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Development of Reliable Power Electronic Systems using Real Time Digital Twin Based Power Hardware-in-the-Loop Testbed

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Abstract—Reliable Power Electronic Systems (PES) are vital for enabling energy transition technologies of the future. Power hardware-in-the-Loop (PHIL) test bed can be used to validate such systems cost-effectively and time-efficiently. In general, the Real Time Digital Twin (RTDT) is a virtual representation of the PES and its operating environment that mimics its behavior in real-time to provide adequate flexibility to the test bed. The workflow of alternating between the prototype and twin, for instance, overcomes the dilemma of needing 100 % details (due to fast dynamics), but optimization during design choices requires cheap flexibility. In this paper, some use cases in applications of RTDT-based PHIL test bed such as fault tolerant converters, power electronic interface for green technologies, survivable all-electric ships, mission profile-based reliability testing, protection of multiterminal dc systems and reconfigurable hybrid ac-dc links is discussed. Furthermore, the co-simulation potential of real-time platforms is briefly described.

1. Introduction

Multi-domain simulation tools are essential for designing mechatronic (mechanics, electric, and electronics) systems and authenticating their operational characteristics [1]. Specifically for power electronics-based energy transition systems, complete life-cycle management can be accomplished using a Digital Twin (DT) that accurately reflects its operating states so as to map the physical body into a virtual body [2]. For developing DT, simulation applications are laying a crucial role. Furthermore, simulation tools are getting more powerful in the way that the behavior of a physical object can be determined due to physical force on it [3]. DT includes the use of simulation, workflows, and seamless simulation along with life cycle phases. From the simulation viewpoint, DT will be the next level in modeling, simulation, and optimization technology, as shown in Figure 1 [4].

In an attempt to clarify the distinction between a DT and a system model, [5] suggests that DT is the highest

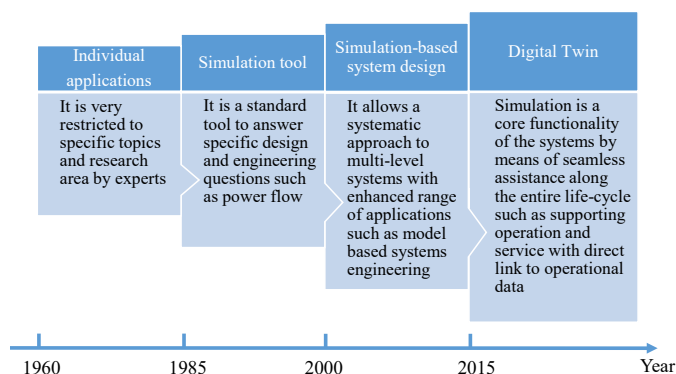


Figure 1: Different waves of simulation technology [4].



Figure 2: Concept diagram of RTDT interfaced physical system.

fidelity computation model that is as close to real-time as possible. Since there is no clearly defined boundary for the fidelity level of the model and clock time for this distinction, we can relax our definition to encompass all system models as fundamentally some form of DT representation of reality. However, Real-Time Digital Twin (RTDT) is a specific class of DTs required when a part of the physical system is integrated with it, as shown in Figure 2. The utility of such a test bed is that it effectively combines the flexibility of software simulation with the fidelity of a physical system in a real-time environment.

Such Power Hardware-in-the-Loop (PHIL) set-ups are a cost-effective and scalable means for de-risking experimen-

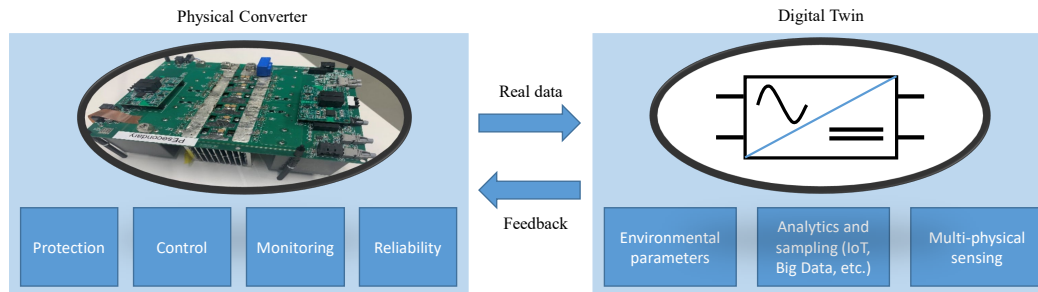


Figure 3: An overview of using DT for PECs.

tal validation of the developed models [6]. Specifically, one or more of the following technical challenges are addressed by utilizing the RTDT-based PHIL test beds:

- Flexibility of RTDT offers a practical and scalable way of realizing very large systems such as electrical networks and high power/voltage multilevel converters. Furthermore, different test scenarios and configurations can be described in real-time simulation, which is difficult to achieve in a reasonable time frame in research labs.
- When fidelity of actual hardware is difficult or impossible to achieve through simulation. This aspect is particularly valid for reliability research because wear-out mechanisms are probabilistic and can never be modelled accurately.
- Real-time clocking is necessary to ensure response validity during fast transients, and random behaviors must be investigated. This is very important for the following goals:
 - Co-simulation of software platforms offering simulation models for different research domains and/or different functionalities.
 - Demonstration of innovative concepts at a higher Technological Readiness Level (TRL-3 or above).

The rest of the paper is organized as follows. Some use cases for implementing RTDT-based PHIL testbed for research in reliable power electronic systems are discussed in Section 2. Section 3 describes the co-simulation on real-time platforms. Finally, the conclusions are given in Section 4.

2. Use cases for Power Electronic Systems

2.1. Fault Tolerant Converters

Most advanced simulators for Power Electronics Converters (PECs) are specified to address one specific problem or investigate a particular part of the system; hence, they result in different descriptions of simulators. Real-time emulation of device-level PEC models is critical by providing precision prediction of element stresses to lay out better control and protection methods. Developing a trustworthy, adequate, and cost-effective PEC requires multiple replications on costly and time-consuming hardware prototypes. Therefore, real-time hardware-in-the-loop (HIL) simulation

systems such as DT can display a substantial role in getting the real system behavior and reducing the cost in the primary design stage. With PECs models, the system's primary circuit is created to evaluate the voltage and currents at various points. In PECs, the system is characterized by multiple requirements such as power transmission, harmonics, time-related load movement, electromagnetic compatibility, fault-tolerant operation, condition monitoring, etc. [7]. By applying DT, as shown in Figure 3, all previous problems can be addressed, and accurate models of PECs can be achieved [8].

PECs are susceptible to errors and may be exposed to mechanical vibrations and electromagnetic interference (EMI) since they contain a control portion, a power circuit, and different sensors, among other things. Due to these problems, fault detection and maintenance analysis in PECs has emerged as a crucial topic that can reduce deviations and transients. While offline simulations might aid in analyzing an uncommon scenario in a specific area, simulating numerous irregularities and defects throughout the entire PECs would be difficult. Therefore, using DT and real-time HIL in this field is crucial [7]. As previously stated, timely defect detection in PECs is essential for availability, reliability, and safety. It is crucial to gather, compile, and process precise data on the technical status of the equipment to reduce the failure risk in PECs. It can offer a forecast for any damage to the electric machinery. Following PECs infrastructure, condition monitoring is fault diagnosis and maintenance [7], [9].

2.2. Robust Interface for Green Technologies

Power electronics for high-power electrolysis require careful design and consideration. The application's low voltage and extremely high current requirement impose constraints for component selection and selected topology of the converter interface [10], [11]. To handle the significant operating current requirements, modular power electronics exhibit much potential. It can be time-consuming and costly to experimentally validate different system configurations and their robustness to different fault scenarios. Therefore, developing an RTDT-based PHIL testbed of such a system, as shown in Figure 4, is essential. A digital twin of the modular converter along with an electrolyzer can be mod-

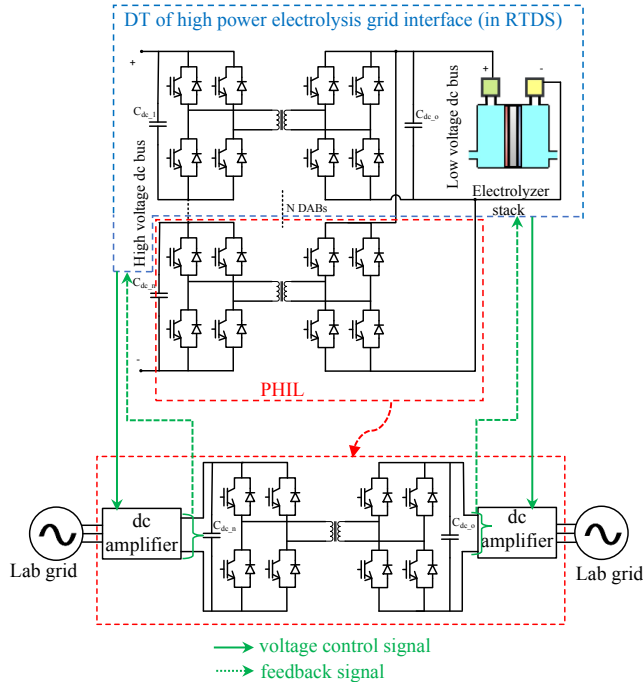


Figure 4: Power hardware-in-loop setup for robustness assessment of high power electrolysis grid interface.

eled in a real-time simulator such as an OPAL-RT. One of the converter modules can be integrated as PHIL with this digital twin, as shown in Figure 4. The data such as stack voltage, current, and hydrogen production profile can also be shared in real-time if the electrolyzer is present as PHIL.

2.3. Survivable All-Electric Ships

With the goal of minimizing the global environmental impact of shipping, a shift in the maritime industry is observed toward all-electric ships (AES). Future AESs are designed using dc shipboard microgrids (dc-SMGs), in which a smart dc system architecture is used to connect shipboard loads like the propulsion system to the power generation modules (PGM) as fuel cells. Current dc-SMGs need to be evaluated in terms of their reliability when operated in hostile environments. Therefore survivability is emerging as one of the critical aspects of future dc-SMG design. Following [12], the survivability of an integrated power system (IPS) is defined by three stages: susceptibility, vulnerability and recoverability. While susceptibility and vulnerability are concerned with minimising the risk of an impacting hit, recoverability involves the ability of the power system to recover after a system failure. Due to the high number of components, large-sized IPSs become complex to model with high fidelity. This complicates the verification and/or demonstration of the power system's recoverability and survivability requirements under different test scenarios.

A solution to verify design choices, like the dc system architecture or a PEC interface, is to develop a real-time

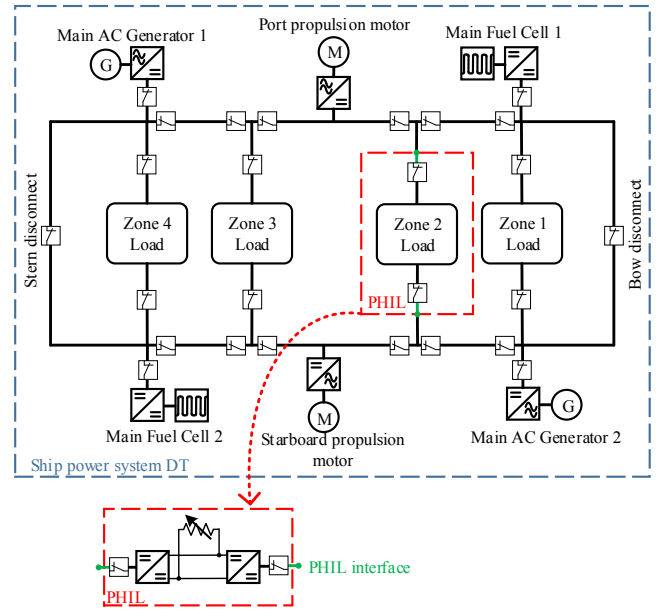


Figure 5: PHIL setup for recoverability testing of AES.

DT of the IPS with PHIL. An example is given in Figure 5, which shows a PHIL simulation of a DC zonal electrical system (dc-ZED) adapted from [13]. Herein, the dc-ZED is implemented as a RTDT, with load zone 2 implemented as PHIL. Using this simulation structure, the zone's power availability and load stresses can be tested during system faults for various PEC choices and IPS implementations. Further, a performance comparison can be made for different fault management strategies. Using the RT simulation, strategies using different reconfigurability schemes will have different recoverability performances. Therefore, the RT simulations can help improve an AES's survivability during its design phase, allowing for better choices in terms of the system architecture, PEC interfaces, and fault management strategy. This is done by utilizing both the DT's flexibility and the HIL's fidelity.

2.4. Test for Reliability based on Mission Profile

Power electronic modules break down slowly over the years, mainly due to thermal cycles associated with the mission profile of the converter integrated with the larger system. The probabilistic deterioration processes change the characteristics of the modules over time. This in turn effects the impact of stress related deterioration of the module. Such system behavior can be simulated in a real-time platform such as OPAL-RT, while the actual stresses can be replicated on multiple identical test samples using a power cycler, as shown in Figure 6.

Since multiple test samples represent the same module simulated in the system, the statistical data on its breakdown characteristics associated with the mission profile can be obtained. Furthermore, with the real-time data sharing between the OPAL-RT and the power cycler, the impact of

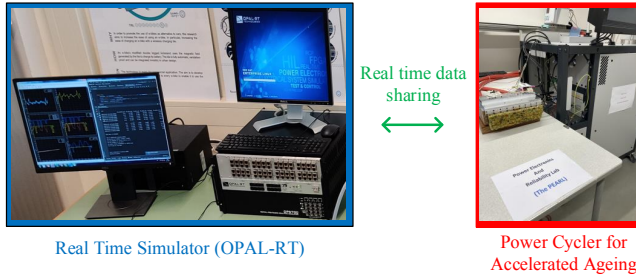


Figure 6: PHIL setup for reliable power electronic systems with ageing characterization using power cycler.

variation in device characteristics on the converter system as well as condition monitoring methods, can be studied.

2.5. Protection of Multi-Terminal DC Systems

Stringent requirements of protection in DC systems restrict the process of fault isolation to a few milliseconds from fault inception [14]. Time-domain-based fault detection algorithms have merit (in comparison to traveling-wave-based methods) of robust performance against high-impedance faults using low computation [15]. As a trade-off, time-domain-based methods inherently depend on parameters (unit resistance, inductance, and capacitance) of overhead lines (OHL) and underground cables (UGC) for fault detection [15]. DC fault transients are low-frequency, meaning the maximum contribution in the total fault impedance is of the inductance of the line (in comparison to DC steady state impedance, which is merely resistive). The contribution is further complemented by the external modification of current-limiting reactors (CLRs) used to limit the rate of rise of current upon a DC fault inception [14]–[16]. This means that any variation in the true value of unit inductance may jeopardize the selectivity and dependability of time-domain-based fault detection algorithms [15].

Since regular monitoring of system parameters is inconvenient and challenging, a real-time DT of UGC and OHL would give accurate values of line or cable parameters. As shown in Figure 7, the inputs can be used to model the line or cable parameters in RTDS. The line parameters would be adaptively adjusted to their true values (r, l, c), which could be then used by the time-domain-based algorithms to detect faults in a multi-terminal DC system. This ensures the selectivity and dependability of the time-domain-based protection algorithms with the inherent merits of low computational burden and robust performance.

2.6. Reconfigurability in Hybrid AC-DC Links

Reconfigurability in the hybrid AC-DC distribution links is being researched due to several benefits such as improved efficiency, increased reliability, enhanced flexibility, reduced costs, and improved power quality [17], [18]. A concept

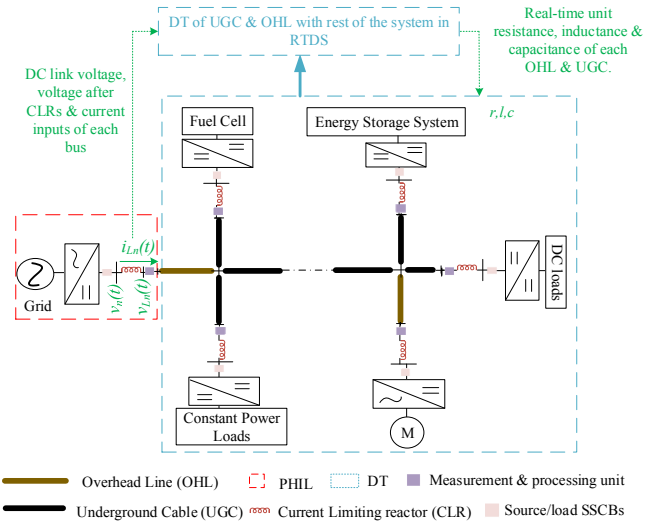


Figure 7: PHIL setup for selective and dependent protection of multi-terminal DC systems.

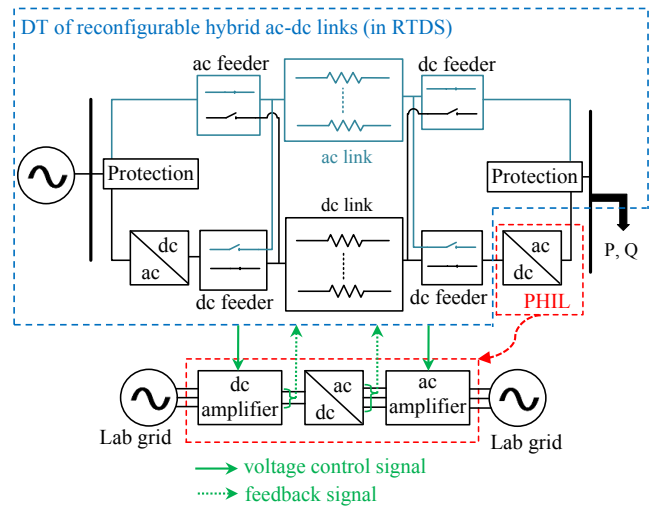


Figure 8: PHIL setup for reconfigurable hybrid ac-dc links.

of offline reconfigurability of such a system is reported in [17]. However, implementing and testing such systems in real time is challenging, complex, and costly. Therefore, the DT with PHIL of this system could be an alternative to test and validate the new configurations and algorithms for a real scenario. Figure 8 shows an example setup of DT with PHIL of reconfigurability in hybrid AC-DC links in case of faults and/or capacity enhancement during (n-1) contingencies. In Figure 8, a digital model of the link's hardware and software components, as well as a representation of the link's operating environment, is highlighted in the blue box, and the PHIL part (i.e., dc/ac converter) is in the red box. In PHIL, dc and ac amplifiers are used at the input and output of the dc/ac converter, respectively, and the power is fed back to the lab grid. The voltage control signals (marked in the green arrow) for dc and ac amplifiers are generated by

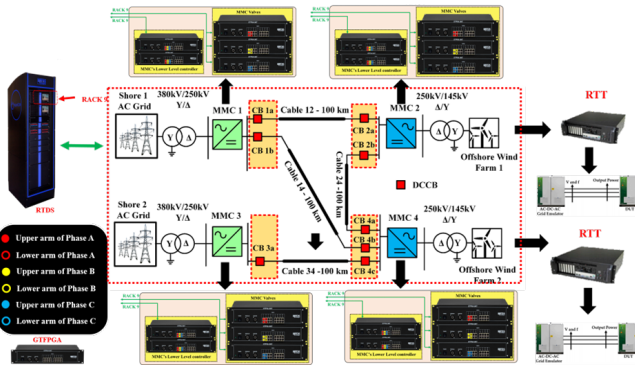


Figure 9: An example of the implementation of the power system in RTDS.

DT, and the feedback signals are given back to the DT. This setup would be able to simulate and test the functioning of the link under a range of conditions, including variations in load levels and configurations of the link in case of link fault(s).

3. Co-simulation on Real-Time Platforms

3.1. RTDS-based Co-simulation

The PE-based power system can be implemented using RTDS (and its simulation tool RSCAD), which represents the state-of-the-art power systems real-time simulation platform. It is possible to achieve software- and hardware-in-the-loop simulations with different amounts of details. The RSCAD/RTDS supports different implementations of converters. For example, MMCs are available averaged, then less complexity GTFPGA U5 model, and generic model with the huge amount of details also implemented in GTFPGAs. The choice of the model specifies the amount of modeling details and the RTDS calculation speed, which can vary from $1 - 2\mu\text{s}$ to milliseconds. This modeling enables studies for controller interoperability, $N - 1$ test (e.g., wind farm disconnection), AC fault analysis, DC fault analysis, change in grid topology, step change of active/reactive power, converter's submodule fault, and controller delay analysis. For the co-simulation, following the principles depicted in Figure 9, the RTDS can be linked to the physical device following Aurora communication protocols, IEC 61850 standard, or similar. PHIL can be formed using various devices. Namely, the RTT can be used, as seen from Figure 9, protection relays, converters, or even cables as it was done for the PROMOTiON project.

RTDS environment offers high flexibility regarding on-line and offline reconfigurations in the power system. Namely, it allows real-time Python or MATLAB-based scripting of the system's parameters, which is very useful for the software-in-the-loop (SIL) simulation. One example of real-time SIL is reading the measurements in the North Sea and adjusting operating states accordingly, as described in [19].

4. Conclusion

In this paper, a real-time DT-based PHIL test bed for reliable PES has been explained, which is a cost-effective and time-efficient way to test the system under development. Some use cases applications such as fault-tolerant converters, power electronic interfaces for green technologies, survivable all-electric ships, mission profile-based reliability testing, protection of multiterminal dc systems, and reconfigurable hybrid ac-dc links have been discussed using this test bed. Besides that, the RTDS-based co-simulation for PE-based systems is also described. Thus, this work shows the potential use of a real-time DT-based PHIL test bed to research popular and new areas.

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