Hardware-in-the-Loop (HIL) Digital Twin for Power from Shore

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Abstract – Power from Shore (PfS) projects present different engineering obstacles from concept to commissioning to life cycle operation. As PfS functionality are primarily grid-related topics, the possibilities of site-specific testing are limited before all equipment are assembled on site and integrated in full-scale into the system. There are possibilities prior to perform "string tests" to bring together transformers, converters, filters and temporary use a of a load bank, where it has its advantages and disadvantages.

This paper will focus on a recent case example of Hardware-in-the-Loop (HIL) Simulator and testing campaign for the electrification and expansion of a Norwegian offshore platform with two medium-voltage static frequency converter systems and two booster compressor variable speed drives as the core part of the HIL.

Index Terms — Hardware-in-the-Loop, HIL, Static Frequency Converter, Variable Speed Drive, Power from Shore, Decarbonization

I. INTRODUCTION

With the decarbonization movement, the shift has started towards electrification of offshore power generation equipment, i.e. power from shore electrification (PfS), using power electronic converter systems also known as static frequency converter (SFC) systems. As these are typically brownfield installations of existing platforms, this presents various engineering challenges from concept to design, then ultimately to normal operation as shown in Fig. 1 [1].

During concept and front-end engineering and design (FEED) studies, basic information on equipment may influence the solution to be implemented. Weight and footprint of the SFC system may limit the possibilities for brownfield installation. With the help of 3-D modelling and CAD, practically all suppliers can provide the mechanical information for the total mass and area needed for such installation.

For the electrical aspects, there are various tools to help design, validate and mitigate risks throughout the project and beyond. For grid integration and behavior, software-based tools are the primary means to test designs, emulate system behavior and ensure expected performance.

This paper focuses on the possibilities of a digital test system and presents a case example how the tool is used towards the end of project execution and prior to commissioning. Importantly, this tool will play a pivotal role in ensuring critical equipment performance and system training after the completion of the project.

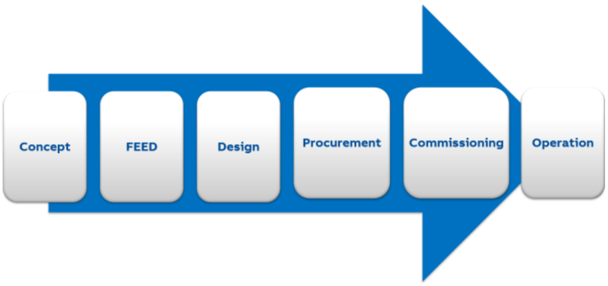

Fig. 1: Stages of project execution [1]

II. SYSTEM STUDIES AND TECHNIQUES

Depending on the phase of the project, different simulation and testing environments are more economic and efficient to deliver the needed outcome. Fig. 2. exhibits the test coverage and performance capabilities of different test possibilities [2]. In the conceptual and FEED stages, software-based simulation tools can be sufficient to qualify and validate an initial system design. During the commissioning phase and operational phases, higher accuracy testing environments can be used for further testing coverage.

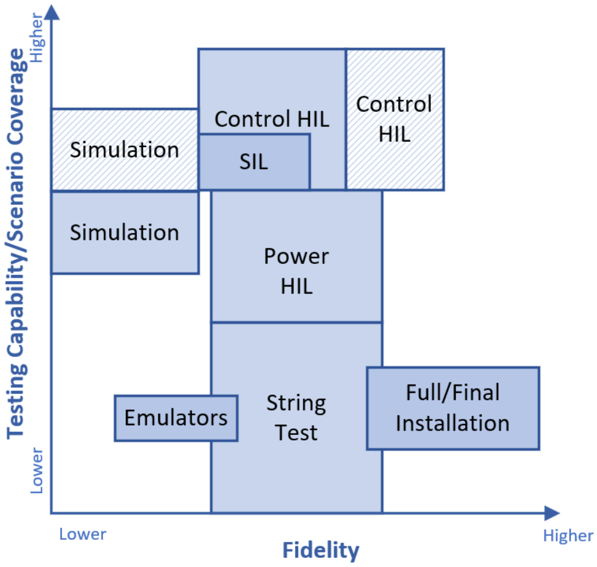

Fig. 2: Performance of different testing possibilities [2]

A. Software-based testing environments

There are many suppliers of software-based testing environments that enable basic verification of the operation. These tools can be used to run some simulations with the main aim of validating the design of the installation and verifying the desired operating points.

B. Hardware emulators

Hardware emulators consist of one or more control electronics making up the control hardware of a converter, integrated in a setup with additional components, for example a laptop, or other control assemblies. This tool can be used to access the converter human-machine interface, or to verify the functioning of certain communication channels such as slow I/O, and fieldbus communication protocols.

C. Software-in-the-Loop Simulators

The term Software-in-the-Loop (SIL) defines a piece of software enclosed in a “black-box” (for example, a .dll or .fmu file) that can be deployed on a compatible platform, where the power carrying components of an electrical system (such as buses, transformer, filters, semiconductors…) are simulated. The platform can be a normal PC running a “simulated” or “virtual” time, or it can be a real-time simulation environment.

A Software-in-the-Loop system concept is depicted in Fig. 3. In such a system, all the main measurement and control loops, protection functions and basic state machine transitions are implemented. Ideally, the whole firmware and software, which in reality runs on several different boards that communicate with one another, are condensed into a single executable piece of code. However, depending on the purpose and intended use, different level of abstractions could be adopted to enhance the scalability of the model or speed up its execution time.

Generally, and depending on the implementation, Software-in-the-Loop solutions can cover the following use cases:

a. Operation validation (steady state): validation of operating point as per design
b. Dynamic behavior: validation of transient response under different circumstances, see Fig. 4 as an example
c. Protection: check alarm and protection settings and response
d. Mechanical system interaction: study of effect of interaction between the subsystem and the rest an electrical network, or between multiple subsystems (for example for SSCI studies)
e. Harmonic analysis: checking the harmonic injection under different circumstances.

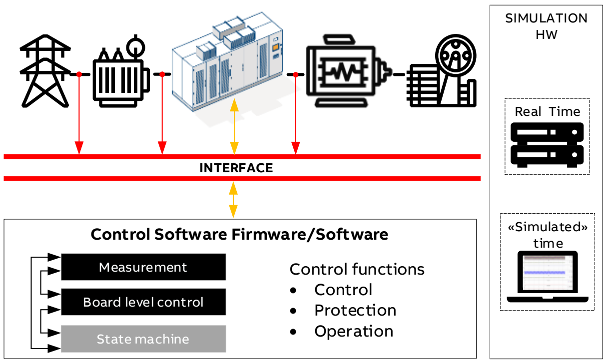

Fig. 3: Overview of a Software-in-the-Loop simulator

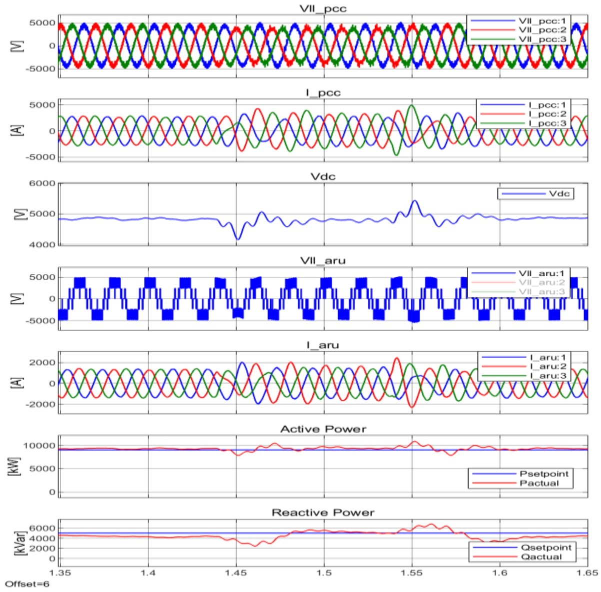

Fig. 4: Example of behavior of Software-in-the-Loop during a single-phase grid undervoltage

D. Control Hardware-in-the-Loop Simulators

In a control Hardware-in-the-Loop simulator, exemplified in Fig. 5 , the whole control hardware is implemented and runs on a platform, where the power carrying components are simulated. The control firmware and software are compiled and embedded on the boards that compose the converter’s control hardware. The simulation is executed in real time. While the power carrying components are simulated, all the necessary measured quantities are interfaced, with proper scaling, to the control hardware. This means that, from a control perspective, there is no difference between the simulated plant and the real plant. Contrary to the SIL, there is no abstraction of the control loops or other functions, providing the highest accuracy.

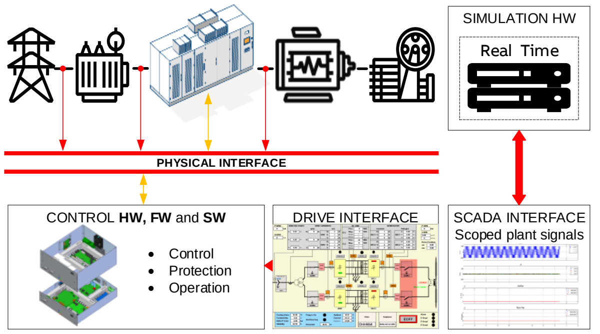

Fig. 5: Concept of a control hardware in the loop system

E. Power Hardware-in-the-Loop Simulator

A Power Hardware-in-the-Loop simulator (PHIL) is utilized when a scaled component of the system is to be tested in combination with a real-time simulator or control HIL. This could be a case when a transformer, motor, converter, or device under test (DUT) is to be tested [2]. This provides the advantage of testing as close to actual implementation but still limited by the physical installation and the HIL implementation and interface.

III. THE CASE FOR DIGITAL TEST SYSTEMS

For complex systems, such as Power from Shore installations, involving many subsystems and components, it is challenging, if not impossible to test the equipment behavior under multiple scenarios. Oftentimes, functionalities or operating scenarios involving more components (for example, several converters, machines, and high-level control) can only be tested on few occasions during commissioning before going online.

In terms of operational testing, typically, such a project may be made up of the following stages:

a. Initial simulation study (FEED): right at the beginning of the project, to validate the general design and operation.
b. Factory Acceptance Test (FAT), for each component delivery
c. System/String test: in a string test a lineup (for example: transformer, converter, machine, and compressor) or a system (for example, that one presented in Section IV.) is run, and the overall communication tested.
d. Commissioning of each subsystem
e. Full operation

The following section presents a project case where the system/string test has been substituted by a full-system Hardware-in-the-loop analysis.

In a string test, the end goal is to build up confidence in the subsystem under test (usually the key one in the project). The focus is put to ensure the studied lineup will run stable and correctly in the operating points given during the design phase.

The scope covered during a string test are thermal stability of components, tuning of controllers, correct communication between different components. The test ends when the stable run of operating points, plus a number of transitions such as starting and stopping the process, are validated.

In a full system hardware in the loop analysis, the starting point is to have a model of the whole system, where all (or the most relevant) components are replicated, either with HILs or SILs. Having a running system with correctly tuned parametrization and tested communication is the prerequisite, while the focus is shifted in testing several scenarios, spanning from startup, sequencing, grid disturbances, load disturbances etc. The focus is then put to the extensive and insightful analysis that is carried out.

Such a full-system hardware in the loop analysis does have limitations, as it will be discussed in the following subsection, but also provide a high level of system understanding.

A string test requires an effort for logistics, procurement, and installations of the studied components.

In order to perform system tests, all sub-systems (e.g. SFC's, transformers, switchgear, etc.) would need to be temporarily installed and operated in a test facility. It would not be possible to simulate a wide variety of scenarios like grid disturbances, short-circuits, dynamic load behavior and many others. In addition, it would be a challenge to perform the tests multiple times and consistently.

A full-system hardware in the loop requires an effort during the integration and test of all the components; this effort directly translates in the understanding of each component behavior.

A. Designing and testing a digital test system

The design of the HIL system plays a crucial role in its capabilities. The integration of different hardware, software, control components to accurately represent a real system is a challenge, which is further amplified by the need to meet the operation requirements and performance benchmarks of the actual system.

Because of the computational challenges that come from real time simulation, Hardware-in-the-Loop have been typically limited in scope, covering just parts of a complex system. In recent years however, technological progress bridged this gap, allowing to architect HILs for wide and complex system, which will be described in the case example (see Section IV.).

The design process of the HIL system enables the engineering team to conduct a comprehensive risk assessment and acquire invaluable insights into the design of the real system, thereby significantly enhancing its capabilities. Depending on the specific technical focus, a HIL system might closely approach a real system. It can be designed with focus on different areas, such as control system, hardware components, critical elements, or even the entire system.

B. Limitations

Most HIL systems are engineered to closely represent real-world systems. The specificity of HIL systems to different projects is due to the unique requirements of each control system, interface, and hardware component involved, which can sometimes limit their scalability and adaptability to different projects.

Furthermore, computing power significantly impacts the scalability and adaptability of an HIL system. To effectively simulate real components, a HIL system necessitates adequate computational resources. The required computation power is determined by the size and fidelity of the simulated component. When configuring the HIL configuration for other projects or applications, additional computing power may be necessary. Increasing computing power involves more than just adding computation units, it may also involve engaging additional interface hardware, and introducing new challenges related to software solutions for interfacing between computation units and allocating computing resources. Re-engineering the HIL system may be required to address such challenges.

However, with a well-thought-out design, it is possible to create a more flexible HIL system that requires minimal reconfiguration for similar projects. This involves careful planning and possibly the implementation of modular design principles, which allow for easier modification of simulation models, and swapping of components and interfaces (e.g. parameter settings or physical connections).

A significant drawback of not having a system/string test is that the power carrying components are not tested. For example, risk of defects in the production must be addressed during the FAT; the thermal stress during full-load operation can only be assessed during the commissioning on-site and the same applies with the actual efficiency of the system.

The way to offset this drawback is by relying on sound design and execution process, and by having a good fidelity model, that helps bridge the gaps between ideal and actual components behavior. For example, torsional resonances issues can be addressed via a Hardware-in-the-Loop, provided an accurate model is generated, losses in different components can be taken into account and modeled to some extent.

C. Benefits

While the design and build up of a HIL system can be time consuming and a substantial investment, the benefits it offers are significant across all phases of a project. It can help decision making, project acceleration, significant risk reduction, cost savings, technical support and provides comprehensive training.

1) **Risk mitigation:** Tests are made with the goal of increasing confidence and reducing risk. Testing a physical system in the real world often presents significant challenges and major cost, especially for large industry system. The testing team frequently needs to collaborate with different parties and spend time to prepare tests, although the scope of testing is often limited to prevent damage or disruption to other equipment or systems that are in operation. The efficiency and coverage of testing with real systems are considerably lower than a digital test system.

A HIL system can provide a virtual testing environment. This means it can offer a risk-free testing environment where extensive testing can be conducted without causing any damaging to physical equipment, system or infrastructure. This allows engineer to perform any type tests with high efficiency and minimal preparation, including some type of tests that might be challenging or potentially harmful scenarios that would be difficult to be performed with the physical system, such as grid voltage variation testing, and short circuit testing. With the comprehensive and efficient testing capabilities of the HIL system, engineers can test systems fully to identify issues, design failures and potential technical risks at an early stage.

2) **Project execution:** A HIL can provide significant cost savings for a project. The cost savings can come from various areas, such as accelerating the design process, avoiding costly rework by catching design flaws early, detecting and resolving issues before physical implementation, and providing cost-effective testing to avoid development of expensive prototype test strings, which can range from two to ten times the cost of a HIL.

Furthermore, any troubleshooting or test activities do not occupy or impact the real equipment and ongoing production.

3) **Systematic improvement:** A HIL system allows extensive testing of all components in a repetitive and systematic way. This allows the operator to understand the system, its behavior under several circumstances and take action when needed.

Being able to repeat tests with the exact initial and boundary conditions allows to close the loop and improve the overall plant behavior.

Furthermore, having a HIL system means to have a “digital copy” of the real installation. The analysis and test phase does not need to stop after the project is commissioned. On the contrary, continuous reassessment can be made to verify new scenarios or mutating circumstances, at any point in time.

4) **Training:** As the real control hardware is in use, the personnel working on a HIL gets an identical experience as if it was running a real installation, without the risk of injuries or damage to any equipment. Trainees can practice operation and learn from mistakes in a safe environment.

Unlike other methods, a design-dependent HIL system can potentially offer a partial or full-scale interface with overriding control system, such as the Power Management System (PMS) and the Power Distribution Control System (PDCS). In such setup, the HIL system emulates the actual system in the real world, leading the overriding control to believe that it is interacting with the actual system. This setup not only provides the benefit of operating the HIL system directly from the overriding control system but also offers the possibility to test the overriding control system in a safe environment without cause any damages, enable to detect design errors and functionality issues of the control functions.

5) **System level understanding:** Once the model is established, virtually any quantity in the installation can be scoped in a HIL system. Being it of electrical, magnetic or mechanical nature, all quantities can be scoped and observed. This is in stark contrast to a real installation, where measurement is usually only available in spot points in the system.

Industrial systems often include many different equipment and complex control systems. It is a challenge for engineers to develop a better understanding of the entire system. Comprehensive trainings are required for application engineers to become familiar with system operation, maintenance and troubleshooting. HIL system allows trainees to interact with a real-time simulation of the system as they operate the actual system. It provides a training opportunity for engineers, from critical equipment (such as SFC and VSD) to a system-level operation in a safe environment, preventing any damage caused by incorrect operation and promotes effective learning.

IV. CASE EXAMPLE

A. Background of project needs

For the electrification of a Norwegian offshore platform, a full "digital testing system" was built to fulfill various needs:

1) Validation of the system design, which would not be easily feasible on a full-scale
2) Validation of the power distribution control system (PDCS) interface, logic and sequencing
3) De-risking the commissioning process by extracting the parameters used in the power electronic converters, which are implemented on the full-scale converters.
4) Converter operation training
5) Power system operation training

The digital test system was comprised of both SILs and control HILs as shown in Fig. 7. A SIL was created for two active-front end variable speed compressor drives (VSD), while a control HIL was created for each of the two SFC's, refer to Fig. 6. This provides actual converter control software to be utilized for simulation and testing. With the support of the system integrator, EPC and customer, the grid system was modelled into the HIL hardware, which includes the network and load behaviors, system components such as subsea cables, and other variables that are crucial for performance. The actual digital test system is shown in Fig. 8.

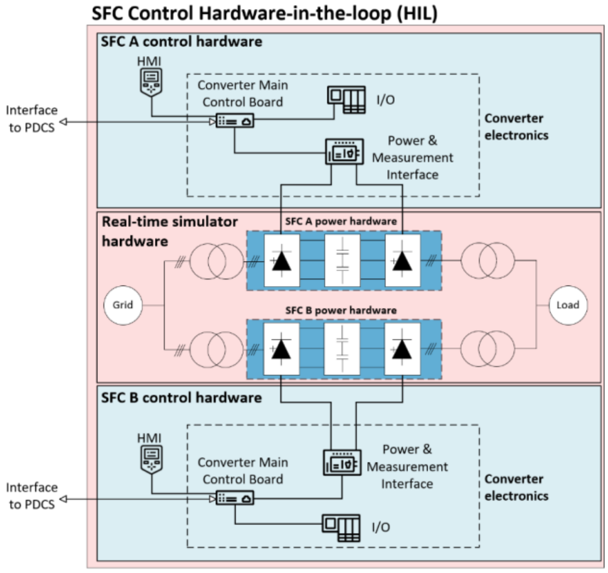

Fig. 6: Overview of SFC Control HIL

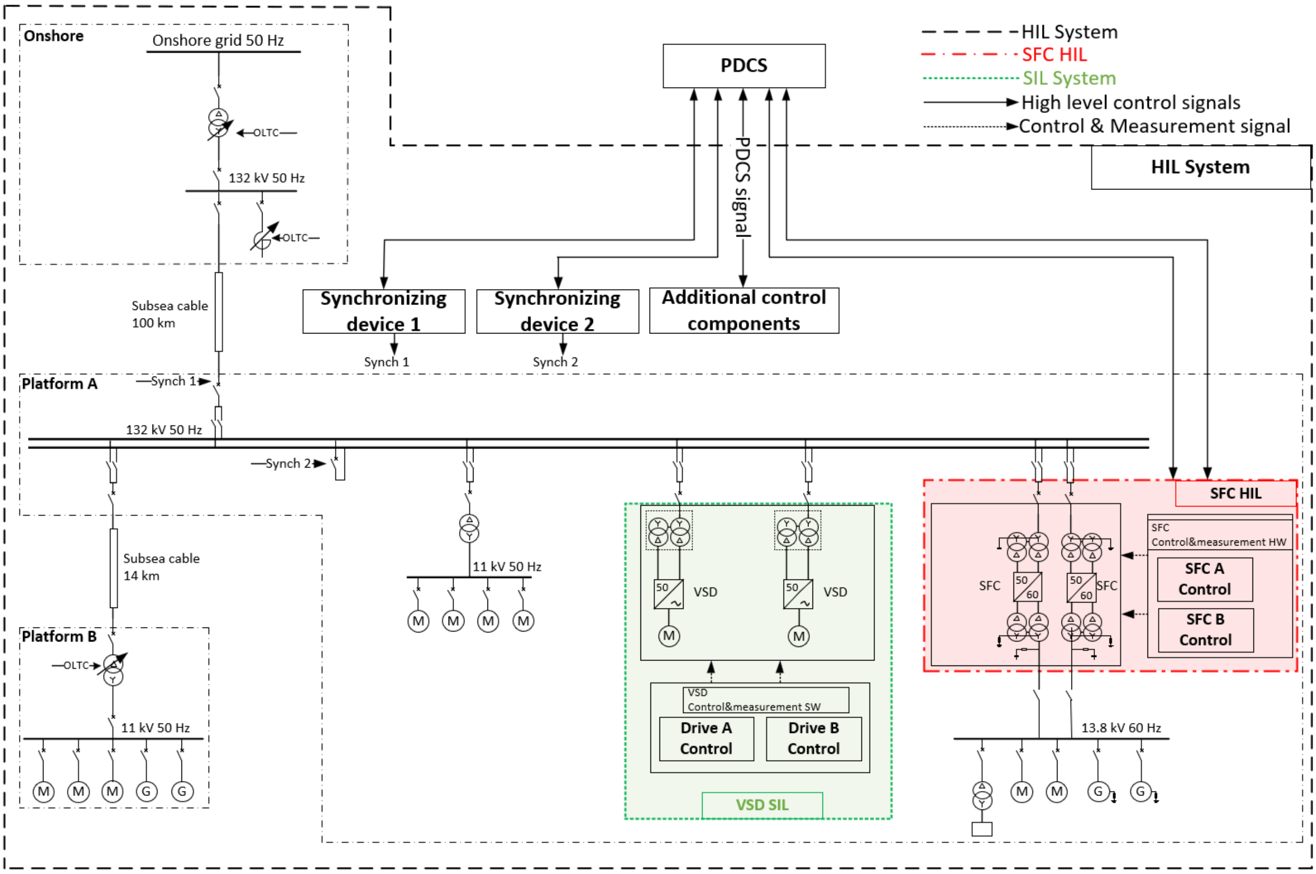

Fig. 7: Single-line diagram of Project HIL compromised of VSD SIL and SFC Control HIL

Fig. 8: Actual digital test system for Norwegian project

B. System description

As seen in Fig. 7, the entire power system is complex. The system for the case example includes four different grids, the onshore 50Hz grid, platform A 50Hz grid, platform A 60Hz grid, and platform B 50Hz grid. From a different perspective, it can be seen that there are three independent power sources within this system, the onshore grid at 50Hz, generators on the platform A at 60Hz, and Generators on the platform B at 50Hz as exemplified in Fig. 9.

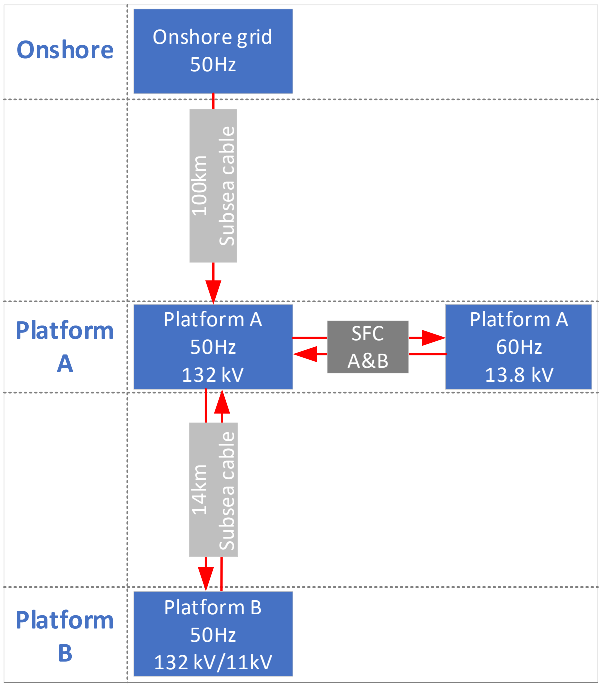

Fig. 9: Overview of power sources for platform electrification project

The onshore grid is connected to the platform A 50 Hz grid via a 100km subsea cable. The power flow direction is always from the onshore grid to the offshore networks. Two SFCs serve as the interconnection point between the two different frequency power networks on platform A. The power flow direction through the SFCs is determined by the power requirement of the system at any given time. Another subsea cable connects the platform A 50 Hz network to the platform B network, allowing transfer of power between these two platforms as needed.

Depending on the platform production and the onshore grid power capability, the system needs to be operated with different operation modes (network configurations). The operation model can be categorized into three types:

1) Power from onshore
In this scenario, onshore grid is the only power source, and supplies all the required power for offshore platform activities. The SFCs need to be configured with the power direction from 50Hz towards to 60Hz, to supply the platform A 60Hz grid.
2) Power from onshore and platform generators
In this scenario, the SFC can be configurated with the power direction towards either 50Hz or 60Hz side, depending on the onshore grid power and the availability of platform generators.
3) Offshore power mode
In this scenario, the platform generators supply all the required power for platform production. Depending on the availability of platform generators, the SFCs can be configured with the power direction towards either 50Hz or 60Hz side.

All the network configurations are listed in the table below:

Oper. Mode	**Onshore Grid**	**Platform A Gen.**	**Platform B Gen.**	**SFCs**
1	Available	Off	Off	50Hz→ 60Hz
2	Available	On	Off	50Hz→ 60Hz
3	Available	On	Off	60Hz→ 50Hz
4	Available	Off	On	50Hz→ 60Hz
5	Not available	On	On	50Hz→ 60Hz
6	Not available	On	On	60Hz→ 50Hz
7	Not available	On	Off	60Hz→ 50Hz
8	Not available	Off	On	50Hz→ 60Hz

A system with different configurations needs to have different power system control strategies. The characteristics of the system such as system impedance, short circuit capability, load capability, will be different when changing the system configuration. For each configuration, the system needs to be analyzed to ensure the design is appropriate, the equipment selection and setup is correct, and the impact from the system configuration changes is minimized. Typical analyses include load flow analysis, energization, load change, synchronization, network disturbance, short circuit, operation mode transition, and more.

C. Test scenarios

With the purpose-built digital test system, a multitude of scenarios can be tested for performance and pre-commissioning. Scenarios to be tested were defined into categories/sub-categories specifying power system configuration and mode as a basis for the case study, along with details regarding online components, system loads, SFC configuration, etc. The table below lists typical tests for the given example project:

Category	Type of testing
1	Network Synchronization
2	Networks Configuration
3	Equipment Energization
4	Stable Operation
5	Black Start
6	Load Change and Transient
7	Short Circuit
8	Grid Disturbance
9	Operation mode Transition
10	PDCS Test

Furthermore, the control mode and parameter settings of the generators and SFCs can be tuned throughout these tests. This includes settings for grid forming or grid following and droop control.

V. CONCLUSIONS

This paper has presented different testing environments and the value of a digital testing framework throughout the platform electrification, power from shore, projects. As projects develop throughout the stages more accurate test systems can be utilized not only to validate the system but also to significantly de-risk the commissioning of the system and operational conditions. The benefits continue throughout the operation of the system as training and further system troubleshooting can be done. In the case example of a Norwegian platform electrification project, a digital test system, which contained a SIL for VSD compressors and a control HIL for SFC's, was built for this purpose which tested grid system behavior, over-riding control interfaces, and multiple frequency converter logic and performances.

VI. ACKNOWLEDGEMENTS

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VII. VITA

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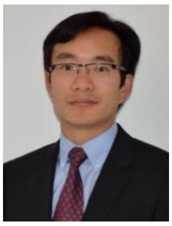

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