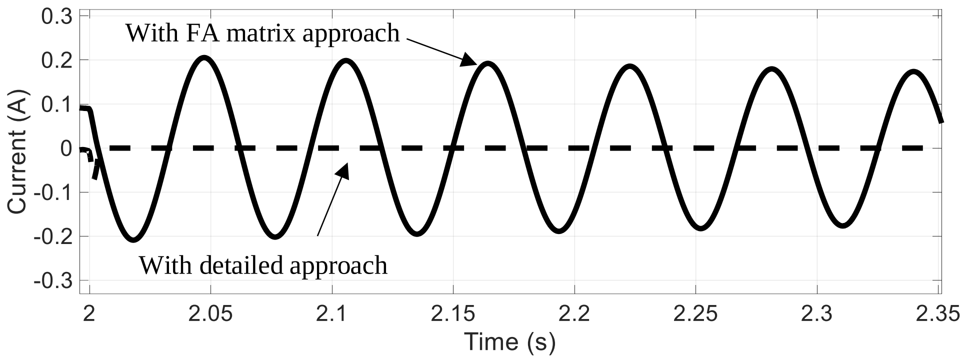


Figure 6-29 – Current in the start point reactor.

This artificial resonance due to the adopted FA matrix approach in the real-time simulation of VSC converters cannot be easily mitigated as its amplitude and frequency depend on the numerical integration time-step. As can be seen in Figure 6-27, it does not decrease when smaller integration time-steps are used. Furthermore, not only does the FA matrix approach can lead to major accuracy issues, but also it is not well suited to solve for nonlinear devices such as surge arresters and nonlinear inductors, with the possibility of introducing artificial delays to for further accuracy degradation. More details on this study as well as other accuracy issues that may arise in real-time simulation due to techniques of simplification can be found in [50].

The example presented above showcases one of the major limitations of the HIL real-time simulation approach, which is accuracy issues brought by the various simplification techniques due to real-time constraints. It further demonstrates the fact that HIL real-time simulation with C&P replicas is a complementary approach to offline EMT simulation and cannot replace the latter. Both approaches would be indispensable to evaluate interoperability issues and to de-risk the design and operation of the multi-vendor, multi-technology NSWPH project.

6.3 Summary

The main conclusions in this chapter are summarized in this section as follows:

The HIL setup with C&P replicas is the go-to approach adopted by many utilities around the world (China, Canada, South Korea, India, Brazil, France, the UK, etc.) to de-risk HVDC projects.

Different options and solutions are available for the procurement of HVDC and OWF C&P replicas, depending on:

- Project requirements and specifics
- Study objectives
- Technological maturity
- Budget

From the experience of RTE/RTEi, the unique advantages of the approach of using the HIL setup with C&P replicas have been extremely useful in resolving a number of issues that occurred on site and in interoperability studies of multi-vendor systems. These issues could not have been resolved merely using the offline approach due to several limitations in the offline EMT models.

However, the HIL setup approach also presents a few limitations in the aspects that would be crucial in interoperability assessment for the NSWPH project. These aspects can be complemented by the advantages of the offline EMT approach. Therefore, as of today (without considering possible solutions offered by future technological advancement), it would be recommended to use both approaches in complement to one another in the dynamic studies of the NSWPH project to adequately assess potential interoperability issues and to confidently de-risk the design and operation of the project.

7 OPERATION OF HIL LAB FACILITIES FOR THE NSWPH PROJECT

The objective of this chapter is to introduce the financial, infrastructural, and human resource aspects of building and operating a HIL real-time simulation laboratory for the various studies and activities required in the NSWPH project. Suggestions and recommendations based on the experience of RTE and RTE-international on handling technical challenges in these aspects are presented, considering the multi-vendor and modular development characteristics of the NSWPH project.

As was agreed between the NSWPH consortium and RTE international, information related to costs of the procurement of real-time simulators and C&P replicas for projects undertaken by RTE and RTE international is subject to NDAs, thus cannot be disclosed to third-party organizations and individuals. Nonetheless, a detailed description of the hardware components of a real-time simulator and its simulation capacity with respect to the scale and complexity of the studied network as well as the number of C&P cubicles and their corresponding functions in past or on-going projects will be provided, which would serve as an adequate reference for the cost estimate of the HIL setup with real-time simulation for the NSWPH project.

Discussions presented in this chapter are based on real projects.

7.1 Real-time simulator hardware and capacity requirements

Real-time simulators are composed of powerful processors and other associated hardware equipment often enclosed and mounted in their dedicated cubicles. The cost estimate for the real-time simulator is strongly dependent on its hardware and capacity requirements, which are determined mostly by the scale and complexity of the studied network.

Several real-time simulation tools are commercially available on the market. The main tools presently used for HVDC applications are RTDS, Hypersim, and RT-Lab (Opal-RT). Hypersim and RTDS are the tools currently used by RTE and RTEi.

In this section, illustrative examples of the hardware components of the real-time simulators are presented for two different projects.

7.1.1 Johan Sverdrup project example

The RTDS real-time simulator is used to perform dynamic network studies in the Johan Sverdrup project.

7.1.1.1 Real-time simulator hardware requirements

The RTDS simulator setup used in the Johan Sverdrup project includes two NovaCor racks (or chassis), one Global Bus Hub (GBH), one GTNET×2 card (Network Interface Card), and I/O cards (GTAO, GTDO, GTDI), in which one NovaCor rack, the GBH and power entry components are housed inside a cubicle, as is shown in Figure 7-1.

Figure 7-1 – RTDS real-time simulator setup for the Johan Sverdrup project

The cubicle is currently available in only one size of 68.3cm×79.4cm×189.5cm and weighs approximately 172 kg alone without any mounted equipment. It is advised to keep the cubicle together with its equipment in a relatively clean environment with the ambient temperature ranging between 15℃ and 30℃ and a relative humidity between 40% and 90% non-condensing.

The rack (or chassis) is the simulator hardware that performs real-time electromagnetic transient simulations by solving differential-algebraic equations (DAEs) representing the power system and its control components modelled within RTDS. For the Johan Sverdrup project, the latest simulator hardware technology NovaCor from RTDS is used, with two NovaCor chassis.

Each NovaCor chassis contains 10 cores, with a license offered for purchase for each individual core. All 10 cores are placed on a single chip and communicate through the embedded circuit board. They are used to solve the overall network solution, auxiliary components (i.e., transmission lines, machines, transformers, electrical machines, etc.), as well as any controls present in the simulation.

Apart from the large time-step simulation mode (e.g., with a numerical integration time-step of 50 μs for power system components and controls), RTDS allows to simulate power electronic based sub-circuits with high-frequency switching operations using smaller simulation time-steps in two modes: small time-step and substep simulation. It should be noted that components that are simulated in either one of the two modes should be enclosed in a sub-circuit that is connected to the large time-step components via interface transmission lines or transformers. The comparison of different features between small time-step and substep simulation modes is presented in Figure 7-2.

	Small Time-step	Substep
Hardware	Available GPC, PB5, NovaCor	Available for NovaCor only
Processor Assignment	One or two full cores Or 1-2 PB5/GPC processors	One full core
Node Limit	Node limit = 30 (PB5/GPC) Node limit = 45 (NovaCor)	Node Limit = 60
Timestep	Small time-step range: 1.4 – 3.75µs	Substep range: no minimum – 10us Range if LC switching included: no minimum – 3.75us
	Time-step *is not* user selectable. Time-step is chosen by RSCAD based on requested time-step by user	Time-step *is* user selectable Substep time-step = 1/N * main time-step, where 5≤N≤64
Switch Model	Most Models: RLC Switching Resistive switching with artificial interface tlines *(for 2 level converter)*	Most models: Resistive switching *without* artificial interface tlines RLC switching *(typically for individual switches/custom topologies)*
Solution process	Constant conductance matrix. No matrix inversion required each time step. If tline decoupled models used, then the conductance	Full decomposition of Network Solution
Resistive Limits	10 resistive breakers	No resistive breaker limit
I/O	Specific process. *See Small time-step tutorial.* GTNET not supported	Same straightforward process as mainstep I/O. GTNET not supported
Components	Only small time-step components	Substep, Controls, Power system components
Other		Easier to use/configure Accurate representation of non-linear elements.

Figure 7-2 – Feature comparison between small time-step and substep simulation modes [43]

It is noted that the small time-step simulation mode has been available since 2005 on various generations of processors (GPC, PB5 and NovaCor) whereas the substep simulation mode, developed in 2019, is only available on the latest processor technology NovaCor. Although it appears that the substep simulation mode has multiple advantages over the small time-step simulation mode in terms of the maximum number of nodes allowed in a sub-circuit, flexibility of choosing the simulation time-step, variety of network components that can be simulated and the number of resistive breakers allowed in a sub-circuit, the HVDC and OWF manufacturers using the RTDS simulator in their own real-time laboratory generally have a higher confidence and a better mastery of the small time-step simulation mode in developing their real-time EMT models to date, owing to longer practical experience and extensive testing. This would require corresponding competence in the operators and engineers for the NSWPH project if RTDS is chosen as the real-time simulator for the studies.

If more than one rack/chassis is used in the same simulation, a common simulation time-step shall be used in all racks/chassis for that simulation, which is coordinated by Global Bus Hub (GBH). If only two NovaCor chassis are used in one simulation, they can be directly connected through a GBH fiber optic cable of no longer than 20m. However, if the two chassis are placed sufficiently far apart from each other (which is the case for the Johan Sverdrup project) or more than three chassis are required in the simulation, a physical GBH device would be required. The front view of a GBH device is presented in Figure 7-3.

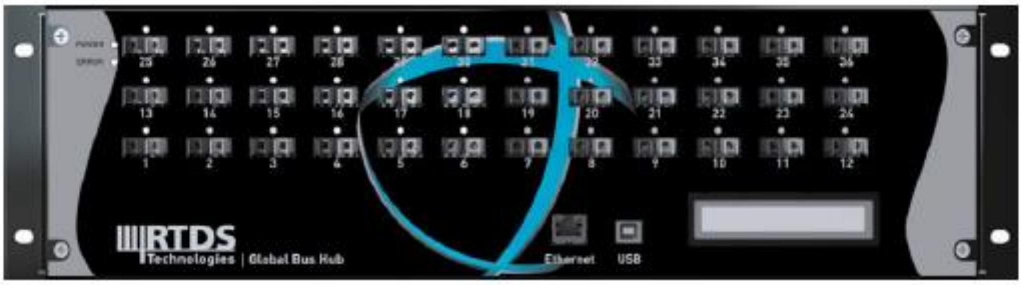


Figure 7-3 – Global Bus Hub (GBH) front view [42]

A GBH device requires its own license which is purchased separately from the NovaCor chassis and cores. The GBH device for the Johan Sverdrup project has been mounted in the cubicle shown in Figure 7-1.

Apart from the NovaCor chassis and the GBH device, A GTNET×2 card is also required in the Johan Sverdrup project, with its front view shown in Figure 7-4.

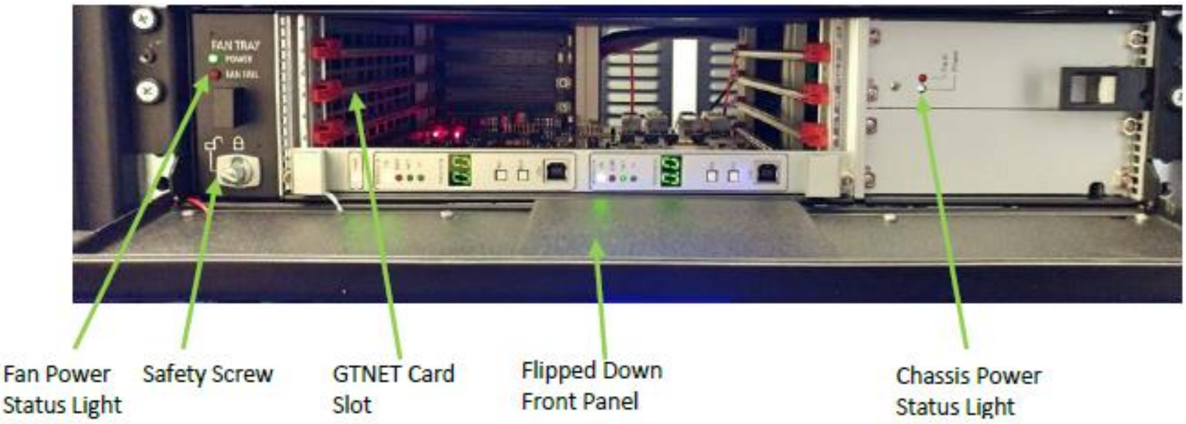


Figure 7-4 – GTNET chassis front view [42]

A GTNET×2 card is used to interface the RTDS simulator to external equipment over a LAN connection using various standard network protocols. The GTNET×2 card can be thought of as a protocol converter accepting packets from the LAN, extracting data from the packets and sending the payload information to the processing unit (NovaCor) via a fiber optic cable. Similarly, data from the RTDS simulation may also be sent into a packet and put out on the LAN where it will be picked up by the external devices assigned to accept the data. In the case of Johan Sverdrup, the GTNET×2 card serves as a communication interface between the RTDS simulator and the PMS and PDCS C&P replica. Multiple network protocols are supported by the GTNET×2, and the Modbus data communications protocol is used in the Johan Sverdrup project.

7.1.1.2 RTDS simulation capacity

The computational capabilities of the NovaCor chassis can be summarized as follows:

- Each NovaCor chassis has one processor with 10 cores. Each core can be assigned 300 load units.
- NovaCor can run an entire large time-step network on a single core, which would include network solution, power system and control components.
    1) For systems containing 90 or fewer single-phase nodes, 120 load units are allocated for network solution, and 180 load units are available for power system components (lines, machines, transformers, etc.).
    2) For systems with greater than 90 single-phase nodes, the network solution requires a full core and up to 300 single-phase nodes can be solved per network solution. Two network solutions are allowed per chassis, which provides a maximum of 600 single-phases nodes split into at least two subnetworks using travelling-wave network decoupling techniques.
- Up to 300 load units are available on each of the non-network solution cores for power system and control components. In particular,
    1) pi-section: 10 load units;
    2) transmission line or a cable: 10 load units;
    3) transformer: 10 load units;
    4) dynamic load: 10 load units;
    5) induction machine: 10 load units;
    6) synchronous machine: 20 load units.
- Passive components such as inductors, resistors and capacitors are solved inside the network solution and do not require additional load units.

Apart from the two entire HVDC links modelled in detail, the RTDS model for the Johan Sverdrup project also includes an onshore transmission and an offshore distribution network. The number of main power system components in both onshore and offshore networks are given in Table 7-1,

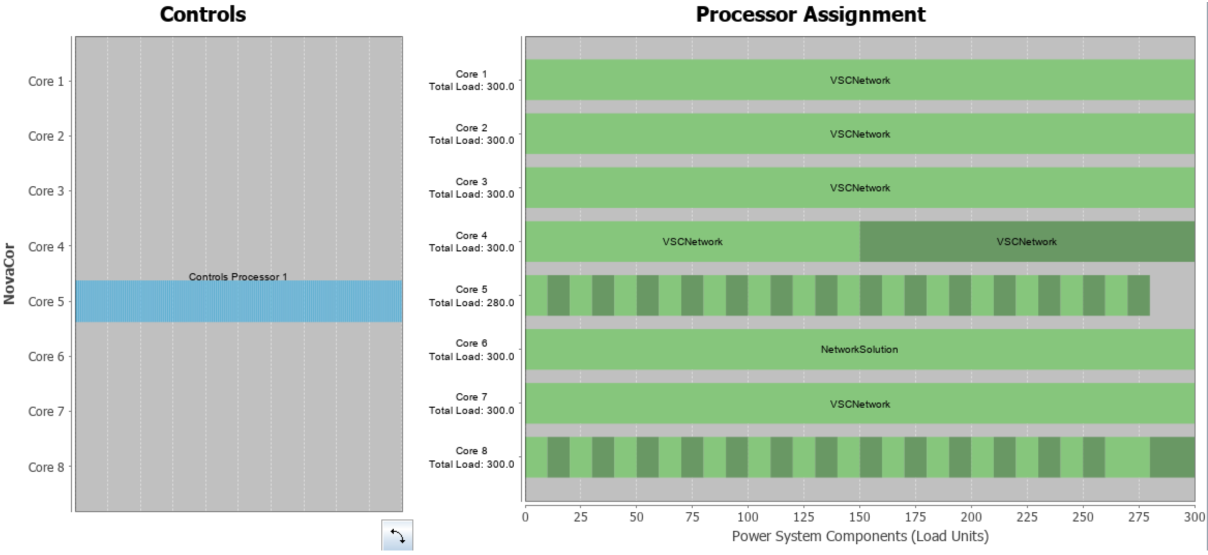
Table 7-1 – The number of main power system components in both onshore and offshore networks for the Johan Sverdrup project

	Transformer	line	cable	3Φ source	Dynamic load	IM	SM
Onshore	6	10	2	3	0	0	0
Offshore	11	0	25	0	11	13	3

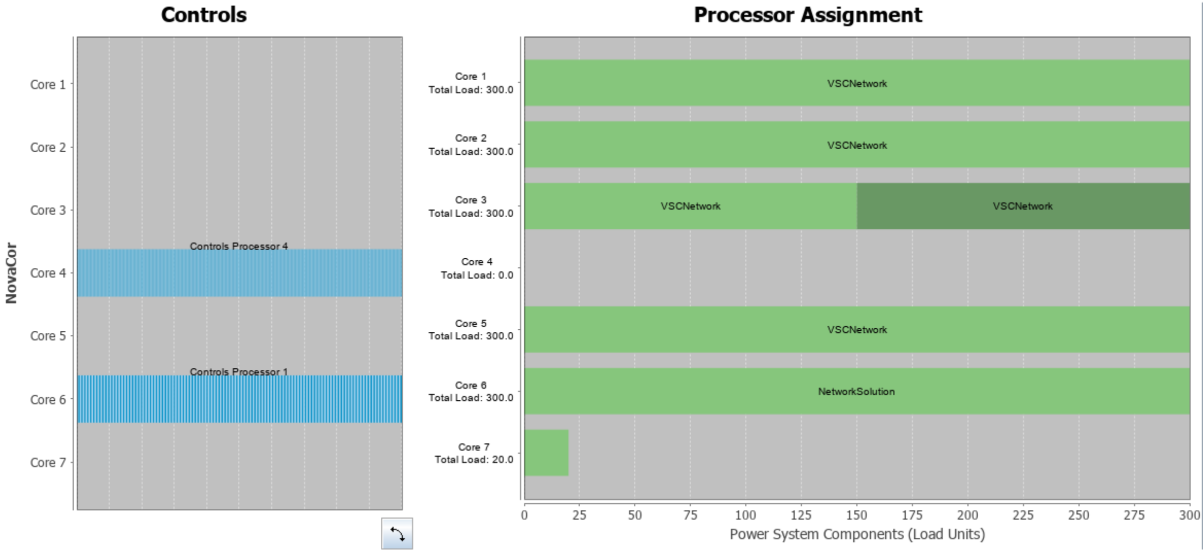
It should be noted that:

- All components (power and control) for the two HVDC links are not counted.
- The number of cables represents the number of cable sections in total (one cable can be modelled by a combination of several sections).
- The dynamic loads and induction machines represent various aggregated or non-aggregated models of pumps and drives.
- Only actual transmission lines are counted. The various interface transmission lines used to decouple the network, catering to constraints of cross-rack communication and node limitation in RTDS simulation, are not included.
- Control devices for all power system devices and the simulation of various dynamic transient phenomena (faults, energization, FALS, load shedding, etc.) are not counted.
- Interfaces with the converter C&P replicas as well as external equipment are not counted.
- Two simulation modes (large time-step and small time-step) are used to model different power system and control components in the entire RTDS model.

The entire RTDS model of the Johan Sverdrup electrical system occupies two NovaCor Chassis with 7 and 8 cores on each chassis, respectively. The processor assignment for both chassis is presented in Figure 7-5.



(a) Processor assignment for Chassis#1



(b) Processor assignment for Chassis#2

Figure 7-5 – Processor assignment for both NovaCor chassis for the Johan Sverdrup project

It should be noted that the models for each HVDC link including its converter station transformer and auxiliary equipment (e.g., filters, surge arresters, etc.) are in small-time step (VSCNetwork) and occupy three cores on each chassis.

Since the cost of purchasing hardware equipment (i.e., NovaCor chassis, GBH, GTNET×2, etc.) and licenses (i.e., cores) can be easily solicited from the real-time simulator manufacturer, it would suffice to scale up the simulator hardware requirements for the Johan Sverdrup project in order to obtain a preliminary cost estimate for the real-time simulator used in the NSWPH project.

7.1.2 BEST PATHS example

The Best Paths DEMO#2 project was carried out in two stages, with the first stage based on offline EMT simulations performed using EMTP whereas the second stage dedicated to real-time simulation.

Three vendors (ABB, SIEMENS and GE) participated in the first stage of the project and delivered their own vendor-specific HVDC converter model based on detailed common specifications for offline interoperability studies. Although only ABB contributed to the second stage of the project as the converter vendor, the Best Paths project of multi-vendor interoperability could carry on thanks to the hardware C&P replicas from another vendor for a different project hosted at the locale of RTE.

The real-time simulator Hypersim was used in the second stage of this project.

7.1.2.1 Real-time Simulator hardware requirements

The HIL setup for the ABB converter station in the Best Paths DEMO#2 project can be illustrated in Figure 7-6 [44].

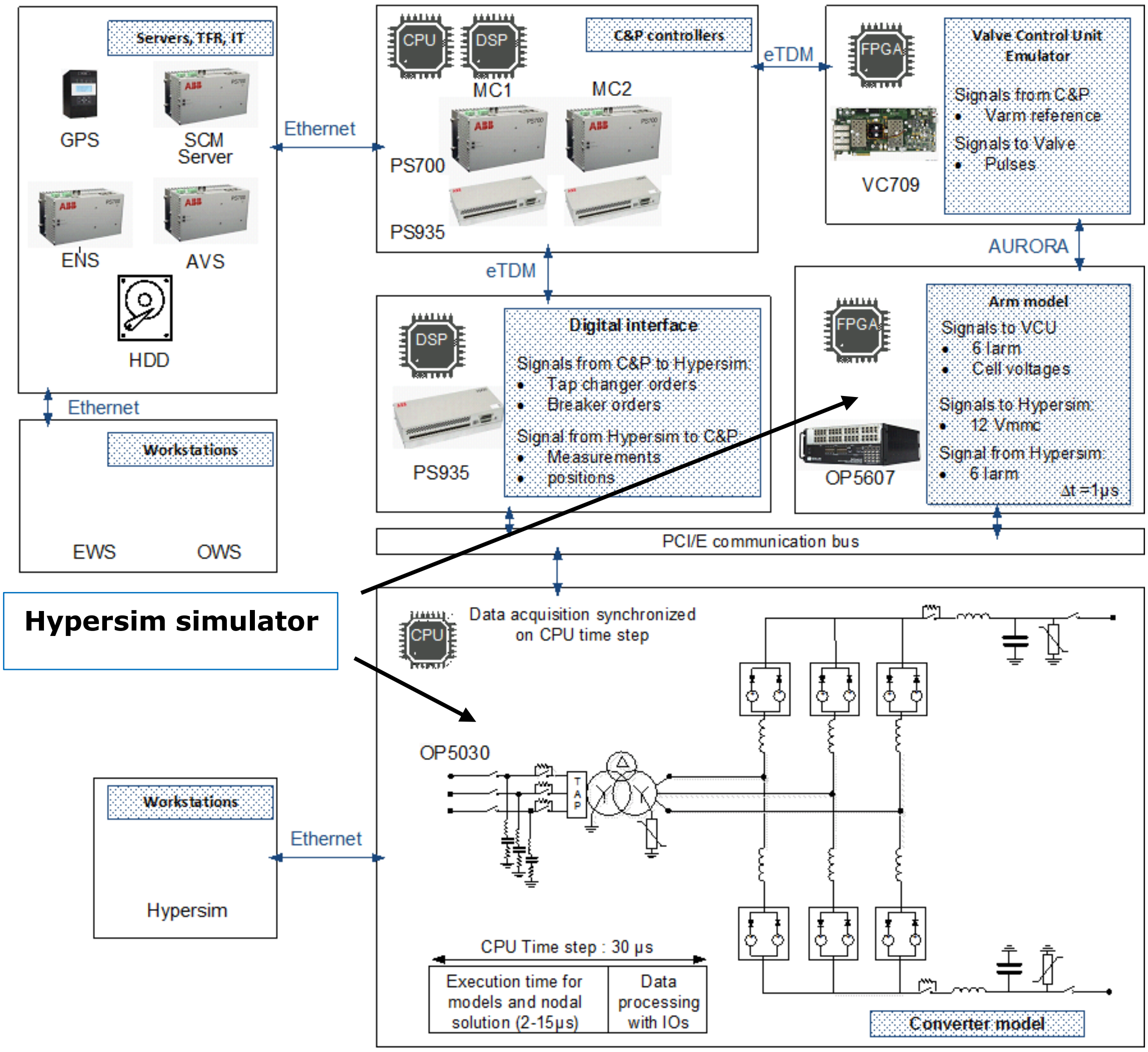


Figure 7-6 – HIL setup for the ABB converter station.

In Figure 7-6, the tasks designated to the Hypersim real-time simulator are the simulation of the power network and the converter arms, which are performed using one multi-core industrial computer (OP5030) and one FPGA board (OP5607), as is shown in Figure 7-7.

a) OP5030 real time computer

b) OP5607 FPGA board

Figure 7-7 – Hypersim real-time simulator setup for the Best Path DEMO#2 project.

While the standard devices of the HVDC converter station and the electrical network are solved on the multi-core OP5030 industrial computer, the OP5607 FPGA board, running at a smaller time-step, emulates each converter arm with accurate representation of the valve levels.

The OP5607 FPGA board is an expansion unit designed with the Xilinx VC707 Virtex-7 FPGA development board intended for the execution of embedded FPGA-based simulations of complex and computationally intensive models (such as the arm model of an MMC). It is connected to the real-time simulator via a PCIe link, and to external controllers and other OPAL-RT chassis through SFR interconnection sockets. In addition, multiple I/O modules are also embedded in the OP5607, with each module controlling 16 analog channels or 32 digital channels. The FPGA bridges the real-time computer and the I/O modules. The system overview of the OP5607 FPGA board is presented in Figure 7-8.

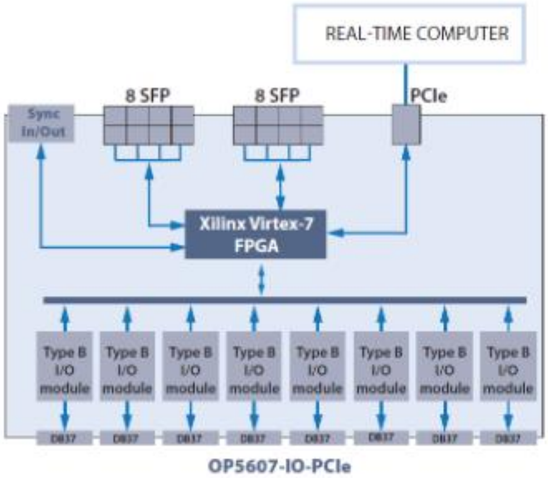


Figure 7-8 – OP5607 system overview.

As is shown in Figure 7-6, the real-time computer OP5030 communicates with the OP5607 PFGA board through the PCI express (PCIe) bus by receiving the voltage sum of blocked and on-state cells and sending arm current values. In an operational project, the Valve Control Unit (VCU) exchanges with each cell through dedicated optical fiber and receives extra information (e.g., temperature, etc.) which is not relevant in a functional project. Due to the I/O constraints on the simulator and reasons of simplicity, it was not possible to have similar arrangement on the real-time simulator. Therefore, the VCU hardware (enclosed in the ABB cubicle) was changed, with the real algorithms for cell selection, cell balancing as well as cell over- and undervoltage and overcurrent protection implemented on an FPGA development board referred to as the VCU emulator (VC709). Two VC709 boards were used in this project, with one for the upper arms and the other for the lower arms. The MMC arm model implemented on the OP5607 FPGA board developed by OPAL-RT was adapted with additional AURORA protocol specifically tailored to establish communication with the VCU emulator of ABB in order to receive cell orders and send arm currents and individual cell voltages.

7.1.2.2 Hypersim simulation capacity

A numerical integration time-step of 1 μs was used to simulate the valve operations in the MMC arm model on the OP5607 FPGA board, while the other electrical components in the network and the converter station was simulated using a time-step of 25 μs. Considering the relatively large latency in the PCI express bus (~ 10 μs), signals exchanged between the OP5030 real-time computer and the OP5607 FPGA board were carefully chosen to avoid simulation accuracy degradation.

It is worth mentioning that contrary to the RTDS real-time simulator, Hypersim also allows offline EMT simulation. The connection with the external C&P replicas is deactivated if this simulation mode is chosen. Instead, an internally implemented C&P model will be used in the same way as in an offline EMT tool.

In general, one OP5607 FPGA board would be required to simulate the MMC arms of one converter station. Due to I/O constraints and the fact that the formulation methods used in the Hypersim to construct network equations differ from that used in RTDS, the exact number of OP5607 FPGA boards and CPU requirements for the real-time computer OP5030 are decided on a case-by-case basis, indicating those obtained for one project cannot be simply scaled up or down to provide an accurate cost estimate for another project. Further discussions and evaluations with the real-time simulator manufacturer would be needed.

7.2 C&P replica requirements and specifications

As was already discussed in Section 6.1.3, the main functionalities of the C&P replicas, depending on their type, are:

- Performing functional and dynamic system studies.
- Testing and validating system software and hardware updates before on-site implementation.
- Station operator and maintenance personnel training.

The principal functions included in the four HVDC C&P cubicles from ABB used in the testing of industrial DC breaker controller and their interoperability with converter controllers, in the context of the Best Paths DEMO#2 project with multi-vendor and multi-terminal HVDC applications, are presented in [44] and [16]. They are also listed as follows for the convenience of the readers:

- Cubicle#1: PCP – Pole Control and Protection
    - High level controls
    - Converter protection (harmonics, balancing, Umax, Imax)
- Cubicle#2: SCM – Station Control and Monitoring
    - Operator workstation (OWS)
    - Engineering network server (ENS)
    - Antivirus server, firewall
    - GPS, TFR, debugging tools, compilers
- Cubicle#3: MCP – Multiterminal Control and Protection
    - Control for 12 hybrid HVDC breakers
    - DC grid line protections
    - DC voltage choppers
- Cubicle#4: SI – Simulator Interface
    - Virtual I/O interface
    - Valve control interface (firing pulses) including valve control algorithms

However, the exact number of cubicles required for a single PED-based system can vary significantly, depending on:

- Project requirements and specifications
- PED manufacturer
- Technology implemented (e.g., for HVDC bipole or monopole,etc.)
- Need of redundancy
- I/O configuration (e.g., full I/O as the on-site system, simplified and/or compact I/O with hardware optimization, etc.)

It is noted that functions of temperature measurements, converter hall or valve cooling systems and other auxiliary systems are usually not included in the C&P replicas delivered by the manufacturer for off-site studies because these functions are not simulated on real-time simulators. The number of one set of cubicles with full redundancy and full I/O could be three to four times as many as that of a set of cubicles without redundancy and with simplified I/O for the same PED system. Therefore, it is up to the project owner to discuss and negotiate with the manufacturer with respect to project needs and budget.

In order to guarantee that the ordered C&P replicas satisfy the project requirements, and the project can progress in a timely manner, it is important for the project owner to specify the type and characteristics of the cubicles for the C&P replicas before manufacturing. RTE has extensive experience in cubicle specifications from various previous projects. Therefore, a general guideline of cubicle specifications for an HVDC project is provided in this subsection as a reference for the NSWPH project.

The cubicle specifications should include the following sections:

- Main description

General requirements on the C&P replicas shall be specified in this section (non-exhaustively):

- The principal functionalities and purposes of the C&P replicas shall be specified in this section.
- If one of the purposes is to perform dynamic studies, then provide a detailed list of all dynamic studies that will be performed.
- Requirements regarding spare parts, documentation and lifetime of the replicas as well as the real-time simulator (if necessary) should be specified.
- Specific requirements regarding the FAT and commissioning tests shall be given.
- Requirements regarding system update and EMT model for real-time simulation shall be specified.
- Possible solutions to reduce the number of cubicles can be proposed by the project owner for the consideration of the manufacturer.
- Transportation, installation and connection of replicas.
- Additional equipment supply for testing, maintenance and training.
- Other relevant project-specific aspects.

It should be noted that the general requirements regarding different aspects of the C&P replicas can be brief in this section and further developed in the following sections.

- Interfaces

If the real-time simulator is not supplied by the C&P replica manufacturer, requirements regarding the digital and analog interfaces between the real-time simulator and the C&P replicas shall be specified by the project owner.

- Real-time EMT models for the converter stations

Detailed requirements on the real-time EMT models for the converter stations that are not tackled in Main Description can be specified in this section. In addition, it can also include (non-exhaustively):

- Requirements on EMT model updates.
- Requirements on EMT model operation.
- Requirements on the real-time simulation environment (HMI) if it is provided by the manufacturer.

- Scope of supply and services

All issues regarding the operation of the C&P replicas shall be elaborated in this section. It can include (non-exhaustively):

- The exact C&P replicas that should be supplied.
- Documentation and/or description and/or signal list and/or single-line diagrams of any interface and cubicle component.
- Requirements on the necessary equipment for inter-station communication and parameter modification.
- Requirements regarding installation and commissioning of the replicas as well as operator training.
- Detailed requirements on the spare parts, auxiliary systems (if necessary), licenses for servers and relevant software, etc.

- Testing and commissioning of the replica

It is crucial for the project owner to set up detailed requirements regarding the testing and commissioning of the C&P replicas in order to ensure a stable operation and facilitate further studies. The requirements should consider the following aspects:

- FAT specifications
- Pre-FAT studies and reports
- FAT at the lab facilities of the manufacturer

- Pre-commissioning and commissioning tests at the lab facilities of the project owner.
- Details regarding updates and modifications of the C&P software.

A detailed timeline of all the items listed in this section should be defined.

- Software, hardware and real-time simulator requirements

Requirements regarding the update and maintenance of software and hardware of the C&P replicas after commissioning till the end of the warranty period shall be specified. In addition, this section can clarify the following points (non-exhaustively):

- Need of intervention from the project owner for the above-mentioned operations.
- Flexibility for the project owner in modifying the parameters in the replicas (configuration, software, hardware).

- Training and documentation

Detailed requirements on the training and documentation of the C&P replicas shall be included in this section. Additionally, the following information can be clarified:

- Format of the signal list
- Scope of training
- FAT test report including unresolved anomalies
- Training duration and language

- C&P software

It is important to address accessibility issues of the C&P software and to specify the control parameters that should be accessible to the project owner to allow normal operation and investigation when anomalies occur on site (e.g., control interactions). In addition, requirements on the training for the modification, update and maintenance of the C&P software should be specified.

- Switchyard, cooling and auxiliary system simulation

Due to the fact that disconnectors and earthing switches are usually not included in the real-time EMT models in order to limit the number of I/O signals, solutions can be proposed by the project owner to simulate these devices without modifying the control logic.

Depending on the project requirements, the controllers for the cooling and auxiliary systems can be included in or excluded from the replicas. In any case, requirements on the location of the controllers used in the cooling and auxiliary systems, both on site and in the replicas, should be specified in order to limit the difference between the software used on site and in the replicas. Moreover, detailed requirements on the signals and switchover logic used in the cooling and auxiliary systems should be specified if it is decided to include these systems in the replicas.

- Converter upgrades after control system FAT

Arrangements with the manufacturer for the network stability tests following the FAT can be specified in this section.

- Converter upgrades after commissioning

Detailed system upgrade (i.e., hardware, software, configuration) methodology including fallback strategies in case of unexpected events shall be defined in this section.

- Space constraints of the laboratory of the project owner

Height and weight requirements for the C&P cubicles shall be specified in this section. Solutions can be proposed in the case that height and/or weight of the C&P cubicle exceeds limits.

- Proposal for price list

If the C&P replicas are included in the basic scope of deliverables, a price list for the various items can also be included in the C&P cubicle specifications.

7.3 Recommendations on multi-party testing using the HIL lab facilities

Since the NSWPH project includes the procurement of complex PED systems from different vendors and is developed gradually and modularly over an extended period, it raises great challenges on the infrastructure, skill development and maintenance of the operators and engineers, as well as how to effectively and efficiently involve all concerned parties into real-time laboratory testing and studies without IP right infringement. Therefore, this section presents recommendations on maintaining the HIL lab facilities (including human resources), and shares experience from RTE and RTEi with the NSWPH consortium in coordinating multi-party testing and study activities.

7.3.1 Human resource requirements

It should be understood that the required expertise to operate an HIL laboratory for real-time studies and testing of a multi-vendor, multi-technology project differs from that required at HIL lab facilities of converter manufacturers or universities. Therefore, the following aspects shall need to be considered prior to undertaking real-time laboratory studies and testing for such a project:

Firstly, the core expertise of performing HIL real-time testing with C&P replicas lies in the competence in real-time simulation and the control and protection systems for both software and hardware. At the HIL lab facilities of manufacturers, this skillset is in general managed and distributed among different personnel across several departments or divisions, whereas at the HIL lab dedicated to interoperability studies of a multi-vendor system (such as the one at RTE international for the Johan Sverdrup project), the personnel involved in the project are required to master the entirety of the multi-disciplinary skillset for reasons of workload and efficiency. In particular, it should consist of (non-exhaustively):

- Competence in EMT offline and real-time simulation with good understanding of the advantages and limitations of the different numerical techniques employed in both approaches.
- In-depth knowledge of the design and operation of HVDC and OWF systems as well as other PED-based electrical components that are connected to the transmission network.
- In-depth knowledge of offline and real-time EMT power electronic device modelling.
- Hands-on experience in the functionality of the I/Os of real-time simulators.
- Knowledge of the software and hardware architecture in the C&P systems commonly implemented by different PED manufacturers.
- Knowledge and hands-on experience of different development and analysis software tools used by different PED manufacturers (e.g., Simatic TDC, HiDraw Studio, MATLAB Simulink, diagnostic tools, etc.).
- Industrial knowledge and experience in the limitations of on-site equipment operation in order to ensure the most pertinent test conditions for the project.
- In-depth industrial experience in real projects and solution of problematics encountered on site.

Only equipped with the above-mentioned skillset can the personnel ensure to perform network dynamic interoperability studies effectively and efficiently for a multi-vendor HVDC-OWF project using the HIL lab facilities.

Secondly, the skillset required to operate an HIL real-time simulation lab for a multi-vendor project is developed gradually over a long period of time and cannot be acquired merely through training on utilizing the offline and real-time simulation tools and operating the C&P replicas for several weeks, as is offered by most PED and real-time simulator manufacturers. In addition, this skillset needs to be maintained regularly in order to ensure an optimal operation of the HIL lab facilities. A common practice currently adopted by RTE and RTE international is that and the teams of network studies, operation and maintenance of any HVDC project should spend minimum two weeks per year post on-site commissioning to test and operate the entire system using the HIL setup with C&P replicas. This can include the start-up, shut-down sequences as well as any other dynamic test of the project owner's choosing. Although the days of these tests do not have to be scheduled consecutively, a total of minimum two weeks per year should be guaranteed to ensure that the operators and engineers can maintain their competence.

Thirdly, it is also worth mentioning that the development and maintenance of the skillset required to operate an HIL real-time lab for the studies and testing of a multi-vendor HVDC-OWF project is not compatible with the research-focused approach in the academia because it entails a well-defined, long-term strategy and structure to develop, maintain, and more importantly, retain such a skillset. Furthermore, a close relationship with various industrial partners (i.e., TSOs, PED owners and manufacturers, etc.) is mandatory, which would be a major disadvantage of universities.

7.3.2 Infrastructural considerations

Considering the multi-vendor characteristics of the NSWPH project and the fact that it will be developed gradually and modularly over a relatively long timespan, the HIL real-time laboratory would need to fulfil several requirements that are usually not satisfied by manufacturer and university HIL lab facilities such that:

- the installed hardware materials can be functional and operational for an extended period (e.g., between 10 and 20 years);
- the IP rights of each manufacturer can be well preserved.

Based on the experience of RTE and RTE international in operating multi-vendor HIL lab facilities, the following recommendations are presented for the consideration of the NSWPH consortium:

- A sufficiently high ceiling is required for the room housing the C&P replicas for better noise dissipation.
- Air-conditioning should be available for all rooms housing the C&P replicas such that they can operate at the desired ambient temperature.
- Easy access to the interior should be available for the delivery of heavy and bulky materials. As is shown in Figure 7-9, the entrance for bulky material delivery should allow easy access for heavy goods vehicles and satisfy the width and height requirements for C&P replicas (e.g., minimum 1.6 m in width and 2.5 m in height for both the entrance and the elevator).
- The lab facilities should be equipped with ample storage area to stock spare parts and other equipment.
- A quiet conference room designated to receive different parties involved in the project is required.
- Technical solutions should be in place in order to allow remote access for different vendors to their own system for software and hardware updates, participation in multi-party testing, result analysis, etc.
- Operator workstations should be located separately from the C&P replicas due to noise concerns and temperature requirements of the C&P replicas.

Figure 7-9 – Entrance for bulky material delivery at RTE international in Lyon.

7.3.3 Effective and efficient multi-party testing

In order to comply with the confidentiality requirements from each manufacturer, an independent third party would be required to de-risk the NSWPH project by performing tests and providing solutions without infringing the IP rights of each vendor. Based on the experience of RTE international and catering to the multi-vendor, modular and gradual development nature of the NSWPH project, the following recommendations are provided in this section in order to effectively and efficiently involve all parties in the HIL laboratory studies and testing for the NSWPH project:

Firstly, the C&P replicas from each manufacturer should be housed in their dedicated room accessible with secure measures to the respective manufacturer and the third party only. An example of such an arrangement for the Johan Sverdrup project is illustrated in Figure 7-10.

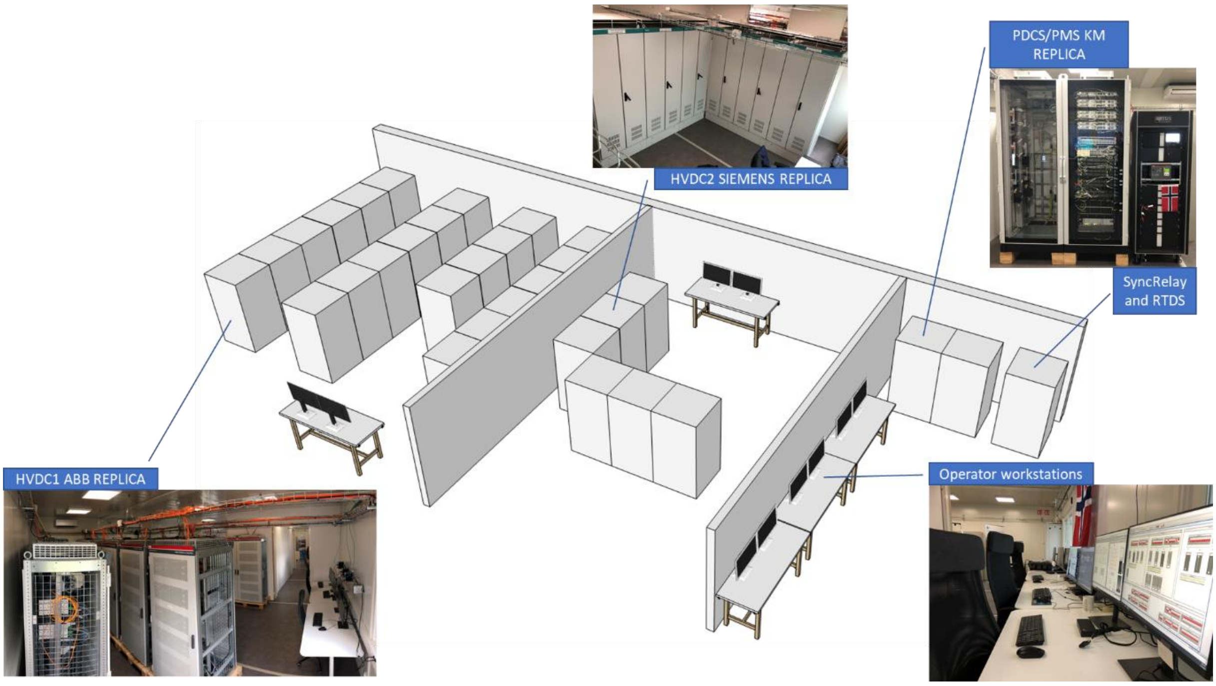


Figure 7-10 – Example laboratory facility arrangement (Johan Sverdrup project)

Secondly, remote access should be established for each vendor to access their workstation and the C&P software. This would facilitate system update and maintenance as well as problem-solving.

Thirdly, there exist two schemes for the access to the real-time simulator workstation:

- Scheme 1: the third party has sole access to the real-time EMT models from all manufacturers and the entire studied network. This is the scheme currently implemented by RTE.
- Scheme 2: an interface in the real-time simulation environment can be constructed such that each manufacturer could access remotely their real-time EMT model on the simulator workstation as well as the signals exchanged with the rest of the network. Currently, this scheme is under development for certain offline EMT tools.

Each manufacturer would need a certain amount of information from each other in the case that adverse interaction phenomena are discovered in the studies. Therefore, it is the responsibility of the independent third party to coordinate with all manufacturers in order to clarify the information that needs to or can be shared among them prior to undertaking any studies or tests. The list of shareable signals, which are subject to further modifications with respect to project development, shall be managed by the third party.

Furthermore, it is a requisite that an iterative approach be established for efficient problem-solving. An example process of such an approach is presented as follows:

1) Perform pre-defined test cases using the HIL setup with C&P replicas;
2) Analyze the results, generate test reports and distribute them to all parties involved;
3) Discuss with manufacturers individually and propose solutions when interoperability issues are detected;
4) Manufacturers implement solutions by updating and adapting the logics in the C&P system, with the help of the test reports, suggestions and propositions of the third-party as well as shareable signals and data from other manufacturers managed by the third-party, then go back to step 1).

The above iterative approach has been applied multiple times in the Johan Sverdrup project. It is noted that the duration of each iteration depends largely on the complexity of the detected interaction phenomenon and the resources available to the manufacturers to analyze different solutions.

In addition, as a lesson learnt from the Johan Sverdrup and the Best Paths DEMO#2 projects, the following recommendations are also provided with the hope of facilitating decision-making for the NSWPH project, considering its multi-vendor and modular development characteristics:

- **Implementation of a centralized Master Control (MC) system for multi-system coordination and interfacing**

This standard interface should be defined to send/receive orders, measurements, and status information to/from each PED system. The PDCS and PMS system developed by Kongsberg Maritime used in the Johan Sverdrup project is such an MC system, providing secondary control actions for both HVDCs. Similarly, an MC was also implemented in the Best Paths project, incorporating functionalities of both "global DC grid controls" and "AC/DC grid controls". It has been demonstrated that the implementation of such a centralized MC system could significantly help to improve interoperability.

- **Provision of detailed specifications to each vendor**

For a gradually and modularly developed project such as the NSWPH, future vendors and technology are usually unknown at early stages of the project. With each PED vendor having no access to the technological details and models of one another, the only way to maximize interoperability is through specifications. Therefore, emphasis should be put on the provision of universal (to a great extent) detailed requirements to each PED vendor, including quantifiable performance indications of each converter control mode, expected dynamic response to setpoints, etc. These requirements should be carefully verified after the delivery of PED models and C&P cubicles. It should be noted that although interoperability issues cannot be fully prevented by strict requirements (nor by standards) at this stage, very detailed specifications and strict performance validations would contribute to maximize interoperability.

- **Limiting software changes in already commissioned and operating systems**

An effective and efficient solution to interoperability issues, proven by the experience from both the Johan Sverdrup and Best Paths DEMO#2 projects, is to restrict as much as possible the software changes to one vendor (preferably the one that arrived later). The last arrived PED vendor shall need to adapt their C&P system according to specifications and third-party expert suggestions. Therefore, it is crucial for the third party to strictly track the software updates from all manufacturers and closely monitor the differences in the overall dynamic performance brought by software changes in the controllers. With the intention of limiting software changes in the already commissioned and operating systems insofar as possible and in regard to the differences in the overall system dynamic performance, the third party shall need to coordinate with the last arrived PED vendor whose system is still under development in the standalone tests (Functional Performance Tests and Dynamic Performance Tests) performed at their facility because any software update from any manufacturer might have an impact in the overall system dynamic behavior and the standalone operation of systems under development.

7.4 Milestones and principal activities in the roll-out of the NSWPH project

Needless to say, system performance testing under all operating conditions in both steady and transient states is the main task of the NSWPH project and entails the majority of resources, which is beyond the scope of this document. Besides the system performance tests, the roll-out of the NSWPH project would include the following milestones and principal activities before the commissioning of the first hub-and-spoke installation in 2030:

Milestones:

1. Specifications of C&P replicas and real-time simulator
2. Preparation of lab facilities
3. Real-time simulator training, grid modelling and clarifications
4. Commissioning of C&P replicas

Principal activities:

a. Testing of software updates on already commissioned systems
b. Testing of interfaces between systems
c. Testing of software updates on systems under development

It is noted that the milestones are presented chronologically whereas the major activities, depending on project specifics, would need several repetitions and iterations. A detailed description of each milestone and major activity is presented in the following sections.

7.4.1 Milestone 1: specifications of C&P replicas and real-time simulator

In order to guarantee that the ordered C&P replicas satisfy the project requirements, and the project can progress in a timely manner, it is important for the project owner to specify the type and characteristics of the cubicles for the C&P replicas before manufacturing, as the first step of the project. For a general guideline of cubicle specifications of an HVDC project, please refer to Section 7.2. Based on the experience of RTE and RTE international, detailed software and hardware clarifications and specifications for the HVDC C&P replicas can take 3 to 6 months. This is followed by the design, engineering, manufacturing, and testing of the C&P replicas, which would take 10 to 12 months, leaving a margin of 13 to

18 months from initial discussions with manufacturers prior to the commissioning of the C&P replicas at the testing facility. Therefore, the following two milestones should be accomplished within this margin. It should be noted that the above-mentioned time margin strongly depends on the complexity and maturity of the involved technology as well as the planning of the system under development, knowing that it would be more difficult to manufacture the C&P replica for a system under development in the modularly developed NSWPH project.

It is possible to purchase the real-time simulator independently from the C&P replicas or include it in the contract with the PED vendor. Regardless of the option, coordination with different PED vendors by the project owner(s) or the third-party would be required at early stages of the project for clarifications of the real-time simulator itself, solver selection, scope of network modelling responsibilities of each PED vendor, etc. The technical specifications of the real-time simulator would depend on the scale and complexity of the system to be studied and they shall cover all the aspects including simulator technology, software and firmware versions, I/Os , other necessary auxiliary equipment, etc. Generally, the technical clarifications and manufacturing of the real-time simulator require significantly less time, ranging from 4 to 6 months in total on average. A close coordination between the vendors of the PED systems and the real-time simulator organized by the project owner(s) or the third-party is required.

7.4.2 Milestone 2: preparation of lab facility

The following provision requirements should be fulfilled for the lab facility housing the C&P replicas and operator workstations:

- Dedicated premises
- Air conditioning adapted to replica requirements
- AC power supply for all equipment installed in the lab based on layout and data provided by each manufacturer. DC power supply may be mandatory for some hardware.
- Installation of separations between each room housing C&P replicas from different vendors due to confidentiality causes
- Restricted access to the rooms housing the C&P replicas
- Internet service of remote access for the manufacturers by a third-party provider dedicated to the project
- IT management of the lab and IT equipment (LAN, storage server, display transfer solutions for various HMIs and screens for display transfer, workstations for the real-time simulator, etc.)
- Security alarm for the lab
- Desks, chairs, and storage cabinets for equipment spare parts
- Operation and maintenance of the lab

The lab facility layout for the Johan Sverdrup project involving two vendors (ABB and SIEMENS) at RTE-international in Lyon is illustrated in Figure 7-11, with its space and arrangement serving as a reference for the NSWPH project. Figure 7-12 presents photos of the lab facility for the same project. It is worth mentioning that the project owner should ensure ample space in the lab facility for the C&P replicas envisioned to be commissioned at a later stage of the project.

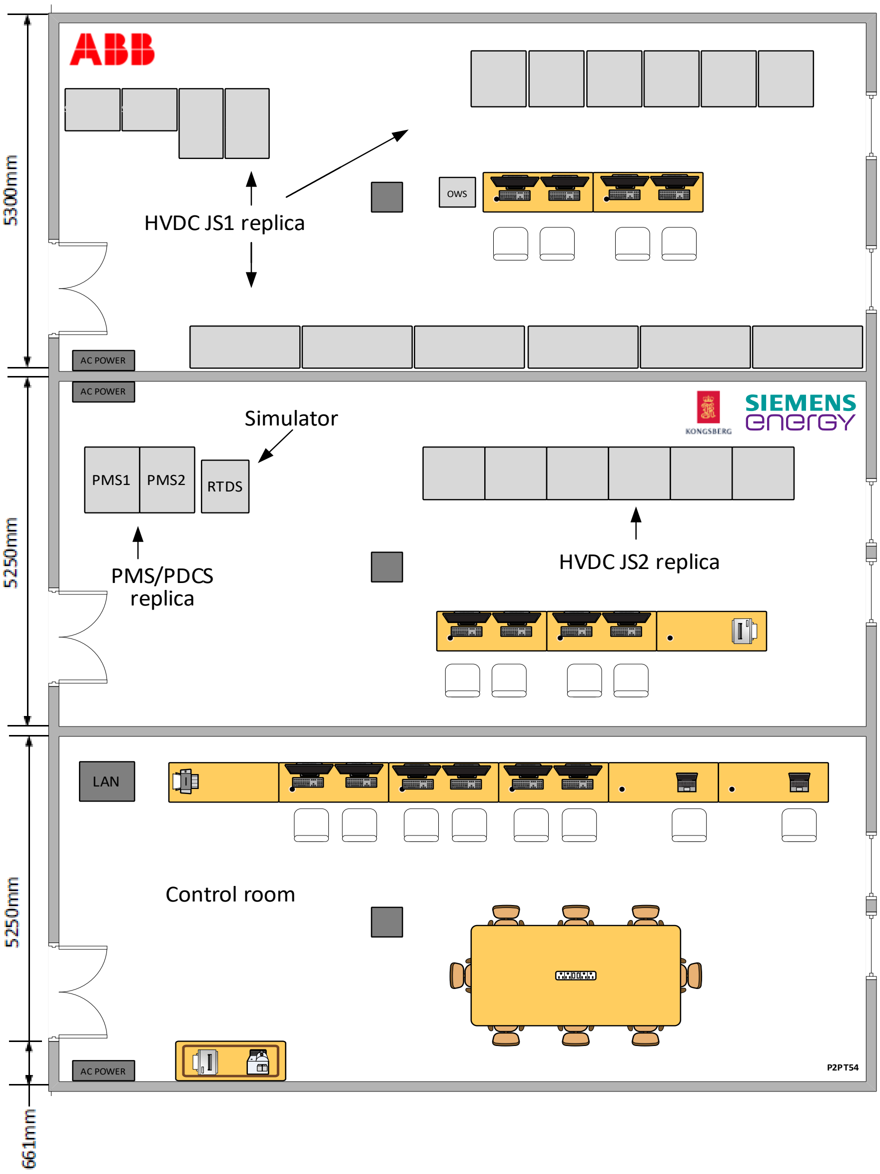


Figure 7-11 – Lab facility layout for a project involving two vendors at RTE international in Lyon

(a) Flooring of the replica room

(b) Complete view of replica room

(c) Operator workstation in the replica room

(d) Operator workstation in the operator room

(e) Storage space

Figure 7-12 – Photos of the lab facility of the project involving two vendors at RTE international Lyon

7.4.3 Milestone 3: real-time simulator training, grid modelling and clarifications

A training session for the real-time simulator can be organized for the engineers and operators engaged in the NSWPH project if necessary. If RTDS is chosen as the real-time simulator for the studies and testing of the NSWPH project, it is required to coordinate with the manufacturer concerning their solver selections (i.e., small time-step, substep, etc.) prior to the training.

The real-time modelling of certain sections of the studied network (e.g., onshore grid, partial or entire offshore grid) might not be in the scope of responsibilities of the manufacturers. Therefore, upon achieving a certain level of mastery of the real-time simulation environment, real-time modelling of these network sections shall be undertaken. Validation of the developed real-time grid model can be performed by comparison with offline EMT models under different operating conditions and for various dynamic phenomena if offline EMT models of the grid to be developed are available. Clarifications and coordination with the manufacturer, developer of the offline EMT grid models, and TSOs would be necessary. The duration of this task is highly dependent on the resource availability and the complexity of the grid to be modelled.

In general, real-time models from manufacturers of their systems can be available several months before the commissioning of the C&P replicas. It is, therefore, suggested to start integrating real-time EMT models from different manufacturers as soon as the model of the rest of the network has been developed. Once again, this process demands close coordination with manufacturers. It should be noted that this process can be rather time-consuming as, more often than not, limitations of the real-time simulator could be manifested, and compromises and alternative solutions might need to be investigated. Support from the real-time simulator manufacturer should be solicited in such cases.

7.4.4 Milestone 4: commissioning of C&P replicas

The tasks related to the commissioning of the C&P replicas are mandatory prior to using the replicas, with the objective of ensuring that the replicas render satisfactory behavior as expected.

Generally, the replicas should be assembled and tested at the facility of the manufacturer before delivery to the testing facility of the project owner or the independent third party, using the same real-time model, firmware and hardware as at the testing facility of the project owner or the third party. The project owner or the third party should be allowed to attend the Factory Acceptance Test (FAT) at the facility of the manufacturer to:

- ensure that all relevant functions have been included in the replicas in terms of hardware and software;
- start training on the replicas and their interface with the real-time simulator.

Since the NSWPH project will be developed modularly, attention should also be paid to the following aspects:

- For a system already in operation, ensure that the replicas behave in the same manner as the cubicles on site;
- For a system that has not been commissioned on site, ensure that the replicas behave in the same manner as the actual cubicles with the current software version. Tests of dynamic performance verifications might need to be reduced depending on the functions available in the C&P software.

The lab facilities should be ready to house the C&P replicas after the latter are fully tested. It is usually the responsibility of the manufacturer (or their assigned subcontractor) to deliver, install, and cable the cubicles at the lab facility of the third party or the project owner. The third party or the project owner should supervise these tasks and provide access to the facility.

After the installation and cabling of all cubicles, the manufacturer should start the replica commissioning without any specific support from the third party or the project owner. The commissioning tests will be solely performed by the manufacturer using the same real-time models as in the FAT, with possible and attendance of the third party or the project owner for further verification and training purposes. At the end of the commissioning, the third party or the project owner shall be able to operate the replicas without any support from the manufacturer. A technical report documenting the commissioning tests and process shall be expected from the manufacturer.

Depending on the manufacturer, transporting, installing, and commissioning the C&P replicas can take between one and six months in case of very complex and/or immature system. Ample time should be anticipated to ensure sufficient operator training and proper installation and operation of the replicas.

7.4.5 Principal activity a: testing of software updates on already commissioned systems

It is noted that software updates on already commissioned systems in the modularly developed NSWPH project should be limited. In case of necessity, the following procedure could be used as a guideline in order to better coordinate with the manufacturer and facilitate this task:

- Define with the manufacturer the test matrix including all tests to be performed and their procedures for this task;
- Operate the C&P replicas in the real-time simulation environment with the new simulation files provided by the manufacturer;
- Perform the tests pre-defined with the manufacturer;
- Verify whether the new functions have been implemented as specified by the manufacturer;
- Verify whether the performance of the system in islanded operation is the same as it was before the update. This would require the FAT results from the actual C&P system on site for superimposition;
- Update the software as recommended.

7.4.6 Principal activity b: testing of interfaces between systems

The multi-vendor NSWPH project will include multiple control systems interfaced to each other. The interfaces shall need to be tested after each system is commissioned and tested. These multiple interfaces could be either hardwired or established using certain communication protocols. The tests shall be conducted for each signal involved in the multi-infeed interoperation but not all signals exchanged between systems. The list of signals to be tests shall be defined together with manufacturers.

7.4.7 Principal activity c: testing of software updates on systems under development

Several software updates are expected from systems under development after replica commissioning due to issues discovered by the manufacturer or during interoperation studies. It is necessary to conduct dynamic studies after the release of each update in order to ensure that:

- performance of islanded operation is satisfactory according to the specifications;
- performance of interoperation is satisfactory according to specifications;
- the identified issue has been resolved.

Similar to testing software updates on already commissioned systems, a test matrix and procedure should be defined together with the manufacturer in order for the tests to be performed in an organized manner.

7.5 Summary

The main conclusions in this chapter are summarized in this section as follows:

Procurement cost of real-time simulators highly depends on the complexity and configuration of the studied network. It should be evaluated together with the manufacturers with detailed information on network configuration.

Procurement cost of C&P replicas strongly depends on the number of cubicles, which is also dependent on the following factors:

- Project requirements and specifications
- PED manufacturer
- Technology implemented (e.g., for HVDC bipole or monopole,etc.)
- Need of redundancy
- I/O configuration (e.g., full I/O as the on-site system, simplified and/or compact I/O with hardware optimization, etc.)

These are the decisions to be made by project stakeholders.

It is important for the project owner(s) to specify the type and characteristics of the functions for the C&P replicas before manufacturing in order to guarantee that the ordered

C&P replicas satisfy the project requirements, and the project can progress in a timely manner.

A list of expertise must be acquired by the project owner(s) to operate an HIL laboratory for real-time studies and testing of a multi-vendor, multi-technology project. The expertise differs from that required at HIL lab facilities of converter manufacturers or universities.

The facilities housing the C&P replicas from different vendors must fulfil certain requirements such that the installed hardware materials can be functional and operational for an extended period (e.g., between 10 and 20 years) and the IP rights of each manufacturer can be well preserved.

The project owner(s) should consider the recommendations provided in this document to efficiently and effectively involve different parties into study and testing activities for the multi-vendor and modularly developed NSWPH project.

The timelines in the major milestones identified for the NSWPH should be respected and the aspects that require particular attention in the principal activities should be carefully considered such that the project could be properly de-risked and progress in a timely manner.

9 CONCLUSION

The report responded to the questions and concerns of the NSWPH consortium in regard to the involvement of HIL setup with C&P replicas in the interoperability and dynamic network studies for the NSWPH project to ensure an appropriate design and stable system operation.

The ten items raised by the NSWPH consortium have been restructured into three chapters, with each chapter focusing on potential risks and their root causes as well as general de-risking methodology, HIL setup with real-time simulation and C&P replicas as well as considerations for different applications and purposes, recommendations on the operation of the HIL lab facilities in terms of resource preparation and management, respectively. All discussions, recommendations and suggestions are supported by the experience, internal studies and knowledge base of RTE and RTE international and tailored to the multi-vendor modular development characteristics of the NSWPH project. Major conclusions in each chapter can be found in the respective summary section.

It should be noted that the solutions, propositions, recommendations, and advice presented in this document are strictly based on the experience of RTE/RTE international to date with respect to the technological status quo. This indicates that they are pertinent in the context of currently available technical development and solutions. Possible enhanced solutions with relaxed implementation constraints thanks to future or on-going technical development is out of the scope of this document thus is not considered. In the end, it is necessary to emphasize one of the most important conclusions made in this document: both the HIL setup with C&P replica approach and offline EMT approach have advantages and limitations that are mutually complementary in interoperability and dynamic network studies for the NSWPH project, and neither is a "one-size-fits-all " approach, as has been demonstrated in the report. In the context of current technological development, it is strongly recommended to use both approaches in complement to one another in order to ensure an appropriate design of all PED systems and optimal system operation, considering the high stakes of the project in question.

10 Q&A

Q1 (Page 6): Please identify which areas need to be de-risked (i.e., information exchange?)

Response:

For each individual system, equipment design (both the electrical circuit and C&P system) so that the behavior of the system, either HVDC or OWF, would satisfy specifications. This can be better achieved with the C&P replicas thanks to its more realistic representation of the actual C&P system on site.

For a multi-vendor project such as the NSWPH project, anticipate, mitigate and resolve interoperability issues by tuning and modifying the C&P functions.

Information exchange, or rather lack of information exchange, would contribute to the reasons why interoperability issues would exist in the NSWPH project since each vendor has very little information about how the C&P functions in the systems of the others are implemented in order to handle dynamic on-site events.

Q2 (Page 6): Include: The NSWPH consortium seek to investigate if C&P replicas and utlization of HIL laboratories is necessary for de-risking.

Response:

Added on Page 6.

Q3 (Page 10): Great table. Interesting to consider if "realtime HIL" should be added to some of the categories in the bottom row on analysis methods.

Response:

EMT time domain simulation is a more general concept that has distinctive feastures as compared to RMS time-domain simulation. Inside EMT simulation, there are two approaches, which are offline and real-time. This table stands on a higher level in its discussion of which types of studies should be performed using which types of tools. Yes, it is possible to use offline and real-time, or only one of these two subtypes for a certain phenomenon in the studies that are marked "EMT time domain", but it should be decided more on a case-by-case basis or through " trial and error" (e.g., to study a certain phenomenon, unsuccessful attempts were made to reproduce it in offline due to insufficiency in offline models, but it was achieved using C&P replicas; in another case, although both approaches can be used, results in offline could be more accurate due to certain accuracy issues in real-time, etc.).

Q4 (Page 12): this is the main topic in Europe. Compared to China, where the station and network control is developed by the TSO, IP is the main driver for problems.

Response:

Agreed.

Q5 (Page 12): As you state in the beginning of the section about MTDC, there is very little to no experience on the electrotechnical risks in MTDC systems. It is great that you bring in the experience from the Best Paths research, however, by reading this part it is still not clear to me which interaction phenoma can occur on the DC grid. Is it possible to expand this part a bit?

Response:

An example is added on Pages 12 and 13. For further details regarding interoperability issues in a multi-terminal HVDC system, please refer to [16] (open access).

Q6 (Page 12): Were these issues witnessed during offline simulations, real-time simulations or both?

Response:

Both offline and real-time.

Q7 (Page 12): Should this be understood as oscillatory behavior in the DC grid?

I understand this list as problems specifically related to the MTDC configuration.

Response:

Yes.

Q8 (Page 13): Great list, which also to me tells the story that this is not an academic exercise, but a problem related to many practical project aspects.

Response:

Yes, it is correct.

Q9 (Page 13) : Is this the main problem? Both the suppliers and the TSO's would like to benefit from this but the system does not require it?

Response:

This is one of the reasons why EMT tools are crucial in studying events with fast dynamics. However, we did not understand the second part of the question.

Q10 (Page 14) : It is great that you mention that there are still improvements to be done to the speed of offline EMT simulation together with the continous increase in computational power, which makes large-scale EMT simulation more and more feasible (and competitive to real time simulation)

Response:

Yes, and speeding up offline EMT simulation is an active research field. Many state-of-the-art techniques and approaches have been proposed in IEEE transactions of Power Delivery, Power System, etc., also in conferences such as IPST, PSCC, etc.

Q11 (Page 14): Could you give more insights into the simplifications that are required? Does this imply that real-time simulation EMT models are less detailed compared to offline simulation models?

Response:

It has been tackled in the report. Please refer to Sections 6.1.5.1 and 6.2.5, also references [37] and [48].

Q12 (Page 15): Very good that you mention this method. At the NSWPH we have similarly come to the conclusion that this approach and type of analysis is a "must do" for the offshore projects.

Response:

Indeed. EMT-support frequency-domain studies are becoming increasingly important especially nowadays because the utilities have become more sensibilized to certain stability issues.

We have given two examples in the report in Sections 5.3.3 and 6.2.1, demonstrating how to use this approach to resolve harmonic instability issues.

Q13 (Page 16): I fully agree to this part regarding the onshore converter and AC interface with the existing grid. But could you discuss this approach in the context of the offshore AC grid. At a starting point there will be no existing back-ground harmonics.

Response:

This is a general approach. In the case of offshore AC grid, the pre-existing harmonics would come from the wind generators instead of the network.

Q14 (Page 17): Do you have specific grid configurations in mind where converters cannot be analyzed independently?

Response:

This is a general approach that is applicable for most studies, independent of the network configurations. However, we can imagine that in some cases, the converter controls would behave differently according to the harmonics emitted by the network. In such cases, it would be less pertinent to isolate the converter and analyze it independently.

Q15 (Page 18): A reflection: I dont know if the "shared among different" stakeholders part will be discussed further down in the report. However, an important aspect around the EMT model environment of an expandable offshore system, is the ability to have version control and share models among stakeholders. The ability to "connect to eachothers models" and share, can be discussed in offline models vs. HIL methods.

Response:

The objective of this section is to introduce different types of offline EMT models in system studies involving PEDs. We believe the handling and responsibility sharing regarding offline EMT models is out of the scope of this project. This statement has, therefore, been removed in the revised version of the report for clarity. Yes, the ability to be able to connect models from different vendors has been discussed in Section 6.1.6. Real-time simulation has a clear advantage in handling the integration of multi-vendor models than offline simulation.

Q16 (Page 19); Typo

Response:

Thanks, corrected.

Q17 (Page 19): Can this part be elaborated a bit? I assume that by network-focused it refers to the onshore system? However, couldnt one argue, that there are several phenomena where the HVDC connected OWF can impact the onshore system, which cannot be shown by a generic model? e.g. interaction at a specific frequency.

Response:

"Can this part be elaborated a bit? I assume that by network-focused it refers to the onshore system?"

No. The term "network-focused studies" is used loosely in this context. It can be onshore or offshore networks.

"However, couldnt one argue, that there are several phenomena where the HVDC connected OWF can impact the onshore system, which cannot be shown by a generic model? e.g. interaction at a specific frequency."

Yes, we agree with your statement here. The type of model to use in the study really depends on:

- The purpose of the study.
- The development phase of the project.
- The availability of detailed models.

It is obvious that if the HVDC or OWF would have a significant impact on the onshore system, and it happens that the manufacturer model is available, it would definitely be advised to use this model for the intended studies. However, even if significant impact of the PED system could be predicted, one would have to resort to the generic model if the more accurate manufacturer model is not available.

Q18 (Page 20): to?

Response:

Thanks, corrected.

Q19 (Page 20): You are almost touching this, but it could be good to clarfiy the concept of manufacturer exporting their exact control and protection code to .dll format to be used in models, unlike .lib format or similar.

Response:

This is further clarified in Section 5.2.3.3 in the revised report where limitations of the manufacturer black-boxed model are discussed.

Q20 (Page 22): What is meant by long run?

Response:

It means "in the long term". Specifically, during the project life cycle, which can be between 10 and 20 years. It has been clarified in the revised report.

Q21 (Page 22): This can be overcome by a solid maintenance contract. Additionally suppliers only remain responsible for the system behaviour if they remain involved in the development of the system

Response:

Theoretically, this is feasible. And this is exactly what RTE intended to do years ago, entrusting the responsibility of offline model management to the manufacturer such that the offline model would always reflect on-site behavior. But our experience over the years in multiple HVDC projects, with various manufacturers, shows otherwise. And this is not because of unclear or insufficient specifications in the contract, but more due to the disproportionateness between the penalty that can possibly or realistically be inflicted for the unfulfillment of such a task and the actual economic consequences brought by on-site system failure. One might still argue that carefully stipulating the clauses in the contract and setting a penalty high enough would resolve this issue, but here are the challenges, which we have experienced:

- Would the manufacturer actually accept the clauses and sign the maintenance contract?
- Would the claim for high financial damage be accepted by the court in case of system failure due to the offline model being out of date?
- The manufacturer can always contest the claim in court, and it becomes a situation where it is "your words against mine". In such a case, what would be the odds for a third-party having little or no expertise in the field of EMT or power systems to correctly assess the issue, recognize the root cause of the case and come to a fair conclusion in the plaintiff's favor?

Further circumventing this issue would require expertise and resources we do not have, which are beyond the domain of HVDC, OWF or power system studies in general. And this is why, at this moment, we consider this aspect of the offline EMT model as a limitation.

Moreover, suppose that it is possible to always keep the offline EMT model updated every time an on-site software update is implemented. However, incompatibility issues with EMT software version update are an independent issue. We have experienced it with certain offline EMT tools, and it takes a lot of effort and time to resolve. This would be unrealistic in a project with clear requirements on the deliverables at different stages.

We are keeping this statement here because we believe it is a disadvantage in offline EMT models in comparison to real-time simulation based on our experience.

Q22 (Page 22): Could this be elaborated a bit? I agree with the statement, but I believe the goal seen from a TSO is to achieve an EMT model which is as close to the real system as possible. But we also know that the manufactureres may leave out control functions etc which they believe arent relevant for the particular studies at hand.

Response:

As was mentioned at the beginning of Section 5.2.3.2, certain functions are usually omitted, resulting in the fact that studies related to these functions cannot be performed with the offline EMT model.

The case study in Section 6.2.2 demonstrates an inter-area oscillation issue that occurred on site but failed to be reproduced with the offline EMT model. This is partially because the AC emulation function was excluded in the offline EMT model. Of course, the offline EMT model not being up to date is another reason, as was explained in the report.

Q23 (Page 22): Do you know of a relevant reference or experience to the functions and parts which are typically left out, but that you have found may have influence on study results?

Response:

The vendors usually would not provide the client with a list of functions being simplified or left out in the offline EMT model upfront. It is usually through discussions with the vendors on issues discovered either during studies or on site that one might be able to know which functions are excluded or simplified. A short list of functions mentioned at the end of the first paragraph of Section 5.2.3.2 are what we found out to be excluded or simplified based on our experience in working with different vendors.

It is worth mentioning that one cannot assume a function would be typically left out or simplified, because:

- The system is different from one vendor to another. Therefore, offline simulation requirements and common practices are also different from one vendor to another.
- Specifications, network and equipment configurations are different from one project to another, indicating that a certain function deemed unimportant thus excluded or

simplified in one project may be important in another project with completely different requirements.

Q24 (Page 22): Is this not the same case for the HIL setup and the replica? Doesnt the replica setup have to be updated every time the real system changes? Can you elaborate why this is an easier smaller task with the replica compared to the offline models?

Response:

First of all, it should be understood that the on-site C&P implementation and the C&P replicas in the HIL lab facilities operate in the same software and hardware environment. A detailed procedure would be pre-defined by the vendor using a particular convention to track the update before each on-site system update. And it suffices to follow exactly the same procedure and convention to perform the update on the C&P replicas. Our experience in working with the vendors shows that system updates on the C&P replicas can be reliably performed and tracked as the on-site system with minimum human error.

However, it is less straightforward for the vendors to update their black-boxed models following each on-site system update because the offline model operates in different software and hardware environments. Automatic code extraction is available in most cases despite the fact that vendors adopt different code extraction approaches and that the codes are usually in different formats. But:

- Please keep in mind that certain functions might be deliberately omitted or simplified in the code extraction for various reasons, as previously explained in the comments and the report.
- In many cases, the extracted code is not the complete system update and additional manipulation, and development are needed because the offline model operates in a different software and hardware environment as compared to the on-site C&P system or C&P replicas, as mentioned earlier. This would lead to potential errors.
- The previously mentioned "disproportionate financial penalty" in offline EMT model maintenance contract certainly does not encourage vendors to engage in offline model update as actively as they do for the on-site system or the C&P replicas. Therefore, they would usually allocate limited resources for such activities.

Once again, our experience in working with different vendors shows that, at this moment, offline EMT models are not being managed as effectively and efficiently by the vendors as the on-site system or the C&P replicas. Apart from missing or incorrect updates, it can also be difficult to track the updates sometimes.

On a side note, we can argue that the principal purpose of offline EMT models is for system and equipment design, but not for maintenance during the entire project life cycle.

Q25 (Page 23): Could you elaborate on what would be the minimum simulation time step applicable for real-time simulation? Do you see limitations when using real-time simulation for very large grids such as the NSWPH ?

Response:

In RTDS, power system components can be simulated with 50 us, and PED-based devices can be simulated in the "small time-step" environment with 1.4-3.75 us (the time-step for PEDs is decided by the simulator), in the "substep" simulation environment, the time-step for PEDs is large time-step (usually 50 us) *1/N (N is an integer between 5 and 64). The time-step for PEDs is similar for the Hypersim simulator.

In offline simulation since the hardware resources are limited (one PC), given a certain time-step, the larger the network is, the longer it takes to simulate. However, for real-time simulation, hardware is expandable. An extremely large network can still be simulated in real-time with sufficient hardware resources (racks, cores, interfacing devices, etc.) with a given time-step.

Q26 (Page 23): Please add UIF and MIIF to the list of abbreviations.

Response:

They have been added.

Q27 (Page 23): Please elaborate. For me it is not clear why the TSO should perform these additional studies.

Response:

The fact that the technology involved is innovative or state-of-the-art indicates that its potential impact on the system performance is uncertain or needs to be verified.

As the TSO of the French transmission grid, this is what RTE believes and practices.

For example, the INELFE project is the second MMC installation in the world and was considered innovative back then. Therefore, during the planning stage of this project, RTE conducted several EMT studies such as DC overvoltages that might impact the cable design. The results obtained from these studies served as inputs for the specifications of cable design.

Q28 (Page 25): This is important but extremely difficult. In NL the TSO has to build to link but the windfarm supplier is only known years later. Government desides who will be the supplier of the windfarm and he is responsible to select the manufacturer.

Feedback into the TSO project will always be too late.

Response:

We understand that it can be difficult in some cases due to various reasons that are beyond the scope of the discussion here. In this case study, we are simply demonstrating the fact that multi-vendor offshore systems could behave differently and unexpectedly although they all comply with onshore grid code.

Q29 (Page 26): For clarification, this is MMC1 in the offshore point?

Response:

Yes.

Q30 (Page 28): Very good point

Response:

Thanks.

Q31 (Page 28): this is due to the selection of symmetrical monopole and has nothing to do with simulation tools

Response:

The purpose of this case study is stated at the beginning of Section 5.3. Simulation tool is irrelevant to the discussion here.

Q32 (Page 29): Agreed, but there may be a time difference betweeen the design of the HVDC and the connection of the wind power - atleast for offshore hub concepts, so this risk may have to be explored by the use of some generic model of the wind.

Response:

Indeed, it would be difficult to have all precise models (either offline or real-time) ready at the beginning of the project.

Q33 (Page 29): As indicated earlier this might come in a too late stage of the design

Response:

We clarified this in a previous comment.

Q34 (Page 31): Is this specific for LCC and VSC converters in combination, or also general for two VSC converters?

Response:

An existing HVDC link would certainly impact the performance of another one being built in close proximity even if both links are of the same technology. However, the TOV characteristics might not necessarily be impacted in the same way and the impact might also be reflected in other electrical quantities. Further clarification has been added in the revised report and a reference has been provided.

Q35 (Page 35): Joris: Could you summarise why this is the go to approach from the point of view of RTE?

Up to now it's not completly clear by pro's and con's of both ways

Laurids: I guess it is because it by these utilities have been evaluated that the pros outweigh the cons. Maybe this could be stated more clearly?

Response:

A summary is added in the section where advantages and limitations of HIL are discussed.

Q36 (Page 36): how about the auxiliary systems that are present on the offshore station, such as power supply, cooling water system, platform security system etc.?

Response:

As was mentioned in the report, these auxiliary systems are usually not included in the maintenance replicas because they are usually not included in the real-time simulator. However, they can be added upon request, as what we have for some (but not all) of our projects at RTE/RTEi. Please keep in mind that in such a case, these systems would also need to be included and simulated in the real-time simulator, extending the scope of the electrical network to be simulated on the real-time simulator (more hardware equipment due to higher capacity requirement).

Q37 (Page 36): This is a good point. It could even be highlighted that this is beneficial when converters are installed offshore, where the accesibility is challenged (transport, whether etc).

Response:

Yes, you are right.

Q38 (Page 36): this is considered as well in TenneT. maintenance training of only a part of the system is usually not enough.

Response:

Agreed.

Q39 (Page 37): Without taking into account the specific AC offshore grid environment?

Based on your expertise, could this become an issue considering AC interconnected hubs?

Response:

You are correct. The AC grid that most OWF vendors use in their design and system studies are, at the moment, rather simplified and standardized (e.g., considering low order harmonics, and impedance at certain harmonic frequencies).

Yes, this would certainly become an issue considering the option of using HVAC interconnection to interconnect offshore hubs due to risks of interactions on the AC grid as explained in the report.

However, this is the status quo at the current stage. We do believe this practice will be improved in the next few years, as we observed how things have been evolving for the past few years.

Q40 (Page 37): Did you already observe significant differences between aggregated PPM-Models and individual wind farm models in terms of control interactions ?

Response:

Yes, actually the aggregated OWF model (Solution 2) would only render reliable behavior as compared to the detailed model (Solution 1) under the following two conditions:

- The OWF system is "balanced". Here the term "balanced" means that each wind generator "sees" its surrounding network configuration similarly. For example, this would certainly exclude the case where all generators are connected to one feeder, whereas several generators are disconnected from another feeder, or a cable is disconnected somewhere in the offshore grid, etc.
- The technology, ratings, and electrical and control components of all generators are identical or at least similar.

The performance of the aggregated approach cannot be ensured if the above two conditions are not met. In the end, the pre-requisite for either solution is that detailed C&P model of the wind generators is available.

Q41 (Page 40): Thank you for the proposal of Solution 1 and Solution 2. Maybe it could be an idea to describe a Solution 3, where the C&P replica is interfaced purely with simulated controller models. This is similar to Solution 1, where some of the wind turbines are represented only by models and not physical control hardware. What would requirements to such models look like? Is it the similar as the model requirements to an offline EMT model? I imagine we would have to update the national model requirements for offshore wind to include it. Do you know a good reference for this? Excuse my lack of experience in HIL simulation if it is a stupid question.

Response:

Actually, you raised a valid point here which challenges the status quo of the current stage and reveals the concern from many. The problem with this proposition, also similar propositions for HVDC converters, is that, currently the offline C&P models, either generic or from the manufacturer, are not adapted for real-time simulation, because the real-time constraints make it that certain simplifications and approximations have to be made in order for the model to run in real-time, as explained also in the report. The relatively easy availability of HVDC C&P replicas, and OWF C&P replicas to a certain extent, also makes it that limited interest has been drawn to this issue.

Therefore, we believe that it is less pertinent to perform HIL with HVDC and OWF, if the C&P replicas of the OWF are not available.

However, there has been some interest and development towards incorporating the entire C&P systems including all relavent control functions, operator HMIs, communication systems, etc. into the offline platform such that the engineer could operate the system offline virtually as if he/she were operating the real system on a workstation with the actual C&P implementation. This would provide a valuable solution to the current constraints in this issue.

Q42 (Page 40): I expect here a chapter on the bandwitdh of the Real Time simulator in comparison with the bandwidth of the C&P system and in relation to the studied phenomena.

Response:

Information on "cut-off" frequencies of general EMT modelling can be found in "IEC TR 60071-4 Insulation coordination - Part 4: Computational guide for insulation coordination and modelling of electrical networks".

It is not possible for us to provide such information on real-time simulators because:

- Simplifications and approximations are adopted in the modelling of electrical components in real-time simulation. In the response to a later comment, we explained why it is not possible to obtain complete information on this. Therefore, it is not possible to further evaluate the bandwidth of EMT modelling in real-time.
- The bandwidth of the C&P systems partially depends on the bandwidth of the measurement sensors implemented on site at the converter stations. This is an expertise owned by the converter manufacturer. Further information regarding this might be solicited from the vendors at the tendering phase of the project if necessary.

Q43 (Page 40): Interesting point. Can it be generalized that the simplifications due to real-time constraints mainly introduces uncertainty on the passive components?

Response:

We believe the several types of simplifications in real-time modelling can impact the accuracy of both passive and active components (e.g., Section 6.2.5).

Q44 (Page 42): Also C&P relays for example have firmware updates. Also system changes need to be implementend in the Real-time system.

So I miss here the maitence you have on the HIL system due to changes

Response:

We did not understand the question.

Q45 (Page 42): Typo

Response:

Corrected.

Q46 (Page 42): This is probably the point where NSWPH (and other hybrid offshore projects) differs mostly. Would you argue that the need for C&P replica is larger for HVDCs connected to OWFs compared to point-to-point HVDC between two "conventional" power systems?

Response:

We believe the need for C&P replicas is due to the potential interoperability issues between multi-vendor PEDs. Whether it is multi-vendor HVDC and OWF, or it is multi-vendor HVDC links connected in proximity, they both involved PEDs from different vendors and that's why C&P replicas would be a valuable solution to project de-risking.

Q47 (Page 43): Consider a case where the replicas has to run together with EMT models (could be from wind turbines), is there an issue with the time-step limitation of the EMT models? Should special EMT models be used for this?

In begin of document is described that, EMT and real time complement each other for verification. How can this still be done if EMT vendor model is limited on time-step range?

Response:

As stated in our response to a previous comment, we believe it is not pertinent to perform HIL with offline OWF C&P models as this approach is technically immature at this stage due to incompatibility of offline C&P models in real-time simulation.

Difference in simulation time-step requirement in the simulation with multi-vendor models is indeed a constraint in offline simulation. Sometimes (not all times), a solution can be achieved in finding a simulation time-step that suits all systems. If this is not achievable, multi-step simulation can be considered. We are aware that multi-step simulation accommodating the use of several different time-steps in the same simulation environment is being developed by certain offline EMT developers, but we do not want to further comment on that because we have yet to test this approach ourselves. Even if this approach is validated and fully commercialized, please beware that:

- Multi-step simulation would usually require an artificial decoupling line in the system so that interpolation can be performed to make the use of different time-steps possible. This can introduce accuracy issues if no existing lines/cables in the actual system could fulfil the requirements.
- The more vendors that are involved, the more difficult it will be to find a time-step that suits the accuracy requirements from all vendors; the more vendors that are involved, the more difficult it will be to fulfil the multi-step simulation requirements without compromising accuracy.

Whatever the issue is, it is much easier for real-time simulation to accommodate multi-vendor models for reasons stated in the report. However, neither approach is a "one size fits all" approach since both have limitations. and it is always better to use both approaches in complement in order to be more confident in the study results.

Q48 (Page 43): This is a very interesting point. Do you have some examples or data on this?

Response:

We have data from internal reports on this topic for certain projects within the French grid. Unfortunately, we are not at liberty to share them here. However, what we can say is that our experience shows that the use of C&P replicas can indeed speed up on-site commissioning by confidently reducing the number of tests that need to be performed on site because these tests will have been performed with the C&P replicas in the HIL lab first with all operating conditions considered.

Furthermore, considering the case where an on-site update is carried out by the manufacturer without validating it in our HIL lab with detailed network configurations, it is possible that this update would lead to unexpected event and even system shutdown, resulting in unplanned system unavailability. However, this issue would have been predicted and corrected if the update had been validated first with the C&P replicas before on-site implementation.

Q49 (Page 43): Do you have examples of transient events that are recommended to be performed offline?

Would the validation of simplified real-time simulation models still require updated C&P software in the EMT offline simulation ?

Response:

Reference [37] sheds some light on real-time model limitations. Therefore, it can be understood that transient events relavent to models that are simplified or approximated in the real-time simulator are recommended to be performed offline. This can include, in general, events involving nonlinear devices (e.g., transformation energization and saturation, etc.), high frequency dynamics, and events where the zero-sequence impedance characteristics of the network play an important role.

We did not understand the second question.

Q50 (Page 43): In an earlier section you described the difference between a study and a maintenance replica. Could one imagine a study replica be specified to have these modifications to part of C&P system? Acknowleding that whenever you change something from the original, you may lose accuracy or introduce errors.

Response:

We have actually discussed the possibility of having such replicas with different vendors. The conclusion is, it is possible to do so, but it would entail modification in the C&P software, which means the C&P software in the replicas would be different from that implemented on site. And this would contradict the fundamental purpose of the use of C&P replicas, which is to have the same C&P systems both on-site and in the lab.

Q51 (Page 43): Could you explain under what kind of circumstance this was and what kind of event or type of simulations triggered this?

Response:

It has happened on a number of events and scenarios we have simulated. For example, certain fault scenarios both onshore and offshore, energization of certain transformers, load rejection, start-up and shut-down procedure, etc. There is no direct link between the event and the consequence because in most cases they are not supposed to happen according to specifications. The reason why they still happen is because of the unexpected C&P interaction from different PEDs, which is exactly the purpose of conducting interoperability studies using the C&P replicas for multi-vendor PED systems.

Q52 (Page 44): Could you categorize these numbers by different type of simulations you have done? Would be interesting to see if their is a difference in ratio in categories of simulations offline EMT vs HIL and so which system focus on which simulation?

Response:

We could not provide exact numbers for each category of tests performed online and in real-time for various reasons, one of them being that the project is still on-going and the number of tests we perform keeps evolving due to client and study requirements. But we can say that the offline tests we perform focus more on dynamics because electrical components are more accuractely modelled, whereas the real-time tests lean more towards functionalities, taking advantage of the various operator HMIs, C&P systems, interfaces, PMS/PDCS that do not exist or are simplified in the offline model.

Q53 (Page 44): Can it disclosed which type of simplifications led to the problem? Has it led to a change in the way you specify model requirements for the offline EMT models?

Response:

As was stated previously in our response to another comment, the manufacturer ususally would not disclose such information. And for this specific issue, we have not received any formal explanation from the manufacturer. However, we believe it might be due to certain simplifications in the system of signal processing.

Another possible reason is that perhaps the offline model was out of date. We were not sure about this despite already having a solid maintenance contract with the manufacturer. The reason behind has been explained previously.

Yes, we have tried to solidify our maintenance contract of offline EMT models with manufacturers (always keep it up to date till the end of the waranty period which is 5 years for us) following this incident and a few others. But again, the end result still leaves much to be desired, as explained earlier.

Q54 (Page 44): why was it not able to do this? What was the key issue here of doing this?

Response:

This has been explained in several of our responses to previous comments. What we want to add here is that up to this incident, there had been 18 updates in the on-site system, but the updates implemented in the offline model were far fewer.

Q55 (Page 45): Very interesting: Was the offline EMT model also updated to 1) first be able to represent the phenomena, and 2) later updated with the dynamic performance degradation?

Response:

No, the performance degradation was observed in various tests we performed with the replicas to validate the update proposed by the vendor.

The actual offline model was never able to reproduce this phenomenon. The further offline investigation was carried out using an in-house generic model.

The actual offline model was not updated accordingly due to contractual issues.

Q56 (Page 46): Is it possible to state a general "cut-off" point of the frequency?

Response:

We believe this is out of the scope of the project. But "IEC TR 60071-4 Insulation coordination - Part 4: Computational guide for insulation coordination and modelling of electrical networks" would shed some light on this matter.

Q57 (Page 47): Could this also be formulated as a general benefit of the C&P HIL system over the offline EMT model? Were these part of the cause why the offline model couldnt recreate the event in this case?

Response:

Indeed, this corresponds to the fact that the C&P system in offline models is less accurate than the C&P replica, as compared to the on-site implemenation. And yes this is partially why it is difficult (or even sometimes impossible) to reproduce certain on-site phenomena using the offline model for further studies and mitigation.

Q58 (Page 48): Is it correctly understood that the replica was updated correctly with the onsite updates? but the offline EMT model was not updated accordingly? Is this a general problem to be aware of when you have both replica and offline EMT? that the offline EMT is "forgotten"?

Response:

Please refer to our responses to previous comments regarding issues with offline model maintenance. Once again, despite a solid maintenance contract, we have experienced over and over again that the offline models are not kept up to date as they should be. And this is one of the reasons why sometimes offline models fail to reproduce a certain event or render expected behavior as compared to on-site observation.

However, it has been corrected in the report because the main reason why the offline model failed to reproduce this event was that the AC emulation function was excluded or simplified in the offline model in this case.

Q59 (Page 48): If the model was black boxed, how did you get the information / parameters for the HIL setup?

Response:

The offline model was completely black-boxed. But the C&P cubicles allowed a certain level of access to its internal structure and parameters, which made it possible to resolve the issue in this case. As state here, it was the case for us in this project thanks to the contract specifications we had with the vendor, but it cannot be guaranteed this would be case for other projects.

Q60 (Page 54): Does this figure indicates that no changes will be made to the ABB system. As there is not dynamic FAT and commissioning block indicated for ABB?

Response:

The ABB system has been in operation in 2019 while the SIEMENS system is still under development and is scheduled to be commissioned in 2022.

Changes made to the ABB system have been strictly limited because it has already been in operation and any update or change that would affect system performance and availability would mean considerable economic impact for our client. This has been clarified in Sections 7.3.3 and 7.4.5 considering the modular development nature of NSWPH.

Q61 (Page 55): It is not clear to me why parallel computing was not used

Response:

This is a misunderstanding. By "parallel computing", we meant to simulate different sections of the network in parallel on different cores of a multi-core PC using the approach of network decoupling via a transmission line. This is not feasible for the Johan Sverdrup project because no existing lines/cables in the network would satisfy the requirements for decoupling.

This has been further clarified in the revised report.

Q62 (Page 55): Based on your experience, would it be possible to provide a rough time estimate of the two different processes? The itterative update of the offline EMT simulations, versus the remote work on the C&P software in the real time lab? I think this is an interesting perspective.

Response:

In fact, it is not possible to generalize the time it takes for this iterative process, or that proposed in Section 7.3.3 because the time consumed in performing the tests and providing the results in both processes is irrelevant or insignificant.

What can be, or usually is, more time-consuming is the result analysis, investigating and implementing a solution at the vendor's. And this is highly dependent on the problematic itself (i.e., its complexity, etc.) and the resources dedicated to it by the vendor, as was explained in Section 7.3.3, ranging from hours to days and even weeks.

Q63 (Page 56): Was there a technical reason for not requiring an offline EMT model of the PMS and PDCS? I assume this could be done, similar to power plant controls or master controls in other schemes.

Response:

The PMS/PDCS system used in this project is from the company Kongsberg Maritime that specializes in marine technology (controllers used in ships and containers). They have no experience in HVDC, EMT and very little in power systems in general. Therefore, it was not possible to obtain an EMT model from them. Choosing them as the supplier for the PMS/PDCS technology was out of our responsibility in the Johan Sverdrup project. Also, the physical PMS/PDCS replicas call for a lot of manual intervention from the operators and the dynamics are usually as slow as tens of seconds up to several minutes for secondary control actions. The PMS/PDCS is only represented by a much simplified logic in the offline model, which was designed by RTE/RTEi internally for offline interoperability studies.

And you are right, we believe it is possible to obtain the EMT model for such a master controller for other projects.

Q64 (Page 56): This is an important dis advantage and should be in summary

Response:

It is included in Section 6.1.6 in the revised version of the report.

Q65 (Page 58): Would it be possible to provide a list of simplified components for real-time simulations compared to offline simulations?

Response:

Unfortunately it is not possible to provide such a list for the following reasons:

- Different real-time simulator manufacturers implement different numerical techniques and methods in the modelling of the electrical components and even in the solution of network equations. One approach used by one manufacturer that could have a negative impact on system performance might not be used by another. Much of this information is hidden due to confidentiality issues. And it is a sensitive issue to associate any specific approach to a specific manufacturer.

- Even if some information on component modelling is publicly available, information on other approximations, shortcuts, etc may not, which makes it difficult to evaluate the overall impact of the modelling approach for a certain component.
- The issues we have observed and shared are based on years of experience working with different real-time simulators in various projects, extensive exchange with real-time simulator vendors and even PED vendors, as well as research work. They are of course not complete due to the first two reasons. Reference [50] can shed some more light on this issue.

Q66 (Page 59): Could one imagine or expect significant improvements in this area in the near future? This could be due to new solutions or improved computational power.

Response:

Indeed. The evolution of numerical techniques in both offline and real-time tools as well as the upgrade of computing resources have significantly improved the capacity and efficiency of both types of tools in recent years. But it might take some time for the real-time simulator to complete rid all the approximations and simplifications imposed by the real-time constraints. For example, RTDS developed "small time-step" simulation environment in 2005. And they commercialized the improved version of this simulation environment, named "substep", in 2019. It took them 14 years to develop this new environment, relaxing certain (not all) constraints on the modelling of certain components.

Q67 (Page 60): Just to make it 100 % clear - so the replica has a risk of an artificial resonance frequency, which can ultimately trip harmonic protection - which would not happen in the real system, because the phenomena is due to the simplification using the FA matrix approach.

Response:

Yes, it is correct.

Q68 (Page 61): To conclude on the given exmple, EMT offline simulation does not make use of FA matrix approach and would have represented the real system behaviour in this case?

Response:

More generally speaking, offline EMT simulation provides a more accurate representation of the electrical components and network than real-time simulation, but real-time simulation represents more accurately the C&P system of the on-site implementation than offline simulation. That's why we proposed to use both approaches in complementary in the NSWPH project.

Q69 (Page 63): Are transmission lines considered as large time-step components (50us)? Overall, is an accurate representation of traveling waves possible within real-time simulation?

How would you evaluate the accuracy of real-time simulations when it comes to DCCB operations with very fast transients?

Response:

In RTDS, large or small time-step components refer to the components used in the large or small time-step environment. For the former, usually 50 us is used; and for the latter, the time-step is between 1.4 us and 3.75 us, which is decided by the simulator itself. A transmission line longer than ~15 km can be modelled in the large time-step environment using 50us because the propagation delay is smaller than the time-step (50us), considering light speed. Therefore, any lines shorter than 15 km would need to be modelled by pi-sections in the large time-step environment. However, those short lines can still be modelled as travelling wave transmission lines in the small time-step environment due to the smaller time-step. Please keep in mind that it is not always possible to reduce the large time-step so that shorter lines can be modelled using the travelling wave model due to real-time constraints, unlike in offline simulation.

In general, transmission lines that actually exist in the network can be rather accurately represented in real-time simulation using either the Bergeron model (no frequency dependency) or the frequency-dependent line model, provided that their length fulfil the aforementioned requirements. However, more complex and detailed models such as the universal line model (as in PSCAD) or wideband model (as in EMTP) are not available in RTDS.

Furthermore, artificial travelling wave transmission lines of length ranging from a few hundred meters up to 21 km might need to be used for network decoupling in real-time simulation in some situations, under the real-time and capacity constraints.

DC breaker models involving high frequency transients are not directly available in real-time simulators. But they can be built manually and render satisfactory results. Further information can be found in [44] where we built a DC breaker model used in the Best Path project. To our best knowledge, certain manufacturers also have in-house DC breaker model available in the real-time simulator of their preference.

Q70 (Page 66): Assuming that multiple extensions of the NSWPH would push the real-time simulation platform to its computational limits. How could further extensions be ensured?

Response:

Computational capacity of the RTDS simulator is strictly dependent on the scale of the network and all the electrical and control components in it as well as the available hardware resources. Detailed network information needs to be provided to the manufacturer such that a reliable estimate can be achieved in terms of hardware resources (as was explained in Section 7.4.1). It suffices to contact the manufacturer again for additional resources (i.e., extra licenses for the cores, extra chassis, etc.) if further network expansion requires supplementary hardware capacity. This happened to us in the Johan Sverdrup project where initial hardware estimate was insufficient and extra licenses were required.

Q71 (Page 66): How does this refer to the nodes mentioned in table 7-2

Response:

The nodes mentioned here refer to the single-phase electrical nodes in the circuit. For example, if a transformer secondary windings were connected to the converter terminal directly with nothing in between, then there would be 3 single-phase electrical nodes (or 1 three-phase electrical node) between the transformer secondary windings and the converter terminal. This section discusses the computational resource allocation inside a single NovaCor chassis with several licensed cores with respect to the number of electrical nodes in the network. In general, each core has 300 load units, if there are 5 licensed cores available in one chassis, then there will be 1500 load units available; as you can see, the network solution will occupy different numbers of load units depending on the size of the network (in other words, the number of electrical nodes in the network), and all electrical components will occupy different numbers of load units depending on what they are exactly, etc. That is why the RTDS manufacturer would need detailed information of the network to be studied in order to obtain an estimate of how many chassis or cores are needed for any project.

Q72 (Page 67): Would it be possible to provide calculated scaled up "shopping list" for the topology shown in Figure 5.2 (could be MTDC configuration). This would help to avoid misunderstandings when we have to use the Johan Sverdrup information to calculate

Response:

It is not possible for us or the real-time simulator manufacturer to do so from a simple schematic because, as was mentioned in the report, and our response to the previous comment, the estimate can only be achieved when detailed network information, including all the electrical components to be simulated, becomes available. As for the HVDCs and OWFs, each manufacturer would have their own preference in terms of simulation environment (i.e., small time-step or substep) and way of modelling (i.e., decoupling the network from DC cables or from converter terminals etc.). This could be different from one manufacturer to another and the associated hardware requirements for the simulator would also be different. It is, therefore, necessary to discuss with the HVDC and OWF technology providers first and to have a detailed network single-line diagram before one can obtain a reliable estimate of the needed simulator hardware resources.

Q73 (Page 71): Is it correctly understood that this is the cubicles needed to represent 1 converter station and its related systems?

Response:

Yes, these are the cubicles and their associated functions for one converter station in this study.

Q74 (Page 77): In a previous section, the itterative process of solving control problems through offline EMT models was described, with the conclusion that it was a long an tedious process. Could the two methods be compared, with a rough estimate of the time involved? This is similar to the comment given in that previous section.

Response:

This question has been answered in a previous comment.

Q75 (Page 78): This is valuable advise. It will be interesting how we will specify the requirement on this in the tendering material and technical specifications.

Response:

In the case of Johan Sverdrup project, this was achieved through discussions between our client and ABB later on during the project because network expansion was not anticipated at the beginning of the project. In the case of NSWPH, we believe the second bullet point in this section would also be important since it has been predicted at the beginning of the project that the network will be modularly developed.

Q76 (Page 78): Would each software update of existing C&P software require total new testing of the system?

Response:

Yes, new tests certainly need to be performed after each software update. And this is what we do for the Johan Sverdrup project. But It is not necessary to re-perform all the dynamic tests scheduled. Only a selection of dynamic tests on which the software update might have an impact need to be performed.

Q77 (Page 79): Could it be argued that ideally the order of milestone 1 and 2 are reversed? The lab and the "standards" of the lab should be known before the replica can be specified? I know this may be sort of the chicken and the egg. But in my mind, it may be necessary to have a lab with sufficient expertise and standard ways of working, before one can specify detailed requirements for C&P replicas.

Response:

Yes, agreed. Ideally sufficient expertise and infrastructure should already be ready before undertaking the first step of the project. In fact, the acquirement of expertise is more important and certainly takes more time to achieve whereas infrastructure is relatively easier to manage. Milestone 2 focuses more on the infrastructural side of the lab facilities, which corresponds to our particular case for this project because a new building that would house all lab equipment was under construction at the kick-off of the project, so a temporary lab needed to be set up. That is why these two steps were arranged in this way in the report. But in general, yes, we agree with your statement.

Q78 (Page 79): Could a rule of thumb be stated for the spatial requirements for each converter system?

Response:

Figure 7-11 provides detailed information on the dimensions of each room housing the replicas for this project. These are the exact measurements, leaving ample space for operator workstations and other equipment, as you can see in the figure. The grey boxes correspond to the C&P cubicles inside each room, and they are also the exact numbers. Please also keep in mind that the study replicas from both manufacturers are used in the project. And as stated previously in the report, the exact number of cubicles depends on project specifics (the fullest installation can include as many as 3 times the number of cubicles as the simplest installation).

11 REVISION HISTORY

Rev R0	Prepared: Ming Cai	Approved: Sébastien Dennetière, Hani Saad, Markus Von Dem Berge
First issue		
Rev R1	Prepared: Ming CAI	Approved: Sébastien Dennetière, Hani Saad, Markus Von Dem Berge
Second issue		
Rev R2	Prepared:	Approved:
Rev R3	Prepared:	Approved:
Rev R4	Prepared:	Approved:
Rev R5	Prepared:	Approved:

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