White Paper

SOLUTIONS AND CHALLENGES TO DE-RISK DEVELOPMENT OF LARGE-SCALE MULTI-VENDOR CONVERTER DOMINATED SYSTEMS

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I. INTRODUCTION

High-performance power electronics devices (PED) have been increasingly penetrating the existing AC grids thanks to their ability to integrate renewable energy resources. This comes with, however, an emerging challenge for grid stability and reliability due to the complex control and protection schemes implemented within these devices, as has already been testified around the world [1]-[4]. On the other hand, as incentivized by the visions laid out in the Paris Agreement [5], European Union's Green Deal [6] and the EU Offshore Renewable Energy Strategy from the European Commission [7], broad collaborations and consortiums have been established such as the NSWPH consortium [8] and the Eurobar consortium [9], with the firm conviction of combatting climate change by actively engaging in seeking solutions to accelerating the energy transition in Europe. Many initiatives have been proposed since, cherishing the ambition of developing and integrating offshore grids spanning across country frontiers on a large-scale. The envisioned projects are set to be developed gradually and modularly in several phases over a long time-span, involving state-of-the-art HVDC and offshore wind technology from different vendors at each project phase. The onerous technical requirements in such large-scale converter dominated systems as well as confidentiality and intellectual property issues raise significant challenges in the aspect of multi-vendor interoperability, further defying global grid stability and reliability. A great deal of interest from network developers has, hence, been drawn towards this issue of late.

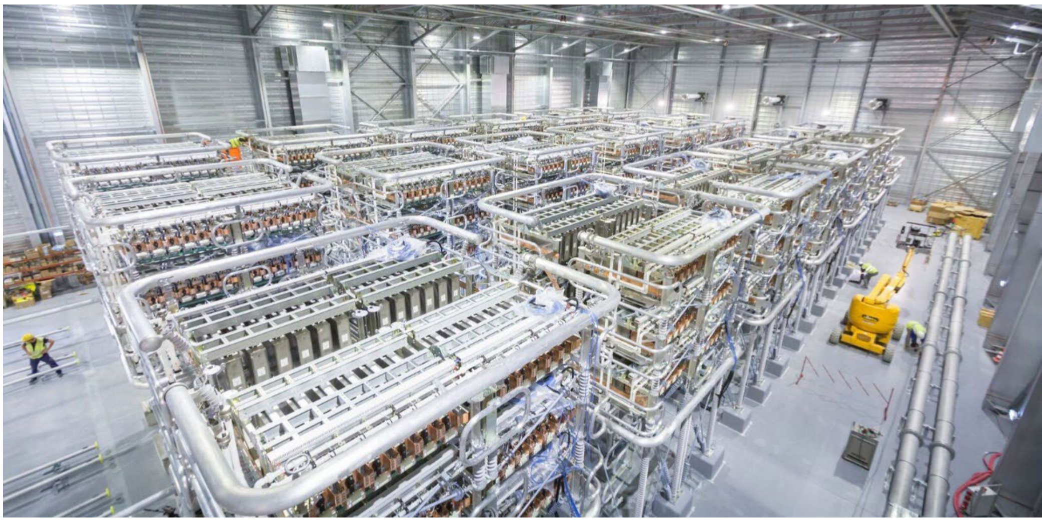
The challenges of interoperability in a large-scale multi-vendor PED-dominated system lie in the grave repercussions of adverse interactions between different PEDs in HVDC and offshore wind farm (OWF) systems, network passive components and/or conventional onshore power plants, on both the AC and DC grids.

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

Due to their faster controllers governed by smaller time constants as compared to conventional synchronous generation-based power systems, PEDs prevailing in HVDC and OWF can excite a broad range of frequencies that, if not properly taken care of, can lead to negative interactions. Moreover, the fast-switching capabilities of PEDs indicate that they can distort the line voltage by injecting additional harmonic voltages and currents into the grid. The complete installation of a PED should, therefore, not be considered as a passive system, as its control mechanisms, if not properly tuned, could possibly amplify rather than attenuate disturbances in a way that the system becomes locally unstable. These local instabilities, either onshore or offshore, could ultimately lead to the trip of the respective HVDC stations or large OWFs, resulting in even greater power imbalances that could further jeopardize the global system stability.

Nonetheless, early identification, analysis, and mitigation of adverse interaction phenomena in a system dominated by multi-vendor PEDs is not an easy task due to:

- high complexity of the Control & Protection (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 by different parties for model representations;
- accuracy of simulation parameters/data of the device model provided by each vendor;
- maintenance of the device model through the lifetime of the project.



Inelfe HVDC converter station

Insight from RTE international (RTEi) on interoperability assessment and technical challenges to de-risk large-scale multi-vendor projects in PED dominated systems is shared in this document.

II. CURRENTLY AVAILABLE SOLUTIONS

Among all the tools and approaches available to engineers and researchers for HVDC and OWF applications, the approach based on electromagnetic transient (EMT) simulations stands out as the approach of choice for interoperability assessment in a multi-vendor PED-based system. It has become essential to de-risk the design and operation of such systems thanks to its capability of accurately representing system components, notably PEDs, and addressing a broader frequency range in the investigations. Simulations are performed in time-domain with the objective of computing the instantaneous waveforms at an arbitrary point in the simulated network.

In addition, the EMT approach has proven to be an appealing alternative for control stability studies, overcoming the drawbacks of the analytical approach in small-signal analyses and offering a valuable solution to multi-vendor interoperability issues.

A. Offline EMT simulation and HIL (Hardware-in-the-loop) real-time simulation with C&P replicas

Depending on the relevance of computing time for the simulation results to become available, the EMT approach can be categorized into offline EMT simulation (without computing time constraints) and real-time EMT simulation (with computing time constraints). Typically, two types of PED models can be used for multi-vendor interoperability studies in offline EMT simulation, as is illustrated in Figure 1. Each type of offline PED models has its own advantages and limitations. Therefore, the type of offline PED model to choose in interoperability studies depends on the study in question and model availability.

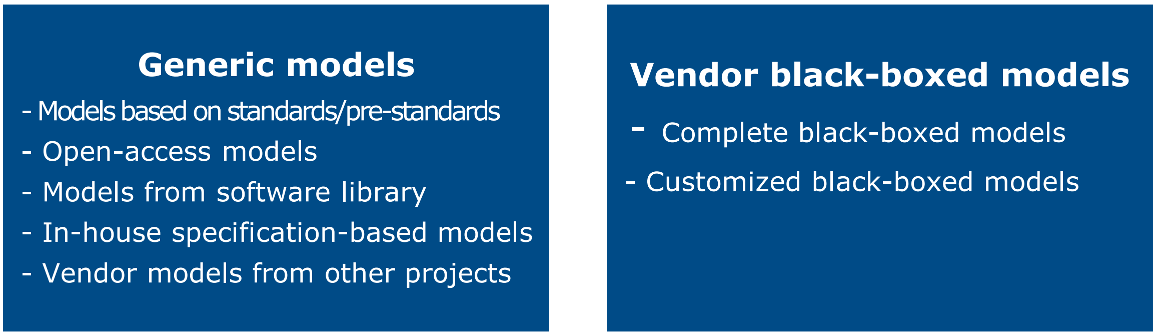


Figure 1 – Different types of offline EMT models

Real-time EMT simulation offers a complementary solution to offline EMT simulations and also possesses the advantage of relatively lower simulation times. One of its main purposes is, therefore, to achieve faster EMT simulation by capturing system behavior in real-time. Additionally, real-time simulators allow the possibility to connect physical external devices (e.g., C&P replicas) to perform HIL (Hardware-in-the-loop) or PHIL (Power Hardware-in-the-loop) simulation. For the definition of C&P replicas and RTE's experience as a system operator in EMT studies using C&P replicas, please refer to [9].

To cope with such faster computation time and additional constraints imposed by the connection of physical devices, simplifications in the real-time EMT models and solvers, as well as dedicated simulators with more powerful processors are needed. This is usually achieved by acquiring and installing a dedicated simulation platform rather than performing EMT simulations on conventional PCs.

For better clarity, the comparison between offline EMT simulation and real-time HIL setup with C&P replicas is summarized in Table 1 for the aspects that are crucial in interoperability assessment for a multi-vendor PED-based system.

Table 1 – Comparison between offline EMT simulation and real-time HIL setup with C&P replicas.

	Offline EMT simulations	HIL setup with C&P replicas
Representation of actual on-site C&P system	Less accurate as only code extracted from the C&P algorithms is used while adopting typical simplifications, approximations, and assumptions.	Highly accurate as the C&P replicas are (almost) exact copies of the on-site C&P installation.
Representation of power circuit components	Accuracy can be easily adapted to the study requirements.	Accuracy is highly constrained by real-time simulation requirements (both software and hardware).
Model accessibility and flexibility	Internal structure is less accessible to the end-user as manufacturer C&P models are usually black-boxed, thus allowing restrictive flexibility in system studies.	Internal structure can be made more accessible to the end-user, together with HMI and associated tools, facilitating system studies.
Following on-site system updates	More involved procedures required in system updates due to cross-platform code extraction and supplementary code implementation, necessitating dedicated resources and special care to avoid uncertainty and human errors.	Easy to track and implement system updates since the C&P replicas operate in the same software and hardware environments as the on-site installation.
Regarding multi-vendor EMT models	Difficulty in resolving issues regarding vendor-preferred simulation software, software version and compiler incompatibility, simulation time-step requirement differences, etc. which would result in accuracy degradation, and in many testified cases, model inoperability.	Easy to resolve issues regarding vendor-specific simulation requirements as the C&P system from each vendor operates on its dedicated platform.
Operational cost	Less costly	Costly investment in infrastructure, hardware and human resources
Studies of system operation involving operator interventions	Not feasible since the functions regarding operator intervention are usually not included in the offline model.	Feasible since the C&P replicas are equipped with associated HMIs and tools including (almost) all necessary functions as the on-site installation.
Studies involving slow-varying dynamics	Possible, but not practical due to the extremely long simulation time required.	Feasible as the simulation runs in real-time.
Automatic run of large numbers of sensitivity studies in parallel	Feasible	Only feasible if the C&P algorithm is modified to deactivate certain functions requiring operator intervention. However, this is not recommended as it could lead to potential accuracy degradation.

From Table 1, it is easy to observe that both approaches have mutually complementary advantages and limitations in the aspects that are crucial for multi-vendor interoperability assessment. Considering the technical status quo, it is, therefore, recommended to use both approaches in complement to one another in during the interoperability assessment for a multi-vendor converter dominated system. One example of this is provided next in the context of interaction studies for the Johan Sverdrup project.

B. Case study - Johan Sverdrup interoperability assessment

Discovered in 2010 and located approximately 140 km from the west coast of Norway, 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 (now Hitachi Energy) in 2015, with the 100 MW, two-level HVDC-VSC commissioned in 2019 and is currently in operation; the phase-2 HVDC contract of a 200 MW, HVDC-MMC link was awarded to Siemens in 2018 and will be commissioned in 2022. The Johan Sverdrup project is set to become the largest offshore distribution grid in the world and the first European multi-vendor parallel connected HVDC systems in grid-forming operation.

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, RTE international was contracted as an independent Third Party to facilitate needed exchanges while protecting sensitive information and to oversee and perform offline and real-time parallel operation studies with data provided by both HVDC vendors. The main objective of these studies is to analyze possible interoperability issues of the two parallel HVDC links, ensuring secure power supply for the Johan Sverdrup field center, its neighboring platforms, and other consumers under all operating conditions.

More specifically, during the design stage of the phase-2 HVDC system, offline simulation studies are conducted to detect potential interoperability issues when both HVDC links are operating in parallel. Then, based on the results from offline simulations, a set of real-time simulation studies with the HIL setup and the C&P replicas are defined to be performed prior to on-site commissioning of the second HVDC link. The following considerations are invoked to prevent IP rights infringement and to achieve effective and efficient multi-party testing:

- The C&P replicas from each manufacturer are housed in separate, dedicated rooms accessible with secure measures to the respective manufacturer and RTE international only.
- Remote access is established for each vendor to access their workstation and C&P software, facilitating system update, maintenance and problem-solving. It is noted that RTE international has sole access to the real-time EMT models from all manufacturers and the entire studied network.
- 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, with information sharing managed by

RTE international under consideration of IP measures.

- A centralized master control system (PDCS/PMS, i.e., Power Distribution and Control System/ Power Management System) is implemented for multi-system coordination, further improving interoperability.
- Software changes in already commissioned and operating systems are strictly limited to avoid possible adverse impact on overall system dynamic behavior.

For further information on the Johan Sverdrup project, please refer to [11] and [12].

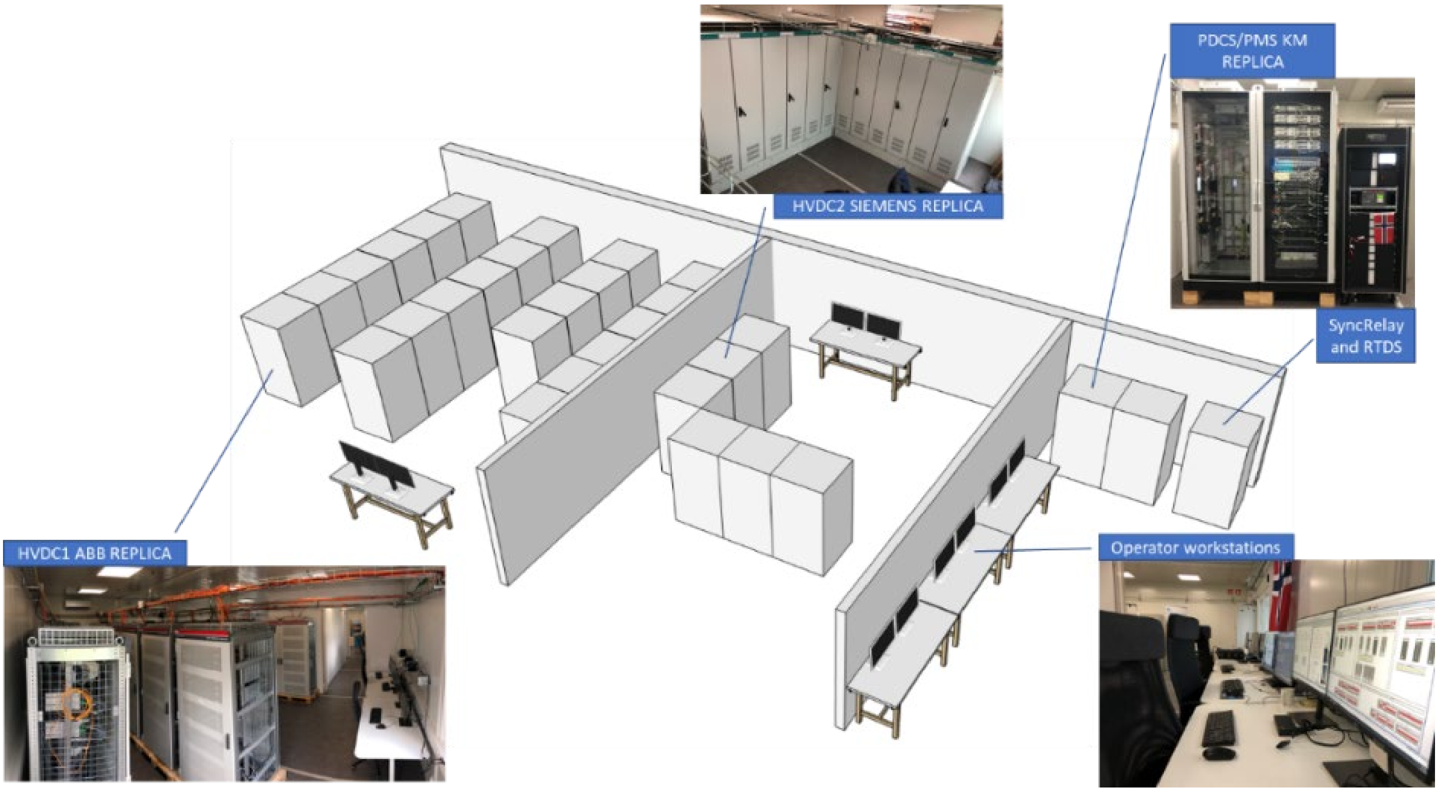


Figure 2 – Johan Sverdrup project facility arrangement

III. CHALLENGES FOR THE DEVELOPMENT OF FUTURE LARGE-SCALE OFFSHORE GRIDS

Currently, the combination of offline and real-time simulations offers an adequate solution to interoperability assessment of a multi-vendor converter dominated system. Nonetheless, the non-negligible procurement cost of C&P replicas and the stringent infrastructural requirements of HIL lab facilities, especially in the context of large-scale offshore renewable power integration with tens of interconnected converter stations installed in several countries, make real-time simulation studies with a set of C&P replicas from each vendor a less feasible solution. However, the technical status quo of offline EMT tools faces the following challenges when used alone in multi-vendor interoperability assessment:

A. Computation time

The computation time in offline EMT tools can be significantly longer than in real-time EMT tools due to more detailed component modelling and the absence of real-time constraints, which is the reason why offline EMT models are currently not the preferred tools for addressing events involving slow variations that last from tens of minutes up to several hours. Several software developments are ongoing to reduce computation time, such as solver optimization, parallel processing, hybrid analysis combining RMS and EMT simulations, etc., in the hope of enabling interoperability assessment solely on offline tools.

B. C&P functions and hardware environment representation

Simplifications and approximations are usually adopted in the C&P system for offline EMT models in order to accelerate offline simulations, leading to discrepancies between the offline C&P model and on-site C&P implementation, which makes it difficult for accurate interoperability assessment as the offline model might not be able to reproduce certain phenomena observed on site, or the behavior obtained from the offline model might not correspond to the actual system behavior observed on site. In addition, functions related to operator Human Machine Interfaces (HMI), communications systems, and other auxiliary functions, such as alarms, etc. that are typically neglected in offline EMT models should as well be accurately represented such that the offline EMT model can offer a “virtual” operating environment that resembles the actual system on site to the largest extent. Needless to say, these two aspects would further challenge the efficiency of the offline EMT tool.

C. Vendor-specific offline EMT models not yet designed for interoperability studies

PED vendors have no access to the technological details in the offline EMT models of one another as the implementation of C&P functions is usually black-boxed due to confidentiality and IP rights concerns. Therefore, a possible solution to maximizing model interoperability is through specifications. To this end, emphasis should be put on the provision of universal (to a great extent) detailed requirements of the offline EMT model to each PED vendor, including quantifiable performance indications of each converter control mode, expected dynamic response to setpoints, as well as simulation parameters (e.g., acceptable time-steps), etc., which are to be carefully verified after model delivery. This aspect is currently not enforced in practice because the principal purpose of vendor-specific offline EMT models is to aid system and equipment design while respecting specifications provided by the client and not for interoperability studies with existing PED systems in the project or future vendors to be involved.

D. Long-term model maintenance

As was mentioned previously, the principal purpose of offline EMT models is arguably to aid system and equipment design. They are not designed to be used for extended studies and testing during the entire life cycle of the on-site installation (i.e., between 10 and 20 years). With the C&P system continually being updated on site, the offline EMT models would become less accurate and reliable with time due to the difficulty in properly maintaining the offline model during the project life cycle. The causes of the difficulty are manifold, e.g., human errors in C&P code extraction and development and difficulty in tracking system updates as the offline model usually operates in a different software and hardware environment, demanding challenge for PED vendors to maintain personnel with specialized skills regarding project specifics due to PED technology evolution. Moreover, EMT software upgrade and development poses further constraints for offline model maintenance in terms of software version incompatibility.

More information on the challenges in future multi-vendor interoperability assessment can be found in [13]. In brief, the feasibility of interoperability assessment of a multi-vendor converter dominated system relies on the fact that the above-mentioned challenges can be overcome with the help of further technical development of offline EMT tools as well as close coordination among PED vendors.

IV. POSSIBLE DIRECTIONS TO SECURE THE DEVELOPMENT OF LARGE-SCALE OFFSHORE GRIDS

The combination of offline and real-time simulations offers an adequate solution to interoperability assessment of a multi-vendor converter dominated system. Nonetheless, this approach exposes several limitations in the context of large-scale offshore grids, making it unfit to resolve interoperability issues for grids expected to be composed of tens of interfaced converters. This has been understood from the previous discussions. Considering the challenges raised in the interoperability assessment for such complex offshore grid configurations, different directions have been identified by RTEi to secure the grid development of such a kind.

A. Improvement in PED models

As was mentioned previously, detailed specification would help maximize model interoperability. In fact, many initiatives have been launched by TSOs and grid developers to improve specifications for PED EMT models to be delivered by PED suppliers, in the hope of facilitating interaction studies during the lifespan of the electrical system. These initiatives principally focus on requirements covering the following topics:

- accuracy (i.e., the minimum level of details);
- interoperability between models provided by different vendors;
- maintenance and update;
- simulation speed.

Specifically, a list of detailed requirements for the PED EMT models defined by the Australian Energy Market Operator (AEMO) can be found at the following link:

https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/participate-in-the-market/network-connections/modelling-requirements

In addition, ENTSO-E established an expert group on interaction studies and simulation models for synchronous power generation modules (SPGM), power park modules (PPM) and high voltage direct current (HVDC) transmission systems. Their recommendations were assembled in a report (available at: https://www.entsoe.eu/network_codes/cnc/expert-groups/) and will be used to elaborate further connection network codes.

Moreover, CIGRE and IEEE organizations have also been contributing to the improvement of PED EMT model specifications and development. For instance, a joint Working Group (JWG B4.82/IEEE) has been setup to provide "Guidelines for Use of Real-Code in EMT Models for HVDC, FACTS and Inverter based generators in Power Systems Analysis". The objective is to specify the requirements that should be considered when requesting accurate models from manufacturers for EMT simulations of inverter-based equipment such as Wind Generators, PV, BESS, HVDC, SVC, STATCOM.

Following specification improvements, the next step would be to bring all relevant requirements into standard bodies. This will only be possible when sufficient experience and best practices become available. One of the final objectives of all these initiatives is to obtain EMT offline models of PED C&P systems that are as reliable, accurate and fast as the physical control replicas. To this end, it is worth mentioning one major upcoming technology that could have a substantial impact on PED modeling– the Digital Twin (DT). As stated in [14], the Digital Twin concept is expected to be the innovation backbone of the future, providing a virtual representation of products and systems in the real world. Development of DT for Wind Turbine (WT) is discussed in [14], including the challenges and possible solutions to improve WT models for DT. In this concept, both the C&P system software and hardware need to be accurately represented. Services based on the Digital Twin concept have already been proposed by main HVDC suppliers in Europe, with improved solutions to model C&P hardware and software being developed.

B. Improvement in EMT offline simulation tools

EMT offline simulation tools provide the most efficient solution to meet accuracy expectations for dynamic studies. Different levels of details can be achieved for the power system components. The fundamental difficulty emerges from the contradictory demands for both accuracy and efficiency, which is especially noticeable for large-scale converter-based systems that contain many complex and detailed models requiring small calculation time steps.

Although this constraint can be partially resolved with parallel computing, it comes with an increased complexity in software development and may lead to accuracy issues when fictious delays are introduced. On the other hand, other parallel solution techniques which are not time-delay based, as described in [14], have also been developed with the intention of enhancing simulation efficiency in offline EMT tools. Furthermore, many ongoing efforts in CPU technology upgrade have been demonstrated to successfully render a continued speedup of between 10% and 15% per year in the single-threaded CPU performance [17]-[18]. Therefore, EMT offline simulation speed is expected to benefit from these technical and technological advancements.

Another major step forward for EMT offline simulation would be the capability to perform cloud-based computing with direct interface to a grid simulator that gathers all relevant parts of the system. The idea is to have an electronic copy of a grid that is maintained by the grid developer. All stakeholders that need to perform studies at different stages of a project can interface their models through a secured access to perform studies. They would be able to access the full details of their models and, at the same time, obtain the fully detailed behavior of the grid where they are connected. The principle of this approach is presented in Figure 3.

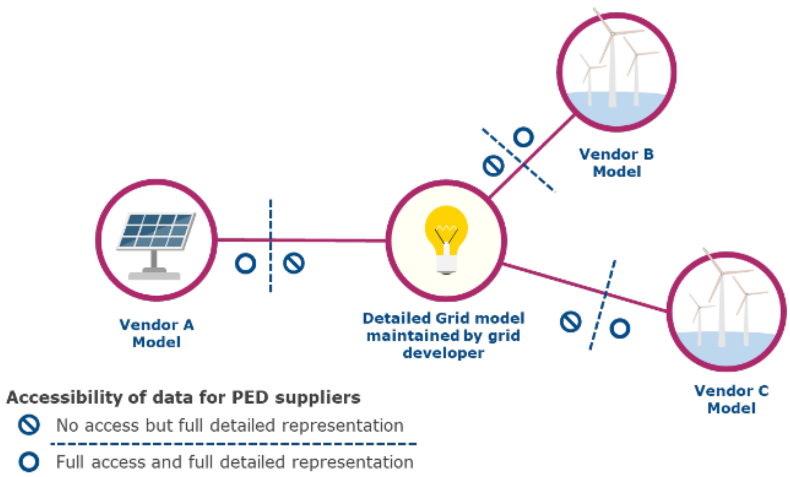


Figure 3 – Manufacturer model interfacing with actual grid representation

C. Towards a qualification process for interoperability

Insights of RTE international's laboratory in Jonage

Large-scale converter-based grids will be composed of multi-vendor and multi-technology solutions. As discussed in the present document, challenges and solutions have been identified to secure grid development of such a kind. Not only will improvements in studies, models and tools be required. But also coordination with all stakeholders at different stages of the project is crucial.

Studies coordinated with all stakeholders are usually demanding in time and resources because of the need to establish an iterative process, as experienced in the Johan Sverdrup project [12]. This is why a qualification process is necessary when large systems are developed and gradually expanded.

In the case of a system expansion, the goal of the qualification process would be to ensure that the new sub-system to be integrated into the existing system has been designed to be interoperable with the system previously designed by another supplier. This process would also apply to the existing system to verify whether it is already prepared to be interfaced with a system not designed and built by the same supplier. Many aspects would be of concern in the qualification process, such as equipment design documentation, C&P philosophy documentation, availability/accessibility of data including models, communication interfaces documentation. In addition, tests would need to be performed with adequate simulation models and/or physical control hardware to demonstrate multi-vendor readiness of the new and the existing systems. Finally, the qualification process would need to include system tests showing that the existing system, including its expansion, can operate as expected under all possible conditions.

VI. CONCLUSION

Aerial view of RTE international's laboratory

This document presents insight from RTEi on the existing challenges to develop large-scale converter-based grids. As part of the RTEi experience, solutions to secure the development of such projects have been described and discussed. The combination of offline and real-time EMT simulations with physical replicas by experienced engineers has been a time-tested approach successfully applied within RTEi in many projects. However, considering that offshore wind energy is one of the key building blocks for the green transition of Europe, challenges and solutions to secure such projects shall be reconsidered.

Improvements in PED models (from specifications to technical solutions), further hardware and software development to enhance EMT offline simulation shall be addressed in the near future. Although tremendous challenges are waiting ahead, many ongoing private and public initiatives have been launched with the hope of finding solutions to securely develop large-scale converter-based grids that are multi-vendor and multi-technology based. The ultimate goal would be to ensure such type of grids can be developed as securely as the standard AC grids, using adequate and tech-ready solutions.

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