IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 6 August 2024, accepted 27 August 2024, date of publication 30 August 2024, date of current version 10 September 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3452468

TOPICAL REVIEW

Power Systems Simulation and Analysis: A Review on Current Applications and Future Trends in DRTS of Grid-Connected Technologies

MOHAMMAD RAJABI NASAB[1], (Graduate Student Member, IEEE),
ROBERTO COMETA[1], (Graduate Student Member, IEEE),
SERGIO BRUNO[1], (Member, IEEE), GIOVANNI GIANNOCCARO[2],
AND MASSIMO LA SCALA[1], (Life Fellow, IEEE)
[1]Department of Electrical and Information Engineering (DEI), Polytechnic University of Bari, 70126 Bari, Italy
[2]Department of Industrial Engineering, University of Naples Federico II, 80138 Naples, Italy

Corresponding author: Mohammad Rajabi Nasab (m.rajabinasab@phd.poliba.it)

ABSTRACT Real-time simulation is a well-established approach employed across various domains, predominantly through Hardware-In-the-Loop (HIL) simulation. HIL technology enables more realistic simulations of complex systems, usually achieved by a closed-loop scheme between the hardware under test and the real-time simulator. In the field of power systems, it is also progressively deployed not only for academic aspects but also for industrial applications. A HIL model takes advantage of such merits as alleviating the risk of damage to the major real objects and reducing the cost as well as tedious efforts during the test. Besides, the evolution and increasing computing power of real-time simulators promise the capability to reach more accurate models that closely represent reality. Accordingly, this manuscript aims to investigate some applications of HIL grid-integrated technologies in transmission systems and discuss some future trends and scopes correlating to this context.

INDEX TERMS Power systems, transmission systems, real-time (RT) simulation, hardware-in-the-loop (HIL), power hardware-in-the-loop (PHIL), control hardware-in-the-loop (CHIL), hardware under test (HUT), device under test (DUT), phasor measurement unit (PMU), wide-area protection transmission networks, substation automation system (SAS).

I. INTRODUCTION

Digital Real-Time Simulation (DRTS) is a practical tool for analyzing the realistic behavior of equipment in power systems. Thanks to the advanced hardware and parallel computing methods, Real-Time Simulators (RTSs) can solve the differential equations that represent the power systems in Real-Time (RT) [1], [2]. Moreover, by adopting Hardware-In-the-Loop (HIL) simulation, a virtual power system can be connected to a real device, often called Device Under Test (DUT) or Hardware Under Test (HUT). The HUT can be either a single piece or a set of hardware of the system of interest, which analyzing its behavior and impacts is the main objective [3]. The major advantage of such configuration is allowing to achieve a realistic, safe, and reproducible test environment where the system can be studied under various conditions with the least possible risk, and avoiding cumbersome tasks or expensive measures [4].

The HIL-based RTS, roots dating back to the mid-20th century, was initially used for aerospace applications to evaluate complex control systems [5]. It started with analog components and basic computing, but progress has led to more sophisticated models and RT interactions between simulated and physical components [6]. An exemplary application is evident in the automotive industry, where TOYOTA used HIL technology during the development

The associate editor coordinating the review of this manuscript and approving it for publication was Kai Song.

of the TOYOTA Prius electric car [7]. They extensively used HIL simulation to optimize control algorithms and the powertrain system, resulting in improved energy efficiency and performance [5], [8]. Beyond aerospace and automotive, HIL simulation has found applications in various industries, including power systems and industrial automation. Today, it stands as a valuable technique, offering a safe, cost-effective, and efficient means to test complex systems, validate control strategies, and facilitate the development of cutting-edge technologies across multiple domains.

The most significant distinction between DRTS and non-RT simulations is the time execution aspect. In DRTS, the simulation runs in real-time, meaning it processes inputs, executes calculations, and produces outputs at the same rate as the real-world system under simulation. This RT aspect is crucial for designing and validating time-sensitive applications such as control algorithms, protection schemes, and so on, in power systems. Note that it is vital because it allows the evaluation of the system's performance under real-world conditions and identifies potential issues that might arise during actual operation [4]. In DRTS, achieving accurate time synchronization between the simulation and the real world is a fundamental issue, especially when interfacing with physical systems. Latency, the time delay between inputs and corresponding outputs, must also be minimized to ensure the simulation accurately reflects real-world conditions [9], [10].

Three widely used simulation models in DRTS-based power system studies are the averaged, phasor, and Electro-Magnetic Transient (EMT), or maybe, a combination thereof [11], [12]. Each model offers distinct features, accuracy levels, and computational complexities, making them suitable for different applications within the power system domain [13], [14]. In other words, each model can be deployed based on the desired level of detail for the study and HIL testing. Utilizing detailed component models of the system enhances the accuracy of dynamic modeling for test applications. However, this achievement comes at the cost of increased computational resources in the DRTS [15], [16], [17].

Considering the aforementioned points, it is worth stating that average model simulation simplifies power system behavior by representing complex elements with average values [18]. This model is efficient and computationally affordable for steady-state studies and long-term planning (e.g., power flow studies, load flow analysis, and steady-state stability assessments), where the variation in system variables occurs over relatively long periods [19], [20]. Phasor model simulation employs the phasor concept to represent power system dynamics. Phasors, which are complex vectors, capture the amplitude and phase angle of sinusoidal quantities in the system, striking a balance between simplicity and accuracy, and hence, making it suitable for medium-term stability assessments and control system design [21], [22]. The phasor model is particularly useful for transient stability analysis and small-signal stability studies, where one can assess the system's dynamic response to system perturbations [23], [24], [25]. Apart from previous models, EMT model simulation provides a detailed representation of power system dynamics by considering the actual physical behavior of individual components [26]. This model captures fast transients and high-frequency phenomena that significantly impact power system performance during disturbances [27]. EMT simulations are essential for analyzing power system responses to fast events such as faults, switching operations, and lightning strikes. While they yield accurate results, EMT simulations demand great computational resources and are primarily used for short-term or event-specific studies [28].

To sum up, It can be stated that, in the selection of an efficient simulation model, the crucial factor is to take into account the nature of the dynamics of the system/component [29]. The time range, or more precisely, the response duration of various potential phenomena in power grids, can be found in [30].

Shifting the perspective to another vantage point, RTSs play a pivotal role in developing models and designing innovative concepts across diverse applications, aiding in prototyping and eventual implementation. Prototypes, approximations of real systems, enable iterative testing and refinement. Rapid Prototyping finds increasing utility in RT contexts. Commercial RT simulators often integrate automatic code generators, bridging model creation and system implementation. Following prototype or device construction, RT testing under HIL conditions offers advantages by emulating real-world environments. Ongoing updates in teaching and training also are vital to match industrial and technological progress. This framework encompasses the various use cases of DRTS and HIL systems, supporting development, testing, and learning amid evolving industries and technology [1].

In the last decades, DRTS has gained significant attraction in both transmission and distribution system applications, primarily driven by advancements in smart grid studies [1], [31]. A noteworthy point is that so far, numerous review articles have comprehensively covered various aspects within the distribution networks domain, some of which are [13], [32], [33], [34], and [35]. In contrast, there appears to be a lack of a survey study that distinctively concentrates on exploring technologies related to the transmission side.

However, the growing complexity of modern power systems poses challenges for RT simulation, especially due to severe transient dynamics and the presence of high-frequency power electronic converters. Notably, the deployment of Modular Multilevel Converter (MMC)-based devices necessitates innovative approaches to handle the complexity of these technologies, including dealing with thousands of switches. Additionally, in the context of HIL simulation, the interface must possess the necessary bandwidth and consistency to accurately apply the required voltages to DUT. As another example, Internet-based infrastructures have opened up numerous possibilities for power system management, protection, and automation, which albeit pave the way for centralized and simultaneous monitoring of a large-scale system, introduces potential vulnerabilities, such as cyber-attacks that can manipulate system behavior by falsifying data [36]. What is of crucial importance in this area of study is to consider the real latency of communication devices for ensuring the reliable and efficient operation of power systems against such threats. To deal with such issues the necessity of providing a remote simulation platform including two or more separated real-world testbeds might be inevitable [37].

In light of the growing complexity of modern power systems and the increasing adoption of DRTS, this survey paper aims to provide an overview of DRTS applied in power system domains, encompassing a broad range of applications from general to specific, including HIL for simulation and monitoring of power systems. Moreover, these applications vary in their specific functions, serving purposes ranging from design and analysis to testing and instructing. Additionally, the paper delves into various DRTS types, such as EMT simulation, and also covers phasor or hybrid simulation. The objective is to summarize the current DRTS applications documented in the existing literature on power systems. Furthermore, the paper focuses on the application of HIL technology in transmission systems, where it appears to be at its early stages, compared to the number and extent of applications at low and medium voltages.

The rest of this survey paper is organized as follows: Section II provides an overview of different categories of HIL architectures. Section III delves into the current state-of-the-art applications of HIL simulation for power systems. In Section IV, some HIL-based laboratories are introduced. Section V discusses the future trends in the realm of DRTS application in modern power systems. Finally, Section VI is dedicated to draw the conclusions.

II. CATEGORIES OF HARDWARE-IN-THE-LOOP (HIL) ARCHITECTURES

In the realm of power systems, DRTS can be categorized into two distinct types. Firstly, fully DRTS, also named Software-In-The-Loop (SIL), Model-In-The-Loop (MIL), or Processor-In-The-Loop (PIL) approaches, and secondly, HIL-based RTS. In a full DRTS, the simulator encompasses the entire system, including control, protection, and other accessories, with no reliance on external interfacing or inputs/outputs (I/Os) [4]. On the contrary, HIL simulation involves replacing certain parts of the fully DRTS with actual physical components. In this mode, the simulation integrates the HUT connected through I/O interfaces, such as filters, analog-digital converters, and signal conditioners. Limited RT controls of the simulation can be executed using user-defined control inputs. In the literature, there are different architectures used in HIL simulation, depending on the nature of the system being tested, the specific requirements of the simulation, and the available resources and infrastructure. Not to mention that different industries and applications might have unique architectures tailored to their specific needs. However, a general description of various commonly used HIL architectures is provided in this section.

A. CONTROLLER HARDWARE-IN-THE-LOOP (CHIL) ARCHITECTURE

A HIL configuration can be called Controller Hardware-In-the-Loop (CHIL) as far as a real controller interacts with the simulated system [4]. In this case, there is no power exchange between the simulator and HUT, and the system (e.g., the power grid) is virtually modeled and interacts with the external real controller by exchanging I/O signals. For better clarity, a comparative visualization between the CHIL and other HIL architectures is shown in Figure 1 [38]. Table 1 presents a comparison between different architectures to assist in selecting the best-suited option.

B. LOW-POWER INTERFACE HIL ARCHITECTURE

In this kind of HIL architecture, the physical components interact with the simulated system through low-power signals, as shown in Figure 1a. However, sometimes the HUT can work with signals that are not compatible with the operating range of the I/O channels. Thus, it might be necessary to introduce signal conditioning stages between the HUT and the RTS [1].

In some cases, the HUT that interacts with the simulated environment can work with voltage and current levels which are significantly higher than those of the simulator. For this reason, interfaces for relatively higher voltages (e.g., 60 to 200 V) and higher currents (e.g., 5 A to 100 A) must be included, such as 2-Quadrant (2Q) power amplifiers. It is worth stating that for the sake of brevity, the term *"low-power"* is typically omitted when referring to this architecture.

C. POWER HARDWARE-IN-THE-LOOP (PHIL) ARCHITECTURE

A PHIL scheme, on the other hand, allows you to develop simulations in which there exist real power components such as batteries, controllable loads, microgrids, etc. As depicted in Figure 1b, in this type of architecture, a power amplifier (e.g., 2 or 4 Quadrants, 2Q or 4Q) is required. This equipment is installed between the RTS and the physical device and is responsible for managing the power flow toward the HUT. In particular, the reference/control signals generated by the simulator are sent to the power amplifier to apply the desired voltages and currents to the physical test system. Subsequently, the voltage/current values measured on the hardware side are feedback to the simulator to close the simulation loop. This approach allows the investigation of the dynamic behavior of real electrical loads or a microgrid's apparatus within the simulated electrical model. Furthermore, PHIL-type simulations can be integrated with communication networks (CAN, DNP3, ARINC, IEC 61850, etc.), allowing the integration of multiple communication protocols in a single system [6], [39]. Concerning the benefits of PHIL simulation in realistically validating the behavior of relatively

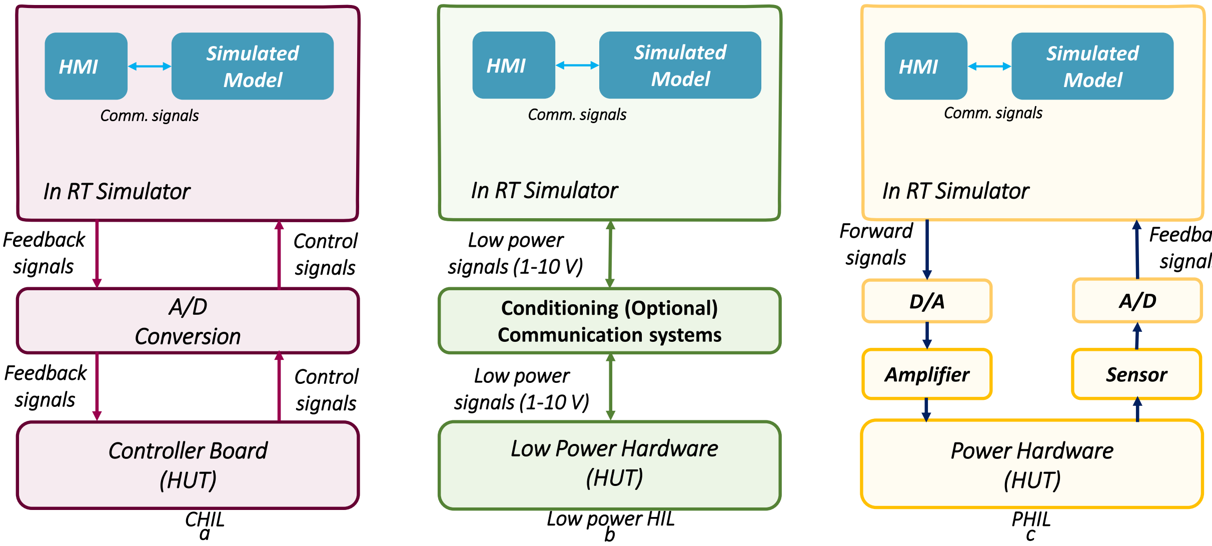

FIGURE 1. Different HIL architectures: (a) CHIL architecture. (b) Low-power HIL architecture. (c) PHIL architecture.

high power components [10], [40], it is important to consider its restrictions: 1) the inherent closed-loop time delays between the RTS and HUT can affect stability and must be managed; 2) the wider the system bandwidth, the more likely the setup will be unstable [41], [42]. There is a heated debate in the literature to address these obstacles and enhance the stability and accuracy of the PHIL testbed, some of which are explored in [31], [43], [44], [45], and [46].

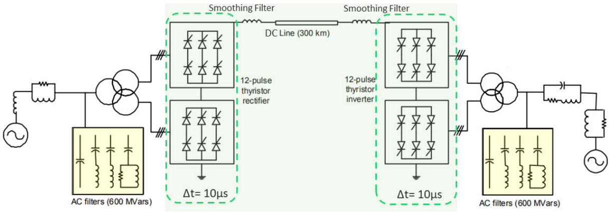

FIGURE 3. HVDC test loop simulated via SIL.

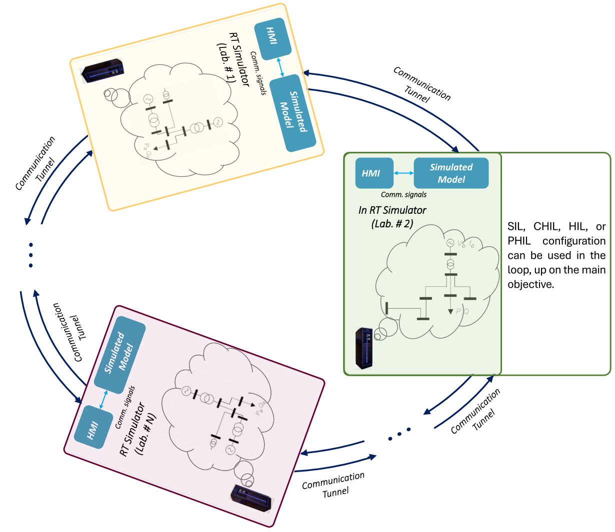

FIGURE 2. Remote architecture, laboratories-in-the-network framework.

D. REMOTE ARCHITECTURE

It is worth highlighting that previous architectures can also be deployed remotely, allowing for the remote testing of real hardware devices located in different laboratories and enabling collaboration between different laboratories by forming a *"laboratories-in-the-network"* framework [47]. This framework is based on geographically distributed simulation, which enables different research facilities to combine their capabilities to simulate complex systems and scenarios collaboratively. The general scheme of remote architecture is illustrated in Figure 2.

Remote setups are becoming increasingly important in the field of smart power systems. This interest might be because this platform paves the way for analyzing the efficient operation of advanced communication technologies as an indisputable part of modern smart grids. Moreover, the high costs of building fully equipped laboratories pose significant challenges for institutions looking to expand their research capabilities. Remote connections between laboratories offer a solution by allowing institutions to share resources, thus reducing the financial burden of developing facilities [48]. Table 2 provides some insights correlating the application of remote simulation in the realm of power systems.

Technical implementation of remote HIL setups involves exchanging electrical variables between laboratories via the Internet. A Virtual Private Network (VPN) is often used to ensure secure communication [49]. Various protocols, such as Modbus at the field device level and UDP or TCP/IP at the application level, facilitate data transfer for real-time simulation and testing [50].

TABLE 1. CHIL, Low-power HIL, and PHIL comparison.

Aspect	CHIL	Low-power HIL	PHIL
Simulation Purpose	Focuses on testing and optimizing control algorithms, usually before the availability of physical instruments.	Validates and analyses proposed algorithms or events using real components under simulated conditions.	Emulates real power system dynamics, components, and interactions.
Application Scope	Used for control algorithm analysis, development, and testing in various aspects.	Applicable to a wide range of power systems engineering domains.	Mainly used for power system and power electronics testing.
Incorporated Hardware	Typically uses lower-power and lower-voltage hardware components.	Includes physical hardware (sometimes reduced-scale) that closely matches actual system components.	Involves actual power components such as generators, transformers, converters, and energy storage systems.
Real-World Interaction	Focuses on RT testing and optimization of control strategies using limited hardware resources.	Simulates the interactions of monitoring, control, or protection algorithms with real or emulated components.	Reflects realistic interactions between power components, allowing accurate analysis of power system behavior.
Complexity of Setup	Setup complexity is generally lower compared to PHIL, due to the focus on control algorithm testing.	Setup complexity depends on the complexity of the proposed algorithms and the required hardware components.	Can be complex due to the integration of real HUT with interface devices and simulation systems.
Use Cases	Ideal for rapid prototyping and early-stage development of control algorithms before the availability of physical instruments.	Suitable for behavior analysis and design algorithm validation in different electrical engineering domains.	Best suited for testing power electronic devices, grid stability, renewable integration into modern grids, and LV/MV power systems.
Resource Requirements (Usually MV-LV applications)	Requires hardware with moderate power for testing and validation of control methods.	Requires components (sometimes scale-down) that sensibly represent the behavior of the actual system.	Requires high-power equipment and specialized hardware for grid emulation, e.g., the amplifier (see Figure 1c).
Flexibility (Compatibility)	Offers flexibility in terms of rapid iteration and optimization of control algorithms.	Flexible in terms of adapting various system configurations and control strategies.	Limited compatibility due to the need to interface with high-power hardware.
Safety	Offers a relatively high level of safety as it interacts with low-power control signals.	Can provide a safe environment for users that is also suitable for training purposes.	Safety cannot be guaranteed since it requires high-power or high-voltage equipment.
Cost Considerations	Generally is a cost-effective option due to the use of lower-power and lower-voltage hardware.	Costs can vary based on the complexity of the hardware components such as HUT, and proposed algorithms.	Typically require higher costs because of the need for high-power and specialized equipment such as amplifiers.

III. HIL INFRASTRUCTURE AND DRTS IN TRANSMISSION SYSTEMS APPLICATIONS

This section highlights the overall topics of interest in the technical applications of RTSs on power transmission systems. It is worth stating that DRTS applications in the power system are widespread, and this survey is not a thorough repertory but relatively serves to offer a panorama of different applications on frequently adopted test cases.

A. APPLICATIONS ON HIGH VOLTAGE DIRECT CURRENT (HVDC) SYSTEMS

In the last decades, system operators and regulators have envisaged the installation of HVDC connections for facilitating the management of energy flows from renewable sources and favor their development. In the cross-border context, these infrastructures make it possible to optimize the energy supply in the import stage and to have greater flexibility in terms of the production of Renewable Energy Resources (RESs) in the export stage. It is worth highlighting that different components including converters, AC equivalents, DC transformers, cables, and so on, could be modeled within an RTS, some of which are addressed in the following.

A SIL-based approach is investigated in [64] that uses an EMT model to simulate a real-time HVDC test scheme with two converters employing 12-pulse thyristors in a back-to-back configuration (see Figure 3). The primary focus is to analyze the fast-switching dynamics of the converters. The simulation adopts different time steps: 10 μs for the converters, 15 μs for the filter banks, and 50 μs for the rest of the model.

In another study [65], a phasor model for HVDC systems is presented, utilizing the quasi-periodic switching behavior of power electronic devices to offer a computationally efficient solution concerning a reasonable level of accuracy. This model represents voltages and currents using

TABLE 2. Types of collaboration of remote (Laboratories-in-the-Network) architecture.

Application	Description and Purpose
Model/Data Sharing and Integration	Laboratories would exchange data on various power system aspects in a co-simulation environment to provide a more comprehensive simulation, especially when studying the behavior of large-scale complex systems. This can enhance the realism and reliability of the results [51], [52].
Facility Sharing	Laboratories could also share their facilities like their measurement instruments or physical electric equipment as HUT. This would be a proper action to avoid constructing expensive fully equipped laboratories [53], [51].
Testing More Realistic Scenarios	Laboratories can also collaborate to develop and test various scenarios, such as extreme weather conditions or high levels of RES penetration in conventional grids, to explore their impacts and responses more comprehensively [52], [53].
Coordinated Experiments	Designing and conducting experiments where results from one laboratory's simulations serve as input for another laboratory's model/HUT, can pave the way for integrated testing of different system elements [54]–[56].
RT Distributed Analysis	Performing RTS with different components or models provides a suitable platform to analyze the dynamic interactions and time-sensitive events, i.e., allows for a more realistic investigation about how various elements of the grid interact and respond to varying conditions [47], [53], [57].
Smart Grids Challenges	Remote collaboration in areas such as smart grid integration with communication and IT infrastructure models can facilitate a holistic approach to ensure that interdependencies between power systems and communication networks are fully understood and managed [58]–[60].
Education and Training	Remote educational programs, such as training or workshops can be a proper way to share knowledge and best practices in simulation techniques and tools, enhancing skills and innovation, and also promote collaboration among researchers and practitioners [61]–[63].

time-varying Fourier coefficients, effectively capturing the system's low-frequency dynamic characteristics without the need for complex modeling of high-frequency transients caused by power electronic switch operations. Additionally, it can be easily extended to account for harmonic components.

Reference [66] introduces a novel approach for running the real-time EMT model of a Hybrid HVDC Breaker (HHB), using FPGA-based HIL emulation. The aim is to attain high-fidelity representation by configuring the HHB model to mirror its real-world counterpart. So, the model includes a thermal network that accounts for the heat produced by IGBTs, impacting their performance and junction temperature, which can enhance the models' accuracy by considering the thermal behavior of the devices. Three IGBT models, namely binary two-state switch, curve-fitting, and extended nonlinear behavioral are proposed to meet diverse accuracy and simulation speed requirements. Circuit partitioning is applied to mitigate both computational load and FPGA resource constraints associated with a complex HHB design. This technique divides each model into physically independent sub-circuits, permitting parallel processing to overcome complexity. Application of these models within a three-terminal HVDC system demonstrates their effectiveness in simulating line faults to trigger HHB protective sequences.

In recent years, ABB company has developed a fast-acting hybrid DC semiconductor circuit breaker that can quickly clear faults in a DC network with minimal losses. To test the protections for a HVDC link and ensure safety and reliability, authors in [67] and [68] use a HIL-type RTS. The test system at ABB's DC test Laboratory comprises three symmetrical monopolar converters connected in a radial configuration. They use ABB's Modular Advanced Control for the HVDC (MACH) platform in the HIL testbed, as shown in Figure 4, for controlling and protecting power system apparatus with high consistency to real-world behavior. To achieve fast simulation and reduce the computational burden, the AC parts are executed with a sampling time of 3 μs, while the DC parts are modeled with a higher time step of 50 μs. Measurement signals are exchanged between the RTS and the MACH system through analog and digital I/O ports. The MACH system sends switching commands to the simulated switches via Valve Control Units (VCUs). However, it is essential to consider communication delays in HIL simulation, particularly when fast control and protection actions are necessary.

Another application of DRTS in HVDC systems is proposed by the authors of [69]. They perform an RTS with CHIL configuration to apprise the replacement of the control and protection systems of the Japanese Hokkaido-Honshu HVDC link from analog to digital.

Lack of sufficient inertia is a concern that has emerged with the increasing integration of converter-based energy systems into the grid. It is worth stating that inertia, which stabilizes power grids by providing kinetic energy that absorbs demand and supply fluctuations, is diminished due to fast semiconductor switches in modern grids, rather than the mechanical rotation seen in conventional generators. This shift raises stability questions during abrupt transient changes such as load shedding, grid faults, etc. In [70], the authors deal with providing virtual inertia as an ancillary service of the 44-Bus Scandinavian grid (i.e., Finland, Sweden, Norway, and part of Denmark) by an integrated HVDC converter. The work is based on a scaled-down laboratory setup for PHIL testing, where a phasor-based RTS model of the network is combined with an MMC presenting a scaled model of an HVDC terminal.

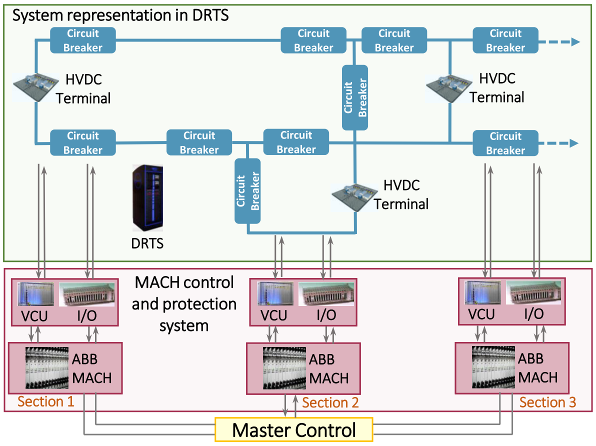

FIGURE 4. Three terminal HVDC HIL setup with ABB test facilities.

Given that MMCs typically employ hundreds of switches per arm in HVDC applications, simulating the entire system using detailed switching models in DRTS platforms can be computationally extensive and highly time-consuming. To enhance efficiency and accelerate simulation speed, reference [71] has utilized the average model to assess MMC performance under different operating conditions. However, the remarkable point in modeling MMC technologies is that due to the fast dynamics of the semiconductor switches, average models might not properly describe the component behavior in detail [72], [73]. Therefore, even when the calculation burden is high due to the large number of switches in MMCs, it might not recommended to rely on this model (evidently, in those scenarios where transient details are crucial and cannot be neglected). In an alternative approach, the paper [74] proposes an innovative method based on parallel processing to efficiently handle the computational demands associated with MMCs featuring a substantial number of switches.

As stated in Section II, the PHIL platform would be a great option to pave the way for analyzing the behavior of power electronic elements. However, to coup with the concerns about the stability and accuracy of this platform, [43] employs a simple low-pass current filter in the feedback path (see Figure 1c) to enhance the connection between the HUT and RTS and improve the stability margin of the PHIL setup. However, this filter influences the phase and amplitude of the feedback signal, and obviously, threatens the accuracy of the simulation. A remedy to improve both stability and accuracy of PHIL platforms has been addressed in [31], presenting a novel technique for interconnecting HUT, based on an external signal processing interface. Herein, All processes involved in signal processing and exchange between software and hardware were modeled as block diagrams, each with a transfer function detailing its impact on time delay and bandwidth. Using the Nyquist stability criterion, the outcomes have been compared with some existing methods in the literature [43], [44].

The emerging reliance of next-generation power grids on communication technologies, creates vulnerabilities to cyber-attacks [75]. In advanced grids with high integration of power electronic devices, cyberattacks on their control system can potentially threaten the grid's safety, and pose economic loss. With an awareness of this issue, a real-time time cyber-physical security testbed seems essential for testing and validating attack scenarios in a realistic environment. In this respect, [76] introduces an innovative real-time HIL cybersecurity testbed for power electronics in cyber-physical environments. This testbed provides extensive real-time cyber system modeling and HIL capabilities, effectively capturing the interactions and impacts of cyber-attacks on grid-connected power electronic systems. Integrating cyber and physical domains allows for the mutual reflection of events, enabling detailed analysis during cyber-attacks. Figure 5 illustrates the testbed's architecture, consisting of three main parts: 1) an RTS for accurate power electronics simulation, 2) a cyber system platform using an actual grid and server to mimic real-world cyber environments, and 3) penetration testing tools to perform real cyber-attacks and create authentic scenarios.

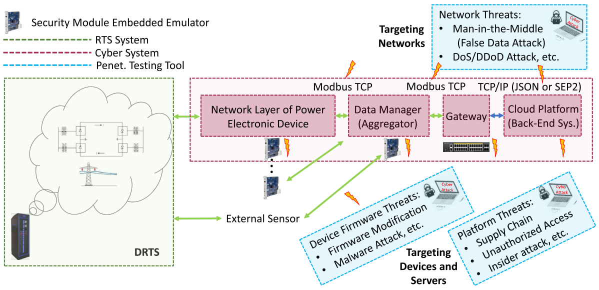

FIGURE 5. Diagram of the HIL-based Cybersecurity testbed.

B. APPLICATIONS ON FREQUENCY REGULATION

Thanks to HIL platforms and such modern measurement technologies as Phasor Measurement Units (PMUs), it is possible to study fast frequency phenomena on low inertia power systems. A PHIL-based study reported in [77] and [78], explains how Synthetic Inertia (SI) can be made through Battery Energy Storage Systems (BESS), controllable loads, and frequency controllers based on the Rate of Change of Frequency (RoCoF) [79]. However, this research area is mainly oriented toward investigating the performance of a protective device [80]. Reference [57] introduces a co-simulation testbed to deal with the under-frequency events in the smart grids, and [81] addresses the problem of detracting the inertia on the transmission network of Great Britain, a phenomenon due to the presence of the RES and HVDC connections. Therefore, the effectiveness of the Loss Of Main (LOM) protection concerning the deviation of RoCoF and vector shift is tested, with the aim of providing a suitable relay.

In the literature, a well-known remedy for frequency stability improvement and blackout prevention is to implement demand control techniques such as load shedding [82]. Keeping in mind that there is a direct relationship between

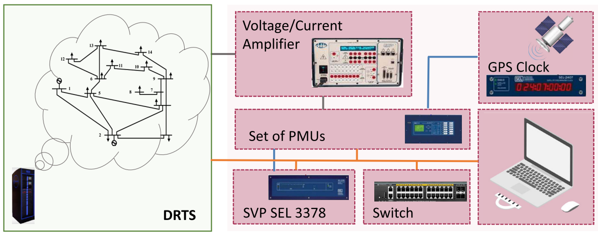

FIGURE 6. Connection between PMU, amplifiers, RTS, SVP, GPS clock, and LAN network.

active power and frequency, load-shedding action during under-frequency events can quickly restore the system balance. Although recent studies have focused on adaptive load-shedding mechanisms, these models are still based on the SIL test bed. However, [83] presents an RT implementation of a centralized and adaptive plan for load shedding through industrial hardware. Concerning the frequency reduction rate, this strategy not only estimates how much load should be disconnected but also distributes the electrical power between different loads depending upon the voltage reduction in those locations. It is worth highlighting that this centralized scheme takes advantage of GPS-synchronized PMUs to send required data to the central unit. As shown in Figure 6, the physical devices involved in the test loop are the PMU, Synchrophasor Vector Processor (SVP), and the RT simulator.

Another PHIL simulation correlating under-frequency load shedding is described in [84], in which an islanded electrical system is modelled. This model is developed to represent the frequency transients during the non-synchronous operation in a small territory. The tests have been carried out to explore the response of the system under relatively high penetration of RES. Other studies related to this field can be found in [85].

C. APPLICATIONS ON PROTECTION DEVICES AND INTEROPERABILITY

In the realm of modern grids, ensuring reliable and secure operation is paramount. This underscores the vital importance of monitoring and protection mechanisms, which safeguard assets, mitigate disruptions, and maintain power network stability. Hence, while this field of interest finds its context within other expensive and pivotal power equipment, as well as certain applications introduced in previous sections, this section is dedicated to delving into the application of DRTS on monitoring and robust protection strategies.

An RT environment can be used to test protection tools and fault ride-through enhancement strategies. Based on the synchrophasor data provided by PMUs with different communication standards and protocols (e.g., IEC 61850, IEEE C37.118, etc.) it is possible to analyze the features and capabilities required to test the protection schemes of power systems [86], [87]. HIL-based DRTS can also be carried out remotely (i.e., R-HIL) as studied in [53], where a configuration is proposed to execute RT tests on a set of relays in a substation. In [88], an RTS is used to test device protection and control methods. Herein, the authors focused on the characteristics and capabilities necessary to test the protection and control of a Wide Area Control System (WACS) based on synchronized data provided by the PMUs. A SIL application, on the other hand, is presented in [89], where a fully software-based synchronized PMU in RTS is used to emulate a large number of PMUs.

D. APPLICATIONS ON FACTS DEVICES IN TRANSMISSION NETWORKS

In [90], it is reported how a low-cost microcontroller can be deployed as a rapid prototyping platform for Flexible AC Transmission Systems (FACTS) to dominate damping inter-area oscillations between two interconnected electrical systems, and evidently, avoid the need to build an expensive large prototype platform in the laboratory. Herein, the control action is made through a Thyristor-Controlled Series Capacitor (TCSC) and Static Synchronous Compensator (STATCOM). Reference [91], deepens the use of STATCOM as a resource to adjust both voltage and power factor. The analysis has been conducted at the Point of Common Coupling (PCC) between a 50 MW wind farm and the transmission grid through CHIL setup.

In [92], a Wide-Area Controller (WAC) for a FACTS device is implemented considering both SIL and HIL schemes. This research work is an experimental setup for testing WACs starting from collecting measured data and ending with the reactive power compensation of the power grid. In short, three main sectors are being introduced in this study: the real-power grid, the local controller of the actual FACTS device (i.e., a scaled-down prototype STATCOM), and the smart power grid containing the PMUs simulated by an OPAL-RT simulator. Figure 7 shows the general scheme of this approach.

Regarding the SIL setup, the RTS simulates the smart power grid, PMUs (based on IEEE C37.118.1-2011), and the local controller. Since performing mathematical computations for complex grids along with the WAC system would be an onerous task, a MATLAB program was specifically created: it starts with the creation of TCP/IP sockets for the PMUs, then receives messages from the PMUs based on the aforementioned protocol standard, and subsequently, extracts the data. According to the authors, the delay related to the MATLAB program execution is short enough and does not impact the RT simulation.

With regard to the HIL testbed, three distinctive boards were used: the Giga Transceiver Digital Output (GTDO) for transmitting the STATCOM PWM pulses; the Giga Transceiver Analogue Output (GTAO), for sending the bus voltage set-points; and the Giga Transceiver Analogue Input (GTAI), for the acquisition of the measured quantities of the hardware (i.e., current and voltages). The response latency of these cards is near microseconds.

As just stated, the transition to converter-based generators in modern grids weakens the inertia and impairs voltage and frequency stability. Therefore, Synchronous Condensers (SCs) have been drawing increasing attention worldwide in

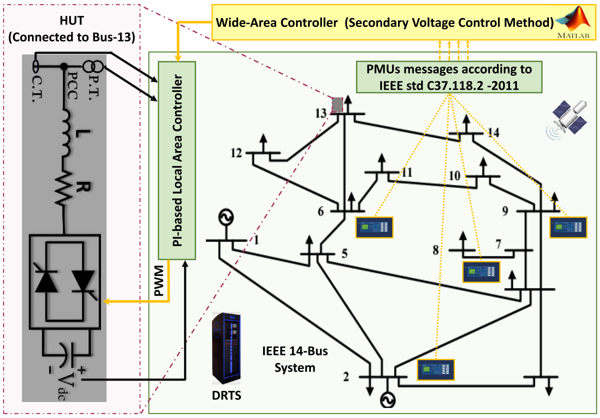

FIGURE 7. HIL and SIL diagram of the STATCOM test setup.

recent years. The Southern California Edison (SCE) Co., for instance, has installed 225 MVAr SCs at the Santiago substation in California to address the post-transient voltage instability following the loss of two 500 kV transmission lines from San Diego to Arizona [93]. An RTDS simulator has been deployed not only to test the control system of the SC in an "Offline" setting but also to train the operators and provide operational support to planning engineers and protection aspects. The HUT in the RTDS-based HIL setup is the excitation controllers and the DC power supply.

Another paper examines the undesired tripping off of an SC by reverse power and over-frequency protection under a certain grid configuration through HIL tests [94]. Here, the SC has been installed at the PCC of an HVDC station. To study this issue, a grid model including an SC and a VSC-HVDC system is simulated in the RTS, while the Automatic Voltage Regulator (AVR) and the generator relay for the SC act as HUT.

E. APPLICATIONS ON WIDE-AREA AND DEFENSE SYSTEMS

RT simulation is useful for studying different aspects of the Wide-Area Monitoring, Protection, and Control (WAMPAC) applications in power systems [95]. In this area of interest, PMUs play a decisive role, i.e., these devices can be equipped with GPS systems, and provide synchronized measurements of electrical quantities. A proven approach for developing such systems is to carry out the PMUs in a HIL setup, allowing the development of new tools and evaluating their accuracy and reliability through certification or pre-commissioning trials. In the literature, there are different architectural models for PMU connection in the HIL platform, each might be employed based on the specific requirements or properties such as test objectives, available facilities, cost constraints, and the complexity of the system under consideration. However, the most well-known configurations can be divided into three generic categories:

- Single PMU as HUT (basic Architecture);
- PMU as HUT with rapid control/protection prototyping;
- Virtual PMU.

According to the aforementioned schemes, either one configuration or a combination thereof can be selected. Note that a comprehensive explanation of the features and applications of these setups is given in [96].

WAMPAC systems should make quick decisions and control actions on the grid, which means they operate under strict time limits. Therefore, it's crucial to carefully evaluate the latency of WAMPAC systems to ensure their effective functionality [97]. Following this necessity, A HIL measurement method was developed in [98] and [99] to assess operational delays. This RTDS-based testbed analyzes these delays and presents an affine evaluation model for various communication latencies. Given the fact that quality-of-service in WAMPAC systems cannot be guaranteed, particularly when dealing with the unpredictable states of communication networks, reference [100] discusses the development of a co-simulation platform based on IEEE Std. C37.118 to study the impact of communication network conditions on the PMU data delivery in power systems. It highlights the challenges posed by latency, packet loss, and data corruption when these measurements are transmitted over wide-area networks. The study uses PMU as the HUT to assess how these adverse conditions affect WAMPAC systems. Additionally, it quantifies the maximum tolerable communication disruptions during emergencies for effective WAMPAC operation.

Comparing SIL and HIL architectures, a wide-area simulation has been described in [101]. Besides, the R-HIL application is addressed in [58], [59], and [60], where protective schemes for the transient stability studies have been tested. These works were based on wide-area measurement/control systems. The setups can be employed for studies on cyber-physical threats and protection in transmission systems, as well as training the operators [59]. It is worth stating that timing constraints were also examined by exceeding network latency limits or slow streaming rates from a remote power system simulator. Additionally, in [95], a Wide Area Damping Controller (WADC) prototype is evaluated in the HIL testbed to feed a damping signal to a commercial Excitation Control System (ECS) (i.e., ABB Unitrol 1020) according to PMU's measured values. In other words, this research aimed to test the WADC response to the Power System Stabilizer (PSS) interfaced with the excitation system during both local and inter-area oscillation. Figure 8 illustrates the essentials for the integration of RTS and PMU and the principle of processing control signals and feeding them back to the RTS in a closed-loop scheme.

Concerning the impact of communication delays on monitoring systems, this issue is treated in [102] by real-time performance evaluation of wide-area protection and control actions. A further experimental platform for real-time monitoring via PMUs is described in [103], with respect to the characteristics and facility architectures reported in [104] and [105]. Further significant experiences of cyber-physical co-simulation on the wide-area network are testified by the authors in [58] and [106].

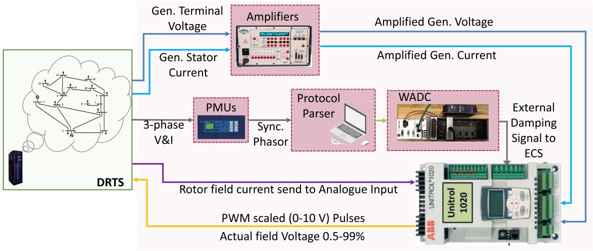

FIGURE 8. Unitrol 1020 ECS interface scheme with OPAL-RT simulator and WADC.

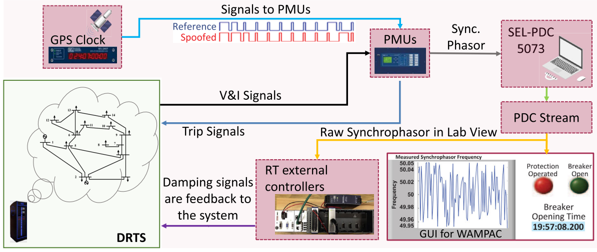

FIGURE 9. Test setup for TSSA analysis.

Cybersecurity can be considered an inevitable issue in modern wide-area communication networks. In this regard, a method is proposed in [107] to evaluate the impact of the Time Synchronization Spoofing Attacks (TSSA) in synchrophasor-based WAMPAC systems. To simulate the grid and initialize the TSSA in real-time, a HIL architecture is used through the GPS's timing signals. The detailed test bench for HIL simulation is demonstrated in Figure 9, which includes a 4-core OPAL-RT to simulate the power network, time code signal generation, two commercial PMUs, and a computer-based Phasor Data Concentrator (PDC) [108]. One PMU is considered as the reference by receiving the authentic timing signals from a GPS-based substation clock, while another PMU is attacked by TSSA by spoofing the time code signal through the RTS. During a TSSA event, the PMU can be fooled by transmitting garbled signals or retransmitting the signals acquired at another time. As a result, the under-attack PMU will compute bogus data that might not meet the requirements and constraints specified by IEEE C37.118, IEC 61850, or other standards, causing the malfunction of the WAMPAC system. Herein, the trip commands from the PMUs are generated in IEC 61850-8-1 format. The RTS subscribes to these messages to open the simulated circuit breakers in the RTS environment. In addition, an external embedded controller is used to receive data from the PMUs, and send the corresponding damping signals to the RTS, analogous to the use case mentioned in previous section.

F. APPLICATIONS ON TSO-DSO COORDINATION

With respect to the coordination mechanisms between the grid operator and electricity distributors, the SIL architecture is dominant for such activities as reactive power control between TSO and DSO, RT voltage control, and performing annual simulations of multi-voltage grid models [109]. In references [54], [110], and [111] the effect of RES on the transmission and distribution networks is investigated using the aforementioned platform. An application of Co-SIL is also presented in [55], in which the problem of co-simulation for coordination between multiple areas is addressed. The authors of [56], dealt with the problem of reactive power control and voltage regulation in a TSO-DSO coordination scheme through a R-PHIL distributed co-simulation. In particular, the authors have employed a co-simulation framework to reproduce the interactions between TSO centralized control of Distributed Energy Resources (DER) and local controllers managed by the DSO, showing how remote co-simulations can join system operators to explore TSO/DSO issues, without the need to share confidential data or information on proprietary technologies. As illustrated in Figure 10, the RT simulation results from a laboratory in the northwest of Italy, which emulates the HV side, can be exchanged with another laboratory's PHIL setup located in the southeast of Italy (about 1000 km far away). The facilities of the second Laboratory model the distribution network's components.

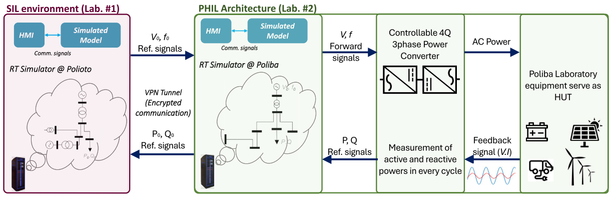

FIGURE 10. Schematic diagram of the Laboratories-in-the-Network platform with geographical distance of about 1000 km.

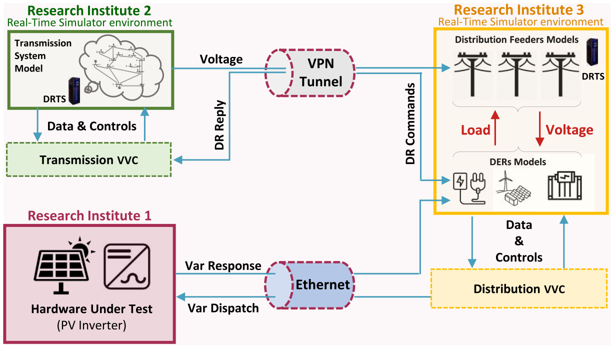

FIGURE 11. R-HIL co-simulation architecture.

Other works address the optimal use of DER in a geographically distributed remote co-simulation framework. One of particular interest is [112], which provides an example of how the coupling of test systems located in different geographical locations can be realized. In this way, several research institutes can work together to co-simulate a large-scale power system to study its dynamics on different levels. The HIL architecture used is based on the communication between different OPAL-RT simulators interfaced for the development of coordinated Volt-Var regulation technologies between transmission and distribution. The testbed used for RT Volt-Var control of a sub-transmission network co-simulates transmission, distribution, and DER systems. It incorporates implementations and simulation models developed by three research groups. The communication required to acquire measurements and carry out control actions between the HIL simulators takes place both via VPN and a shared file-based method (see Figure 11). For this reason, the communication interval between two test systems can be varied due to communication delays caused by the update rate of the shared file. The communication delay experienced in such applications is typically in the order of hundreds of milliseconds, as it is determined by the Modbus transmission frequency. The control algorithms can be implemented externally to the HIL test bench, therefore, load flow routines and optimization solvers can be integrated [112].

G. BATTERY ENERGY STORAGE SYSTEMS (BESS) SIMULATION APPLICATIONS

According to the International Energy Agency's (IEA) report published in 2023, electricity storage solutions can overcome the challenges regarding the large-scale integration of intermittent RESs, concerning both short- and long-term transients [113]. Large-scale BESSs have already been deployed in the United States, Europe, and Australia to manage the balance between supply and demand. The perspective of the growing integration of RESs into modern power systems affirms the significant role of BESSs and reveals the reason behind their attraction in both academic research and industry.

On this regard, the authors [114] explored real-time simulation modeling of AC smart grids, incorporating power generation sources like BESS. The primary goal of this HIL test bench is to construct a flexible, secure, cost-effective, and scalable representation of a relatively complete smart grid system. This setup facilitates diverse experiments, including steady-state studies, long-term planning, investigation of EMS, control validation, communication tests, and performance analysis. The test configuration introduces a decentralized droop control scheme to govern the BESS across various operational conditions. Additionally, the paper simplifies the model of the interfaced voltage source converter of the battery using an average model.

It should be stressed out that mathematical battery models suitable for real-time and transient simulations often lack accuracy due to factors like internal electrochemical reactions and external reasons such as loading conditions. Precise modeling of these complex processes while maintaining a low computational burden for RT simulations poses a considerable challenge. Considering the aforementioned fact, instead of a mathematical approach, paper [115] introduces an alternative simulation configuration where actual batteries, specifically Li-ion, interface with a DRTS. The devised setup incorporates reduced-order models for power electronic converters [116], balancing computational efficiency and the necessary detail for HIL simulation.

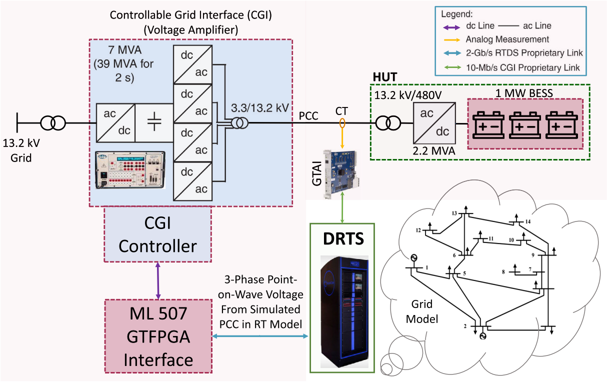

FIGURE 12. **Test setup of the island of Maui.**

PHIL experimental tests allow to validate the behavior of BESSs and their control system in more realistic conditions. The inclusion of physical batteries in tests allows to avoid the approximations due to modeling and take into account the actual response of the entire communication and control chain. This kind of test can be used to reproduce the response of physical batteries in the provision of services based on fast power regulation. For example, BESS and other storage systems are often proposed to achieve synthetic inertia (SI) in systems characterized by low rotational inertia. However, the efficacy of the inertial response can be significantly affected by the time response of the physical power device and of its control system. In [117], the authors proved through PHIL simulations how SI control can be achieved on off-the-shelf BESS even adopting low-cost controllers. The tests included both PHIL and CHIL approaches since both the physical power device and the SI controller were included in the test. The SI controller was programmed to autonomously measure frequency and RoCoF, and calculate the RT control action to be actuated by the BESS. Clearly, the drawback of this approach is that physical components are limited in power capacity and nominal voltage, and simplifying assumption are needed to scale-up the PHIL response to achieve significant interaction with the RT power system simulation. Nevertheless, the study allowed to prove the feasibility of the control and analyze under realistic test conditions the impact of real-time measurements, errors delays and filter stages to be added in the control chain.

From the real-scale point of view, an approach is thoroughly addressed in [118], which is one of the first experimental demonstrations of the ability of grid-forming inverters to improve the stability of a modern transmission grid with high penetration of RESs. The empirical study was described using PHIL simulation to connect a real 1 MW BESS along with its inverter to the Maui (Hawaii) transmission system (See Figure 12). Hence, it could be possible to observe the dynamic interactions between the inverter and the grid without putting the main power network at risk.

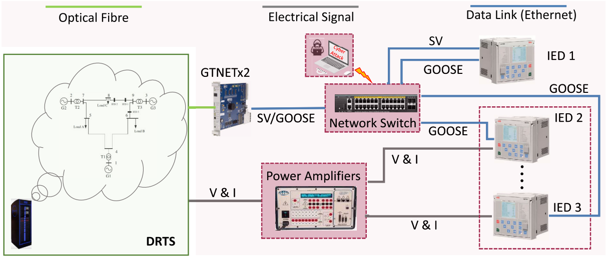

FIGURE 13. **HIL empirical framework to analyze the impact of cyber-attack on SAS.**

H. REAL-TIME SIMULATIONS OF SUBSTATION AUTOMATION SYSTEMS (SAS)

Substation Automation Systems (SAS) encompass an array of functionalities including protection, control, automation, monitoring, and communication, forming an integral facet of a comprehensive substation monitoring and control framework. In essence, the SAS is a set of hardware and software components used to monitor and control an electrical system, both locally and remotely to increase the efficiency and overall productivity of the system. The advent and swift evolution of microprocessor technologies have driven digital protection and control devices into a realm of heightened intelligence. Today, Intelligent Electronic Devices (IEDs) occupy pivotal roles within substations and contain valuable reservoirs of information that can be exchanged between them and external sources. Noteworthy instances of such devices encompass multifunctional electronic meters, digital relays, and controllers, which seem feasible solutions to improve reliability, achieve operational efficiency, and enable asset management programs—by minimizing the need for human intervention–-, including predictive maintenance, life extension, and better scheduling. Modern SAS infrastructures are increasingly software-based and connected through communication systems and protocols.

Among the most commonly adopted ones, IEC 61850 is a widespread protocol that enables RT data exchange between critical SAS devices. However, this communication standard is vulnerable to cyber attack execution [119]. Hence, reference [120] presents the dangerous implications of this non-secure standard. Cyber-attacks might exploit the vulnerabilities of the Sampled Values (SV) and Generic Object-Oriented Substation Event (GOOSE) protocols of IEC 61850 by injecting spoofed SV and GOOSE data frames into the substation communication network [121]. In this research work, it is demonstrated that such cyber-attacks might impress the system dynamics and lead to obstruction or tripping of multiple digital protective relays that are using such communication protocols (e.g. distance, out-of-step, frequency, etc.), and eventually, can result in a partial or complete blackout [76]. Experimental verification of the physical implications of cyber-attacks on substation automation and protection is attained using an empirical framework that closely resembles real-world digital substations. It is implemented through the HIL test bed of commercial relays with an RTDS simulator that simulates the power grid (see Figure 13). Herein, IEDs 1-3 are actual commercial devices that use GOOSE protocol for messaging through switched Ethernet. IED 1 employs SV to calculate fault conditions and trip status, whereas IEDs 2 and 3 are hardwired and receive analog signals from RTDS through power amplifiers. The remaining relays are modeled inside the RTDS. As shown in Figure 13, the relay data links are connected to a network switch which also has a connection to the RTDS GTNET 2x card. The card is interfaced to the RTDS through an internal optic fiber connection. The card publishes SVs to IED 1 and acts as a subscriber to the GOOSE messages from IEDs 1-3.

Accordingly, it is obvious that SAS communication integrity shall not be manipulated by strangers [122]. Note that this issue, termed cyber security, was not a major concern when IEC61850 was published [123]. Therefore, IEC Working Group 15 of Technical Committee 57 published IEC 62351 on security aspects of IEC 61850 profiles. However, the use of authentication methods for SV based on IEC 62351 standards has not yet been integrated and validated with commercial-grade equipment. Thus, reference [124] investigated the performance of safety-enabled *Secure* SV packets transmitted between protection and control devices in the substations by appending a message authentication code to the extended IEC 61850 packets. Different message authentication codes, concerning IEC 62351, were evaluated in the HIL environment to verify the performance of this standard.

To analyze the performance and cybersecurity vulnerabilities of IEC 61850 in a realistic setup, reference [125] provides a flexible, and general-purpose HIL testbed for a smart SAS using built-in IEC61850 protocols [126]. The testbed comprises the supervisor, substation bus, and process bus communication layers, facilitating local network data exchange at various levels, considering both physical and emulated IEDs, detailing the communication protocols implemented in each case, and noting the additional delays introduced. Additionally, different protection scenarios have been examined, and the communication protocols across these scenarios contribute to the analysis of communication delays, data accuracy, and cybersecurity vulnerabilities in IEDs utilizing GOOSE messages, SV messages, and the MMS server protocol of the IEC61850 standard. Another work [127] has proposed a test framework for distance relays performance evaluation in the presence of converter-based-DERs, according to IEC 60255-121 standard [128], which introduces the minimum requirements for proficiency evaluation of distance relays. The HIL test framework has been developed in a closed-loop fashion and is composed of an RTS, a host PC, and a commercial digital relay as HUT. The authors stated that the RTS is a feasible approach because it can extend the SAS tests to assess protection interaction with power system dynamics in a fairly realistic manner. Moreover, not only would the protection and control function be evaluated, but also full coordination between protection devices as well as DER controls might be introduced.

Besides, such factors as the impact of communication delays can be covered.

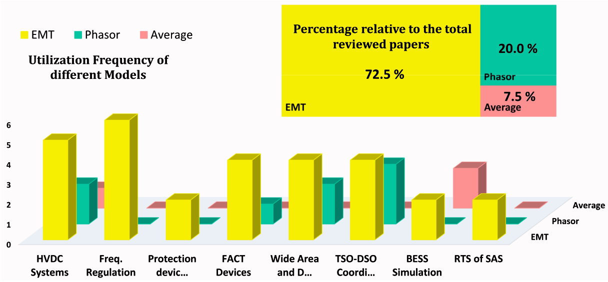

FIGURE 14. **Utilization frequency of different RT simulation models in the areas under consideration.**

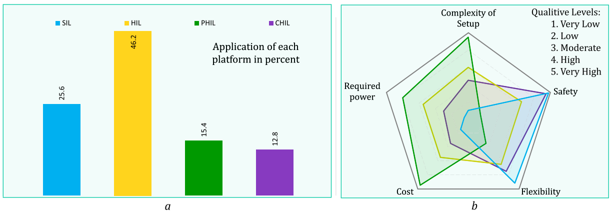

FIGURE 15. **(a) Graphical illustration of the participation percentage of each platform on the transmission side. (b) Qualitative comparison between different platforms.**

I. DISCUSSION OVER PREVIOUS STUDIES

Table 3 summarizes a concise overview considering previously published papers mentioned in this Section. All considered works have been categorized according to the main topics of each subsection. Some information has been described in terms of: 1) simulation platform used depending on the system under consideration (e.g., SIL, PHIL, etc.), 2) simulation model depending on the desired accuracy levels, and computational complexities (i.e., EMT, phasor, etc.), and 3) the possible hardware being tested, namely the HUT. Also, a review note part is dedicated to drawing some useful extra discussion about each reviewed paper.

Figure 14 depicts the utilization span of different simulation models in diverse technical applications of RTSs on power systems. Referring to this figure, which introduces another statistical representation of Table 3, it is evident that the majority of DRTS-based articles focused on detailed simulation models, namely the EMT model. It should be noted that, albeit the comprehensive overview of all the articles in the literature might be an unrealistic claim, given that the studied papers were not intentionally selected, it might be reasonable to state that this figure can draw a fairly general perspective of the whole picture, and provide qualitative insight into the utilization diversity of simulation models in this realm. In other words, although various modeling spectrums of power system elements have been introduced in the literature [1], [2], [4], [133], [134], the EMT model seems the most popular in DRTS-based manuscripts and covers many practical applications. The reason might arise from the fact that most of the dedicated main topics in this review paper examine a system in dynamic mode which requires a relatively high level of detail, while as stated in the introduction section, simulation models such as the average model are more prevalent in scenarios involving steady-state conditions, long-term planning, and similar cases. Furthermore, this tendency could be due to the rapid processing speed and capability to handle the computational burden of available real-time processors, which causes a strong trend toward employing accurate system models, with exceptions arising only in cases where hardware limitations come into play.

Moreover, concerning the ever-increasing evolution of high-speed processor technologies, there seems to be a transition from simplification in modeling, which potentially overshadows calculation accuracy toward high computing resources, and makes the DRTS testing more expensive. Thus, in the future, there will be a growing desire to employ detailed models for systems under study and more sophisticated computer architectures. The average model can be used in such applications as TSO-DSO coordination, long-term simulations, energy management, and other similar fields.

Referring to Figure 15a, it becomes evident that the HIL-based platform is predominantly utilized in the transmission domain, even regarding high-voltage equipment. This testing approach sometimes employs small-scale hardware, offering a cost-effective and safe method for testing. Nevertheless, it is crucial to note that reduced-scale models might not consistently replicate the behavior of real-scale HUT. This issue will be delved into further explanation in Section V. However, although the technological improvement in achieving test beds at an affordable price significantly boosts the adoption of PHIL equipment, the progress of high-voltage and high-power platforms is still in its early stages. This can be revealed in Figure 15a, where the considerable fraction of PHIL-based articles compatible with low-voltage HUTs, such as batteries, indicates a relative interest in the low-power domain. To tackle this obstacle, it seems sometimes feasible to focus on emulating the real-scale behavior of a critical parameter of the HUTs. As an exemplary justification, a remedial solution is demonstrated in [135], showing how a low-voltage PHIL test environment can effectively be used to test some grid facilities in almost their high rated-currents, when the real-scale behavior of current matters. Concerning the mitigation of these alternatives, it is anticipated that the deployment of real-scale PHIL platforms will continue to grow in laboratories worldwide in the future [136]. On the contrary, the SIL platform appears to be the most popular approach on the transmission side. This can be attributed to the relatively low costs associated with simulation platforms, the paramount importance of security during testing, and the ease of defining various scenarios, modifying parameters, testing different configurations, and analyzing results quickly. This fact can also be inferred from Figure 15b, which qualitatively compares different

TABLE 3. Summary of references.

Main topic	Ref.	Sub-title	Simulation Platform	Simulation model	HUT	Review note
HVDC systems	[64]	Dynamic behavior analysis	SIL	EMT	N.A.	The work identifies areas to boost inter-PC communication, considering different CPU architectures. This underscores the dedication to enhancing the simulator's capabilities for valuable benefits in future complex system endeavors.
	[65]	Dynamic behaviour analysis	SIL	Phasor	N.A.	Albeit beneficial, pure SIL simulations lack real-world validation, risking credibility or accuracy. Inaccurate models yield unrealistic results and misinterpretations.
	[66]	Dynamic behavior analysis concerning the thermal model of IGBTs	HIL	EMT	HHB integrated onto an evaluation platform	By studying long-term thermal stress on reliability and exploring new thermal management strategies, equipment lifespan can be extended. RT thermal-aware control enables adaptive actions based on current thermal status, optimizing performance while ensuring safe temperatures [129].
	[67], [68]	Protection	HIL	EMT	Protection relays	The platform can facilitate verifying new protection schemes and seamless wide-area coordination, aiding operator training, evaluating cyber resilience, and analyzing protection system's behavior in modern intricate grids.
	[69]	Control	CHIL	EMT	MMC control scheme	HIL testing can also verify MMC control-protection synergy for their coordination and fault-tolerant capability studies during faults and transients.
	[70]	Virtual inertia as an ancillary service	PHIL (60kVA, 700V_{DC})	Phasor	MMC	A similar SI-based testbed can be deployed for other concerns of future power grids like damping inter-area oscillations, etc. Shifting to the other side, the paper could consider how to adapt these strategies to intermittent RESs like wind and solar, which are crucial in future grids. This broader perspective would enhance its relevance.
	[71]	Behaviour Modelling and analysis	SIL	Average	N.A.	As semiconductor switches with fast dynamics may not be accurately represented by average models, a comprehensive analysis of different simulation models in a certain scenario can clarify the suited scope of application of this tool for RT simulation.
	[43]	providing stable testbed	PHIL	N.M.	(Non)linear load, Inverter	Advanced analytical methods can be investigated to specify the parameters of the current filter instead of a trial-and-error approach.
	[31]	testbed's stability and accuracy improvement	PHIL (4KW, 400V)	N.M.	Converter	Future advancements in PHIL platforms may simplify external signal processing integration and use AI-driven optimization to reduce complexity, enhancing stability and accuracy while minimizing computational demands.
	[76]	Providing a Cyber-Physical testbed	HIL	N.M.	cyber-physical System	This testbed can be used to study the vulnerabilities within various cyber-physical systems, promoting security protocols.
Frequency regulation	[77], [78]	Application of BESS on frequency control	PHIL (16kVA, 400V_{AC})	EMT	BESS	Research on the long-term performance and maintenance considerations of the SI controller, including issues related to hardware degradation, coordination with other control strategies, and adaptability to changing grid conditions, could be considered. (continued on next page)

* N.M.: Not mentioned in the reference, N.A.: Not applicable.

TABLE 4. Summary of references (Continuation).

Main topic	Ref.	Sub-title	Simulation Platform	Simulation model	HUT	Review note
Frequency regulation	[57]	Protection	Co-SIL	N.M.	N.A.	There is a need to consider different symmetric or asymmetric contingencies. The paper does not address the interaction among various protection schemes prevalent in modern networks [130], [131].
	[81]	LOM protection in low inertia systems	HIL	EMT	LOM relay	Other works can involve verifying the reduced Great Britain system model for HIL studies and subjecting the LOM relays to stress testing, evaluating their communication and coordination with other protection utilities in wide-area schemes.
	[83]	Frequency stability	HIL	EMT	PMU, GPS, and SVP	Given the limited system size, PMU placement algorithms were not explored. For larger systems, cost considerations arise. However, exploring and comparing PMU placement algorithms for optimal surveillance can be the next step.
	[84]	Frequency control	HIL	EMT	BESS and PV panels	Coordination among protection and control schemes during diverse transient scenarios could be considered.
	[85]	Under frequency load shedding	PHIL (16kVA, 400V$_{AC}$)	EMT	Street light and BESS	PHIL testing facility can be expanded to handle a broader range of real-world grid challenges with advanced controls, protection, and communication.
Protection devices...	[53]	Providing RTS design for relays	R-PHIL	N.M.	PMU	Remote testing facilitates power grid reliability studies concerning complexity from RES, WAMPAC systems, and critical components.
	[88]	RT testbed for WACS	SIL	EMT	N.A.	Future of WACS testing with RTS can involve enhancing capabilities for evolving PMU-based data, ensuring comprehensive validation of advanced protection and control methods in complex power grids.
	[89]	Monitoring and protection	SIL	EMT	N.A.	Utilizing the platform, various ICT architectures' influence on WAMC can be studied. Additionally, exploiting the vast phasor signal availability via ICT networks enables assessing network latency effects on grid control applications like inter-area oscillation damping and voltage regulation.
FACTS devices	[90]	Damping inter-area oscillation	CHIL	EMT	FACTS control scheme	The study involves a sensitivity analysis to assess its robustness by evaluating how parameter and operating condition variations impact damping controller performance. Additionally, a comparative analysis with other methods highlights the strengths and weaknesses.
	[91]	Voltage and power factor control	CHIL	EMT	STATCOM control module	Given the proposed test platform, future studies could include exploring advanced control algorithms, integrating with renewable sources, enhancing cybersecurity, and optimizing multi-objective performance.
	[92]	Wide-area reactive power compensation	HIL/SIL	EMT	STATCOM (Scale-down)	The proposed method has not been explicitly compared with the existing methods or standard techniques. Building on the testbed's capabilities, future research could focus on integrating bad data detection algorithms and dynamic state estimation techniques to enhance system observability and reliability. (continued on next page)

* N.M.: Not mentioned in the reference, N.A.: Not applicable.

TABLE 5. Summary of references (Continuation).

Main topic	Ref.	Sub-title	Simulation Platform	Simulation model	HUT	Review note
FACTS devices	[93]	Control and protection of SC, and training the operators	HIL	Phasor	SC's control scheme	Given the growing integration of RESs and thanks to this platform, considering the interaction between various controllers and RESs dynamics could be precious for enhancing damping control strategies.
	[94]	Undesired tripping off conditions	HIL	EMT	SC's reverse power relay, over freq., AVR	Future research should explore advanced protection algorithms tailored to SCs' unique characteristics and their interaction with converter-based devices. This may include adaptive protection schemes, etc.
Wide-Area and Defense Systems	[98], [99]	Assessing the operational latency of WAMPAC systems	HIL	N.M.	PMU	Incorporating emerging technologies such as 5G communication and IoT devices could provide deeper insights into minimizing delays and improving system reliability across different geographical and operational contexts.
	[100]	Studying challenges posed by latency, etc.	Co-HIL	N.M.	PMU	Future research could focus on developing adaptive control strategies such as machine learning techniques that dynamically adjust to varying delay conditions in real-time, thus, enhancing the robustness and efficiency of power grid operations.
	[101]	RT testing of synchrophasor-based WAMPAC systems	HIL/SIL	Phasor	PMU	Further studies can explore how the delay arising from PMU's communication channel would affect these methods.
	[58]–[60]	Transient stability study	R-HIL	EMT	Special protection systems, PMU, and PDC	Some recent major blackouts were attributed to voltage issues, elevating the need for system security strategies. Augmenting the centralized adaptive security improvement methods could enhance system protection.
	[95]	WADC	HIL	EMT	ECS (ABB Unitrol 1020)	The test platform offers a controlled environment to evaluate and refine power system control strategies, optimizing performance and mitigating risks before real-world deployment.
	[104]	Impact of communication delays of WAMPAC systems	Co-SIL	N.M.	N.A.	The ongoing development of ICT technologies can be extended to novel WAMPAC applications, as well as the evaluation of different communication architectures and technologies with limited bandwidth and network failures, emphasizing an evolving approach.
	[103]	RT dynamic monitoring and control	CHIL	N.M.	SG, Exciter, PMU	Investigating the role of human operators in the proposed testbed could provide insights into the human-system interaction aspect of wide-area control and monitoring.
	[62], [106]	Exploring the application of WAMPAC technologies	Co-SIL/Co-HIL	EMT/Phasor	PMU	The platform enables easy evaluation of network aspects for WAMPAC, including wireless vs. wired media, protocol comparisons, and bandwidth allocation. It facilitates studying the impact of diverse ICT architectures on WAMC [106].
	[107]	Studying the impact of TSSA in WAMPAC systems	HIL	EMT	PMU, GPS, and PDC	An uninterrupted GPS clock is crucial. Lack of attention to this issue might cause PMU problems in delivering data. So, further focus is needed due to potential adverse effects in the field. (continued on next page)

* N.M.: Not mentioned in the reference, N.A.: Not applicable.

platforms based on such aspects as the complexity of setup, safety, flexibility, cost considerations, and the required power resources.

IV. SOME EXAMPLES OF PHIL LABORATORIES

The inclusion of Multi-Megawatt PHIL architectures allows to streamline compliance testing by simulating the dynamic

TABLE 6. Summary of references (Continuation).

Main topic	Ref.	Sub-title	Simulation Platform	Simulation model	HUT	Review note
TSO-DSO Coordination	[110]-[54]	Impact of RES on Transmission and distribution grids.	Co-SIL	EMT/Phasor	N.A.	Future research could explore the integration of machine learning techniques to enhance RT co-SIL accuracy and enable adaptive control strategies within the distributed laboratory framework.
	[55]	Coordination of multiple areas.	Co-SIL	EMT	N.A.	Concerning the critical nature of grids, future works can focus on integrating robust communication methods into the co-simulation framework to ensure the secure exchange of sensitive data between institutions, thereby addressing potential cybersecurity vulnerabilities.
	[56]	Voltage regulation in TSO-DSO coordination.	R-PHIL (16kVA, 400V_{AC})	EMT	Wind turbine, Battery, EV, and PVs	It is worth considering the security studies in critical applications involving TSO-DSO coordination.
	[112]	Coupling different areas to study the large-scale grids' dynamic events.	Co-HIL	phasor/EMT	PV panel's inverter	Since the HIL system involves integrating multiple test systems across different locations, consideration of cybersecurity issues seems possible.
BESS Simulation	[114]	proposing a complete modeling of smart networks.	HIL	Average	Battery	To facilitate a precise examination of potential rapid transient events, it could be also valuable to explore the EMT model of the equipment and contrast the outcomes. This comparison can clarify the best-suited option in the dilemma of fast processing and accuracy.
	[115]	Developing an accurate battery-in-the-loop test bed.	HIL	Average	Battery (Li-ion)	Ongoing research could focus on refining and developing more advanced state-of-charge estimation algorithms to further improve the accuracy of predicting battery states during dynamic scenarios. Also, incorporating machine learning algorithms for advanced prediction and optimization of battery performance based on real-time data could be a promising future trend [132].
	[117]	SI actions by means of BESS.	PHIL (16kVA, 400V_{AC})	EMT	Battery	As SI is a remedy to improve system response during transient events, adaptive PI controllers can offer better advantages to handle changes in system dynamics or uncertainties.
	[118]	Stability improvement using grid forming inverters.	PHIL (2.2MVA, 480V_{AC})	EMT	Inverter, Battery	Given the large power systems, incorporating communication tools in a co-simulation environment can enhance realism for tackling recent problems in smart grids, such as data delivery concerns in WAMPAC systems.
RTS of SAS	[120]	Cyber security issues of IEC 61850.	HIL	N.M.	IEDs	Evolving grid digitalization and uptake of additional IEDs and other standards highlight the greater need for cybersecurity measures.
	[124]	An extended secure packet based on MAC algorithm.	HIL	EMT	IEDs	A distribution method for MAC could be investigated. Also, performance evaluation of multiple SV streams and interoperability issues between different sections in the power system could be addressed in future works.

(continued on next page)

* N.M.: Not mentioned in the reference, N.A.: Not applicable.

and detailed model of a system in an RT manner, where a full-scale HUT interacts dynamically with a simulated power system. Not to mention that due to the staggering cost of these test facilities, only a few investments have been made in this regard so far. However, concerning the importance of the electricity industry as the infrastructure of other industries,

TABLE 7. Summary of references (Continuation).

Main topic	Ref.	Sub-title	Simulation Platform	Simulation model	HUT	Review note
RTS of SAS	[125]	providing a realistic testbed to analyse IEC61850.	HIL	N.M.	IDEs	This setup allows researchers to better understand cyber-physical threats, leading to enhanced security for SAS.
	[127]	Distance relay evaluation in SAS.	HIL	EMT	Distance Relay	In wide-area self-healing power grid, a smart automated protection system relies on communication data for grid status awareness, efficient data processing, and effective decision makings [32].

* N.M.: Not mentioned in the reference, N.A.: Not applicable.

it can be predicted that remarkable investments will be made in the future. In the following, some applications and examples of these architectures will be introduced.

A. MULTI-MEGAWATT PHIL ON RENEWABLE ENERGY RESOURCES

The paper [137] deals with the issues related to the establishment and development of a multi-megawatt mechanical and electrical test facility intended for renewable energy research. The mechanical test devices have been established to study the dynamics of wind turbine nacelles as well as other analogous apparatus up to 15 MW. It is worth stating that electrical tests can be interconnected with mechanical platforms to facilitate the comprehensive mechanical and electrical evaluation of wind turbine performance according to Grid Codes. In the cited manuscript, the test platforms have been equipped with fully controllable hydraulic actuators to apply mechanical stress to the HUT. This configuration is capable of emulating all dynamic non-torque loads associated with the wind blades, which is ideal for the turbine's longevity evaluation.

Figure 16 indicates a simplified single-line layout for the test facility, where a 23.9 kV utility bus supplies power to a motor which, in turn, is connected to a variable frequency drive. The motor supplies mechanical power to the HUT. During the test, the electrical energy generated by the tested component circulates through a recirculation bus in the drive. In this way, the only power consumed by the system is due to losses. What is more, using a modular power amplifier and a configurable reactive power divider, the electrical test system can operate in four quadrants, which facilitates both the injection and absorption of reactive and active powers. Thanks to this design, various investigations on the power equipment such as operational tests, fault ride-through tests in both low and high voltages, power quality analysis, etc. might be carried out.

B. ENERGY LAB 2.0 AT THE KARLSRUHE INSTITUTE OF TECHNOLOGY (KIT)

Figure 17 implies an example of the PHIL test facility of the KIT installed in Germany. The 1 MVA plant is used for investigation or testing the components such as flywheels, and such storage systems as super-capacitors and electrolyzers. Therefore, these are mixed AC and DC networks, which include various systems developed with new emerging technologies. The laboratory is equipped with a 1 MVA power amplifier working up to 1.5 kV DC, as well as RTSs of OPARL-RT and RTDS. There is also a second area, the Intelligent Energy Systems Control Laboratory, which enables real-time simulation of transmission grids with a multitude of associated large-scale components. These components include WAMPAC infrastructure, various photovoltaic systems, and flexible switching for the interconnection between grids and storage systems. Thus, it is possible to simulate different network scenarios, including the control and stability of autonomous networks and ancillary services. Examples of PHIL experiments include the DRTS of German networks with a particular focus on studies related to grid harmonics. The KIT also has an Energy Smart Home, an intelligent and automated residential building that provides ancillary network services through household appliances, batteries, and other integrated systems [138].

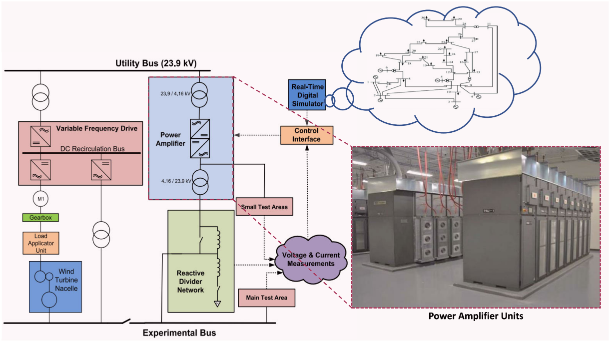

FIGURE 16. Single-line layout for the test setup addressed in [137].

C. SMARTS LAB: A LABORATORY FOR WAMPAC SYSTEMS

The Smart Transmission System Laboratory (SmarTS Lab) is a cutting-edge facility designed to advance the development and testing of applications for WAMPAC systems using synchronized phasor measurement data. This laboratory addresses the progress in creating new PMU-based WAMPAC applications by adopting an RT-HIL approach to explore and analyze smart transmission grid paradigms.

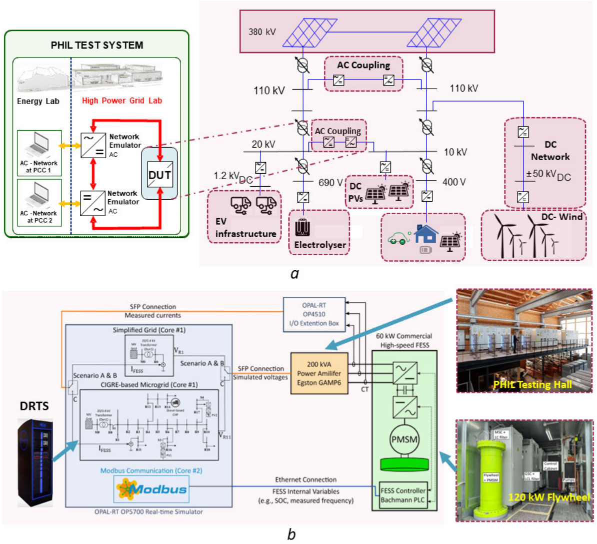

FIGURE 17. **Lab 2.0 of the Karlsruhe Institute of Technology (KIT): (a) Graphical illustration of high power grid laboratory. (b) PHIL setup (RTS, communication, HUT).**

The SmarTS Lab's architecture allows for innovative proof-of-concept developments, highlighting the potential for virtualization to overcome technical and economic limitations associated with the number of PMU interfaces and computational complexities. Despite these challenges, the laboratory offers unique capabilities for RT deterministic computing applications, such as wide-area power oscillation damping and coordination of RT controllers with protective relays, capabilities not feasible with traditional platforms [139].

D. ENSIEL NATIONAL ENERGY TRANSITION REAL-TIME LAB (ENET-RT LAB)

The ENET-RT Lab is an RT co-simulation laboratory composed of numerous Italian partners that aims to become one of the main platforms for testing new solutions and innovative technologies that can effectively support the energy transition (see Figure 18). The number of laboratories associated in ENET-RT Lab is constantly growing. So far, published results of co-simulation have included the following laboratories [51], [140]:

- the laboratory LabZERO of Politecnico di Bari with CHIL and PHIL tests on flexible resources and microgrids;
- the Network Infrastructure and Complex Energy System Laboratory of the University of Genoa with CHIL tests of frequency control of large interconnected wind power plants;
- the Smart Polygeneration Microgrid (SPM) of the Savona Campus (University of Genoa) with real time measurements and SIL;
- the Smart Grid Interoperability Laboratory (SGILab) of the Europe Commission - Joint Research Center (JRC) in Ispra (Italy) with HIL and SIL simulations of power systems and microgrids;
- the RT laboratory of the Department of Industrial Engineering of Naples University "Federico II" with SIL tests;
- the RT laboratory of the University of Sannio (Benevento, Italy) with SIL tests;
- the Global-Real Time Simulation Lab (G-RTSLab) of the Politecnico di Torino with PHIL and SIL simulations of large interconnected power systems.

Further and more recent research activities have involved also other RT laboratories at the University of Palermo and University of Genoa. Each associated laboratory employs different RT or PHIL technology (for example Opal-RT, RTDS, Speedgoat, etc.). Simulators and other equipment can interact by means of the VILLAS Framework, managed by the Aachen University, which also collaborated to the geographically distributed co-simulation demonstrations in [140]. Available RT technologies allow a wide range of simulations, with time performances ranging from microseconds (for electromagnetic transients) to milliseconds (for electromechanical dynamics) and power amplifiers (from 15 kVA to 60 kVA) to implement PHIL configurations [51]. In particular, the LabZERO test facility has an OPAL-RT simulator coupled, through a 16 kVA three-phase 4Q programmable power amplifier, with a fully equipped microgrid for PHIL tests. The microgrid comprises photovoltaic arrays, a small wind turbine, a battery storage system, an electric vehicle charging station, and a small-scale combined cycle biomass generator. Recently, the microgrid has been integrated with a smart parking station equipped with more than 60 kW solar canopy.

Among the applications, the PHIL plant has recently been used to study the dynamic response of power components and their controllers to electromechanical transients in systems characterized by low inertia. These experiments have been performed to test new frequency meters and SI controllers [117], to validate fast frequency regulation techniques [141], and as already mentioned, to integrate new control strategies into non-synchronous island microgrids [84].

V. FUTURE TRENDS

DRTS stands as a pivotal tool in modern grid simulation and analysis. Modern energy systems exhibit greater complexity than their conventional counterparts, due to their cyber-physical and multi-domain/modal characteristics [35]. This article provides a synthesis of DRTS and HIL-based validation approaches, which align better with future requirements and have witnessed substantial development in recent years [34], [142]. However, the cyber-physical nature of modern energy systems calls for further refinement and harmonization, including standardization efforts for RT systems or HIL-recommended practices [143]. While the implementation of DRTS-based applications still relies heavily on tools from manufacturers, the need for improved model exchanges and the integration of DRTS systems

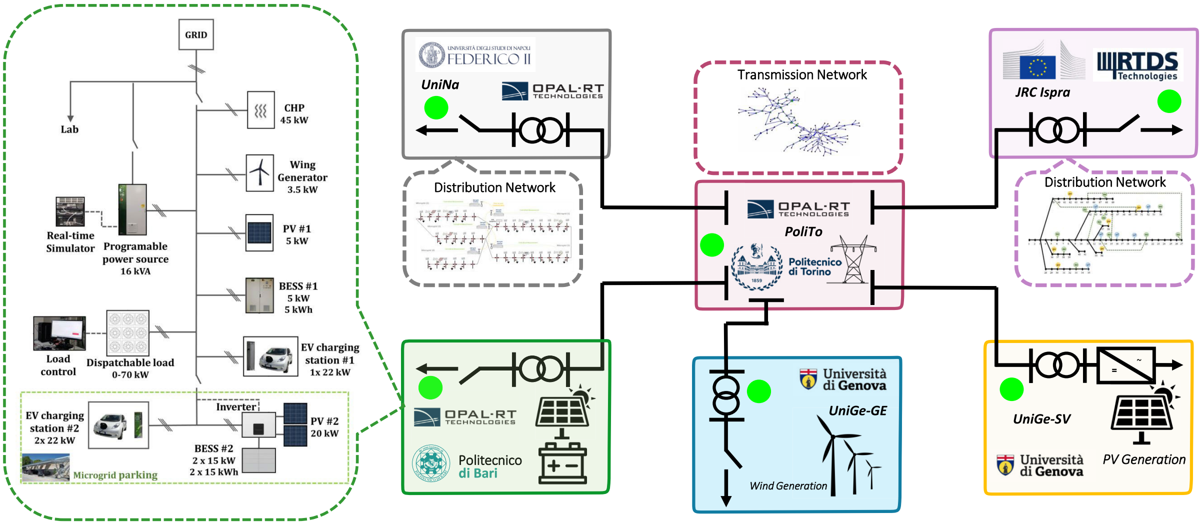

FIGURE 18. Graphical diagram of the ENET-RT Laboratories involved in [51].

from various vendors keeps a priority on facilitating multi-domain analysis of modern energy systems. Undoubtedly, enough opportunities for future research and technological advancements persist in this domain. This section delves into the growing importance of HIL within power systems, examining its future trends and highlighting its crucial role in improving system modeling and validation concerning different aspects.

When it comes to testing equipment used in power transmission, it is evident that employing full-scale testing equipment with nominal high voltage levels and power is uncommon in both industry and academia. This rarity stems from the significant cost associated with the equipment itself, the financial risk of potential damage during testing, and the substantial expense of the laboratory facilities, as can be perceived from the literature review in section III. Consequently, it is more common to construct prototypes on a smaller scale. While these scaled-down prototypes can effectively replicate system behavior in proper detail, conducting power system tests at a full-scale size, including investing in PHIL testbeds, holds paramount importance for several compelling reasons, some of which are listed as follows:

- **Scale-Dependent Phenomena:** Power systems often involve scale-dependent phenomena, such as surge voltage drops, voltage gradient fluctuation in high-voltage equipment, current flows, thermal effects, and electromagnetic interference that are hard to emulate exactly in smaller-scale tests [144]. Realistic tests replicate the actual conditions and ensure that the behavior of the systems is accurately assessed. This level of realism is essential for validating and fine-tuning the control algorithms, equipment, and so on before actual deployment, thus, guaranteeing grid stability and efficiency.
- **Security Challenges:** Power networks might face significant security challenges, and real-scale testing allows for the identification and mitigation of potential risks and vulnerabilities. PHIL testbeds enable the study of how power components interact under various conditions, which can ensure the security and reliability of the systems.
- **Complex Interactions:** Power systems are highly interconnected and represent complex behaviors. Real-scale testing captures the complicated interactions between various components, such as generators, transformers, and control systems. Understanding these interactions is essential for optimizing system performance.
- **Scalability:** Power grids must be scalable to meet future expansions. Real-scale testing helps to ensure that the infrastructure can adapt to increasing demands and seamlessly integrate new technologies.
- **Unexpected Conditions:** Power grids might need to operate under intensive conditions, such as during grid emergencies or extreme weather events. Real-scale testing allows for the system responses' evaluation and using strategies to enhance resilience.
- **Proper Decision Making:** Real-scale testing provides accurate data about the performance of power systems, allowing the evaluation of efficiency, reliability, etc. This data is valuable for making decisions about system design and operation.
- **Regular Testing:** On a regular basis, power systems need testing of control systems, protection devices, and some pieces of equipment at the full scale. As an example, considering black-start functionalities under load shedding, special protection infrastructures, WAMPAC schemes, etc., PHIL can help to test the virtual system without endangering the whole network or power station.

According to the above, it is evident that the objective is to balance the cost of the HUT with the level of accuracy needed in modeling the system behavior in a specific test. This determination will dictate whether a small- or full-scale

HUT should be employed. Moreover, it is worth noting that in some cases, while there might be initial costs associated with investing in HUT for a PHIL-based test, it can ultimately result in cost savings and improved reliability in the long duration. By identifying and addressing issues in a controlled environment, it becomes possible to prevent costly failures in real grids. However, given the substantial expansion of the power grid, there exists a compelling need for additional investment in expanding laboratory capabilities for realistic tests, and subsequently, ensuring the reliable performance of modern grid-integrated equipment. To reduce cost, it can be expected that mobile-full-scale PHIL might be employed to test more than one facility, or STATCOM utilized for operating requirements could serve as a PHIL testbed, when not used in RT operation.

HVDC technology plays a vital role in the expanded integration of renewable energy sources and the enhancement of security and reliability, particularly in complex operational scenarios. With the advancement of power electronic components capable of withstanding higher voltage levels, several critical areas have emerged in HVDC research and development [145]. These encompass explaining innovative testing methods, including PHIL techniques, to address the robust breaker-network interaction [146]. Furthermore, practical analysis for HVDC arcs, especially during high-current conditions and interruption phases, is of paramount importance [147], [148], [149]. Extending the applicability of medium-voltage circuit breakers to higher voltage levels, whether through technological enhancements, series connections, or breakers applied across medium-voltage levels within multilevel converter topologies, is another significant focus area. Considering the growing adoption of HVDC technology, there is an inevitable need to improve the reliability of power electronic devices, which can be achieved through condition and health monitoring [150]. Ensuring the safety of converters and minimizing interruptions during DC line faults in MMC-based HVDC grids is essential, emphasizing the need for rapid fault detection and coordinated protection measures that align hardware, control systems, and protection algorithms effectively [20], [151], [152], [153]. Furthermore, the interaction of offshore wind farms with HVDC systems presents complexities due to such issues as noise, randomness of event timings, and hardware design, which are not thoroughly investigated [65]. While numerical simulations offer cost-effective testing, their fidelity can be challenging to assess. Scale-down experiments provide higher fidelity but limited test coverage. PHIL testing offers a balanced approach, fidelity and test coverage.

Future research in the context of RESs such as offshore wind farm interactions with HVDC systems will focus on enhancing wind power generation models, incorporating pitch angle control for turbine control across varying wind speeds, and improving wind profile representation to achieve more accurate results [154]. Additionally, aggregated models might replace single turbine models, and novel technologies such as modular multilevel concepts might be employed in depicting HVDC systems with twin converters [12].

In the realm of electro-hermal research within HVDC and power electronic devices on HIL platforms, numerous promising directions await exploration [155], [156]. These include the advancement of accurate electrothermal models, innovative thermal management strategies, RT integration of thermal modeling with control algorithms, and the study of long-term device reliability [66]. Additionally, investigating the impact of electrothermal considerations on renewable energy integration, RT thermal simulation methods, and the impact of thermal failures on devices seems crucial. Incorporating online thermal monitoring, continued model validation, and addressing human factors in decisions related to thermal conditions also play pivotal roles in achieving more resilient and efficient HVDC systems [129].

Furthermore, the deployment of PMUs in power systems is poised to revolutionize the way we monitor and manage electrical grids. PMUs are designed to provide real-time situational awareness for control centers, empowering operators to make informed decisions and take swift actions when needed. The widespread installation of PMUs by various utilities is a testament to their potential. However, there remain substantial challenges in harnessing their full capabilities. Consolidating, analyzing, visualizing, and effectively utilizing the wealth of data generated by thousands of PMUs is no small feat. One significant challenge is the integration of PMU data within SCADA systems. While the benefits of such integration are clear, achieving seamless coordination and situational awareness across the grid through SCADA and PMU data integration will require considerable effort and time.

It is worth noting that PMUs are not limited to the realm of transmission systems alone. They have found innumerable applications in distribution sectors and can be integrated with distribution management systems. Moreover, to truly unlock the potential of PMUs, research efforts have been conducted to establish a uniform and comprehensive wide-area monitoring, protection, and control scheme across the power grid. As the energy landscape evolves, PMUs will play an expanded role in ensuring grid reliability and stability, which positions PMUs as the new heartbeat of the power grid. As a result, the importance of conducting future tests in a more realistic environment, analyses, and studies on PMUs from various angles cannot be overstated.

In this context, the most effective test platform for PMUs is one that closely resembles real-world conditions. Real-time HIL tests emerge as a critical method for evaluating PMU performance and functionality. These tests provide a realistic environment for assessing how PMUs interact with the complex dynamics of the power grid, making them a crucial component of future research and development efforts.

Turning the attention to another aspect, the widespread use of communication systems also exposes smart grids to the risk of destructive cyber attacks, potentially jeopardizing the effectiveness of their protection systems. These cyberattacks come in various forms, including confidentiality attacks, eavesdropping, account cracking, false data injection, and so on. These threats can be coordinated simultaneously from multiple points in space and time. To ensure the security and reliability of cyber-physical systems, precise design of various aspects including risk prevention, detection, mitigation, and resilience is essential. Consequently, redesigning security schemes in a realistic environment should pay particular attention to address cybersecurity concerns.

VI. CONCLUSION

DRTS, particularly through HIL technology, has evolved into a fundamental and authentic approach employed across various domains, including power systems. HIL simulations offer realistic closed-loop interactions between virtual systems and physical hardware, reducing risks, costs, and complexity associated with testing. With the continuous computing power advancement of RTSs, the accuracy of models to closely represent reality is on the rise. While DRTS has greatly advanced power system analysis and design, it faces challenges in handling the increasing complexity of modern power systems caused by such technologies as high-frequency power electronic converters, etc. Additionally, the rise of wireless communication infrastructures introduces new opportunities and vulnerabilities. Addressing these challenges may require remote simulation platforms and a deeper consideration of communication device latencies.

Concerning the aforementioned issues, this survey paper has provided an extensive overview of DRTS applications in transmission power systems, highlighting their versatility and significance. From design and analysis to testing and monitoring, real-time simulation continues to shape the power system industry. It seems that as technology advances and power systems evolve, the role of HIL-based DRTS is expected to grow, further enhancing our understanding and management of complex cyber-physical systems.

It appears that the future of HIL-based DRTS on the transmission side holds exciting prospects. This paper has also endeavored to shed light on not only the present-day uses but also some potential future scopes related to the application of DRTS in modern grids.

REFERENCES

[1] X. Guillaud, M. O. Faruque, A. Teninge, A. H. Hariri, L. Vanfretti, M. Paolone, V. Dinavahi, P. Mitra, G. Lauss, C. Dufour, P. Forsyth, A. K. Srivastava, K. Strunz, T. Strasser, and A. Davoudi, "Applications of real-time simulation technologies in power and energy systems," *IEEE Power Energy Technol. Syst. J.*, vol. 2, pp. 103–115, 2015.

[2] L. Graber, T. Chiocchio, J. Kvitkovic, S. Pamidi, M. Steurer, and A. Usoskin, "Finite element model of a superconducting fault current limiter calibrated by hardware-in-the-loop measurements," *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, pp. 1–5, Jun. 2014.

[3] G. Lauss, Z. Feng, M. H. Syed, A. Kontou, A. D. Paola, A. Paspatis, and P. Kotsampopoulos, "A framework for sensitivity analysis of real-time power hardware-in-the-loop (PHIL) systems," *IEEE Access*, vol. 10, pp. 101305–101318, 2022.

[4] M. D. O. Faruque, T. Strasser, G. Lauss, V. Jalili-Marandi, P. Forsyth, C. Dufour, V. Dinavahi, A. Monti, P. Kotsampopoulos, J. A. Martinez, K. Strunz, M. Saeedifard, X. Wang, D. Shearer, and M. Paolone, "Real-time simulation technologies for power systems design, testing, and analysis," *IEEE Power Energy Technol. Syst. J.*, vol. 2, pp. 63–73, 2015.

[5] F. Mihalič, M. Truntič, and A. Hren, "Hardware-in-the-loop simulations: A historical overview of engineering challenges," *Electronics*, vol. 11, no. 15, p. 2462, Aug. 2022.

[6] (2014). *RTDS Technology, Winnipeg, MB, Canada*. [Online]. Available: https://www.rtds.com

[7] E. Vinot, J. Scordia, R. Trigui, B. Jeanneret, and F. Badin, "Model simulation, validation and case study of the 2004 THS of toyota prius," *Int. J. Vehicle Syst. Model. Test.*, vol. 3, no. 3, p. 139, 2008.

[8] R. M. Schupbach and J. C. Balda, "A versatile laboratory test bench for developing powertrains of electric vehicles," in *Proc. IEEE 56th Veh. Technol. Conf.*, vol. 3, Sep. 2002, pp. 1666–1670.

[9] Y. Chen and V. Dinavahi, "Multi-FPGA digital hardware design for detailed large-scale real-time electromagnetic transient simulation of power systems," *IET Gener., Transmiss. Distrib.*, vol. 7, no. 5, pp. 451–463, May 2013.

[10] P. C. Kotsampopoulos, V. A. Kleftakis, and N. D. Hatziargyriou, "Laboratory education of modern power systems using PHIL simulation," *IEEE Trans. Power Syst.*, vol. 32, no. 5, pp. 3992–4001, Sep. 2017.

[11] H. Zhao, S. Fan, and A. Gole, "Equivalency of state space models and EMT companion circuit models," in *Proc. Int. Conf. Power Syst. Transients*, 2019, pp. 1–5.

[12] A. A. van der Meer, M. Gibescu, M. A. M. M. van der Meijden, W. L. Kling, and J. A. Ferreira, "Advanced hybrid transient stability and EMT simulation for VSC-HVDC systems," *IEEE Trans. Power Del.*, vol. 30, no. 3, pp. 1057–1066, Jun. 2015.

[13] W. Du, A. Singhal, F. K. Tuffner, and K. P. Schneider, "Comparison of electromagnetic transient and phasor-based simulation for the stability of grid-forming-inverter-based microgrids," in *Proc. IEEE Power Energy Soc. Innov. Smart Grid Technol. Conf. (ISGT)*, Feb. 2021, pp. 1–5.

[14] K. Sano, S. Horiuchi, and T. Noda, "Comparison and selection of grid-tied inverter models for accurate and efficient EMT simulations," *IEEE Trans. Power Electron.*, vol. 37, no. 3, pp. 3462–3472, Mar. 2022.

[15] P. Kotsampopoulos, D. Lagos, N. Hatziargyriou, M. O. Faruque, G. Lauss, O. Nzimako, P. Forsyth, M. Steurer, F. Ponci, A. Monti, V. Dinavahi, and K. Strunz, "A benchmark system for hardware-in-the-loop testing of distributed energy resources," *IEEE Power Energy Technol. Syst. J.*, vol. 5, pp. 94–103, 2018.

[16] J. Allmeling and N. Felderer, "Sub-cycle average models with integrated diodes for real-time simulation of power converters," in *Proc. IEEE Southern Power Electron. Conf. (SPEC)*, Dec. 2017, pp. 1–6.

[17] K. L. Lian and P. W. Lehn, "Real-time simulation of voltage source converters based on time average method," *IEEE Trans. Power Syst.*, vol. 20, no. 1, pp. 110–118, Feb. 2005.

[18] S. Chiniforoosh, J. Jatskevich, A. Yazdani, V. Sood, V. Dinavahi, J. A. Martinez, and A. Ramirez, "Definitions and applications of dynamic average models for analysis of power systems," *IEEE Trans. Power Del.*, vol. 25, no. 4, pp. 2655–2669, Oct. 2010.

[19] R. Yonezawa, T. Noda, K. Fukushima, T. Nakajima, Y. Sekiba, K. Utsunomiya, E. Ito, K. Misawa, T. Chida, N. Yamaguchi, and Y. Takeuchi, "Development of detailed and averaged models of large-scale PV power generation systems for electromagnetic transient simulations under grid faults," in *Proc. IEEE Innov. Smart Grid Technol. Asia (ISGT-Asia)*, Nov. 2016, pp. 98–104.

[20] J. Peralta, H. Saad, S. Dennetiere, J. Mahseredjian, and S. Nguefeu, "Detailed and averaged models for a 401-level MMC–HVDC system," *IEEE Trans. Power Del.*, vol. 27, no. 3, pp. 1501–1508, Jul. 2012.

[21] J. Vega-Herrera, C. Rahmann, F. Valencia, and K. Strunz, "Analysis and application of quasi-static and dynamic phasor calculus for stability assessment of integrated power electric and electronic systems," *IEEE Trans. Power Syst.*, vol. 36, no. 3, pp. 1750–1760, May 2021.

[22] V. Jalili-Marandi, V. Dinavahi, K. Strunz, J. A. Martinez, and A. Ramirez, "Interfacing techniques for transient stability and electromagnetic transient programs IEEE task force on interfacing techniques for simulation tools," *IEEE Trans. Power Del.*, vol. 24, no. 4, pp. 2385–2395, Oct. 2009.

[23] K. Mudunkotuwa, S. Filizadeh, and U. Annakkage, "Development of a hybrid simulator by interfacing dynamic phasors with electromagnetic transient simulation," *IET Gener., Transmiss. Distribution*, vol. 11, no. 12, pp. 2991–3001, Aug. 2017.

[24] M. R. Nasab and H. Yaghobi, "A real-time out-of-step protection strategy based on instantaneous active power deviation," *IEEE Trans. Power Del.*, vol. 36, no. 6, pp. 3590–3600, Dec. 2021.

[25] M. R. Nasab and H. Yaghobi, "An analytical method for detecting instability in grid-connected doubly-fed induction generator," *IET Renew. Power Gener.*, vol. 15, no. 4, pp. 778–793, Mar. 2021.

[26] A. Ametani, "Electromagnetic transients program: History and future," *IEEJ Trans. Electr. Electron. Eng.*, vol. 16, no. 9, pp. 1150–1158, Sep. 2021.

[27] V. A. Lacerda, E. P. Araujo, M. Cheah-Mañe, and O. Gomis-Bellmunt, "Phasor modeling approaches and simulation guidelines of voltage-source converters in grid-integration studies," *IEEE Access*, vol. 10, pp. 51826–51838, 2022.

[28] Z. Shen and V. Dinavahi, "Dynamic variable time-stepping schemes for real-time FPGA-based nonlinear electromagnetic transient emulation," *IEEE Trans. Ind. Electron.*, vol. 64, no. 5, pp. 4006–4016, May 2017.

[29] S. Favuzza, R. Musca, G. Zizzo, and J. A. Sa'ed, "Comparative modeling and analysis of EMT and phasor RMS grid-forming converters under different power system dynamics," *IEEE Trans. Ind. Appl.*, vol. 60, no. 2, pp. 3613–3624, Mar. 2024.

[30] P. W. Sauer, M. A. Pai, and J. H. Chow, *Power System Dynamics and Stability: With Synchrophasor Measurement and Power System Toolbox*. Hoboken, NJ, USA: Wiley, 2017.

[31] G. Lauss and K. Strunz, "Accurate and stable hardware-in-the-loop (HIL) real-time simulation of integrated power electronics and power systems," *IEEE Trans. Power Electron.*, vol. 36, no. 9, pp. 10920–10932, Sep. 2021.

[32] A. Chandra, G. K. Singh, and V. Pant, "Protection of AC microgrid integrated with renewable energy sources – a research review and future trends," *Electr. Power Syst. Res.*, vol. 193, Apr. 2021, Art. no. 107036.

[33] M. Debouza, A. Al-Durra, T. H. M. El-Fouly, and H. H. Zeineldin, "Survey on microgrids with flexible boundaries: Strategies, applications, and future trends," *Electr. Power Syst. Res.*, vol. 205, Apr. 2022, Art. no. 107765.

[34] S. Beheshtaein, R. Cuzner, M. Savaghebi, and J. M. Guerrero, "Review on microgrids protection," *IET Gener, Transmis. Distrib.*, vol. 13, no. 6, pp. 743–759, 2019.

[35] R. Ahmadiahangar, A. Rosin, A. N. Niaki, I. Palu, and T. Korõtko, "A review on real-time simulation and analysis methods of microgrids," *Int. Trans. Electr. Energy Syst.*, vol. 29, no. 11, Nov. 2019, Art. no. e12106.

[36] G. Bedi, G. K. Venayagamoorthy, R. Singh, R. R. Brooks, and K.-C. Wang, "Review of Internet of Things (IoT) in electric power and energy systems," *IEEE Internet Things J.*, vol. 5, no. 2, pp. 847–870, Apr. 2018.

[37] Y. He, G. J. Mendis, and J. Wei, "Real-time detection of false data injection attacks in smart grid: A deep learning-based intelligent mechanism," *IEEE Trans. Smart Grid*, vol. 8, no. 5, pp. 2505–2516, Sep. 2017.

[38] M. Steurer, F. Bogdan, W. Ren, M. Sloderbeck, and S. Woodruff, "Controller and power hardware-in-loop methods for accelerating renewable energy integration," in *Proc. IEEE Power Eng. Soc. Gen. Meeting*, Jun. 2007, pp. 1–4.

[39] P. Imris, M. Bradley, G. Taylor, and Y. Li, "Development of a Great Britain transmission system reduced model for hardware-in-the-loop studies," in *Proc. 55th Int. Universities Power Eng. Conf. (UPEC)*, Sep. 2020, pp. 1–6.

[40] M. Steurer, C. S. Edrington, M. Sloderbeck, W. Ren, and J. Langston, "A megawatt-scale power hardware-in-the-loop simulation setup for motor drives," *IEEE Trans. Ind. Electron.*, vol. 57, no. 4, pp. 1254–1260, Apr. 2010.

[41] A. Monti, H. Figueroa, S. Lentijo, X. Wu, and R. Dougal, "Interface issues in hardware-in-the-loop simulation," in *Proc. IEEE Electric Ship Technol. Symp.*, Jul. 2005, pp. 39–45.

[42] H. Miao, "Modeling, stability and accuracy of power hardware-in-the-loop simulation of power electronic systems," Ph.D. dissertation, Osaka Univ., Osaka, Japan, 2010.

[43] G. Lauss, F. Lehfuß, A. Viehweider, and T. Strasser, "Power hardware in the loop simulation with feedback current filtering for electric systems," in *Proc. 37th Annu. Conf. IEEE Ind. Electron. Soc. (IECON)*, Nov. 2011, pp. 3725–3730.

[44] G. Lauss and K. Strunz, "Multirate partitioning interface for enhanced stability of power hardware-in-the-loop real-time simulation," *IEEE Trans. Ind. Electron.*, vol. 66, no. 1, pp. 595–605, Jan. 2019.

[45] E. G. Sansano, "Novel methods for enhancing accuracy and stability of power hardware-in-the-loop simulations," Tech. Rep., 2018.

[46] A. Markou, V. Kleftakis, P. Kotsampopoulos, and N. Hatziargyriou, "Improving existing methods for stable and more accurate power hardware-in-the-loop experiments," in *Proc. IEEE 26th Int. Symp. Ind. Electron. (ISIE)*, Jun. 2017, pp. 496–502.

[47] E. Bompard, S. Bruno, A. Cordoba-Pacheco, C. Diaz-Londono, G. Giannoccaro, M. L. Scala, A. Mazza, and E. Pons, "Latency and simulation stability in a remote power hardware-in-the-loop cosimulation testbed," *IEEE Trans. Ind. Appl.*, vol. 57, no. 4, pp. 3463–3473, Jul. 2021.

[48] A. Mazza, A. Estebsari, G. Morandi, E. Bompard, and H. Lok, "Remote hardware-in-the-loop measurement system for electrolyser characterization," in *Proc. IEEE Int. Conf. Environ. Electr. Eng. IEEE Ind. Commercial Power Syst. Eur. (EEEIC/I&CPS Europe)*, Jun. 2019, pp. 1–6.

[49] B. Palmintier, B. Lundstrom, S. Chakraborty, T. Williams, K. Schneider, and D. Chassin, "A power hardware-in-the-loop platform with remote distribution circuit cosimulation," *IEEE Trans. Ind. Electron.*, vol. 62, no. 4, pp. 2236–2245, Apr. 2015.

[50] B. Lundstrom, B. Palmintier, D. Rowe, J. Ward, and T. Moore, "Trans-oceanic remote power hardware-in-the-loop: Multi-site hardware, integrated controller, and electric network co-simulation," *IET Gener., Transmiss. Distrib.*, vol. 11, no. 18, pp. 4688–4701, Dec. 2017.

[51] G. Benedetto, E. Bompard, A. Mazza, E. Pons, S. Bruno, G. Giannoccaro, M. La Scala, F. De Caro, A. Bonfiglio, S. Bracco, M. Invernizzi, M. Rossi, A. De Paola, D. Thomas, E. Kotsakis, G. Fulli, and D. Villacci, "Ensiel national energy transition real time lab: A novel tool to shape the future energy system," in *Proc. AEIT Int. Annu. Conf. (AEIT)*, Oct. 2022, pp. 1–6.

[52] S. M. Mohseni-Bonab, A. Hajebrahimi, I. Kamwa, and A. Moeini, "Transmission and distribution co-simulation: A review and propositions," *IET Gener., Transmiss. Distrib.*, vol. 14, no. 21, pp. 4631–4642, Nov. 2020.

[53] P. G. McLaren et al., "Using a real-time simulator to design, prove, and test power system protection systems," in *Proc. CIGRE*, 2011.

[54] C. F. Covrig et al., "A European platform for distributed real time modelling & simulation of emerging electricity systems," JRC Tech. Rep. JRC101772, EUR 27941 EN, 2016.

[55] C. D. López, A. A. van der Meer, M. Cvetkovic, and P. Palensky, "A variable-rate co-simulation environment for the dynamic analysis of multi-area power systems," in *Proc. IEEE Manchester PowerTech*, Jun. 2017, pp. 1–6.

[56] E. Bompard, S. Bruno, S. Frittoli, G. Giannoccaro, M. L. Scala, A. Mazza, E. Pons, and C. Rodio, "Remote PHIL distributed co-simulation lab for TSO-DSO-customer coordination studies," in *Proc. AEIT Int. Annu. Conf. (AEIT)*, Sep. 2020, pp. 1–6.

[57] X. Lin, A. M. Gole, and M. Yu, "A wide-band multi-port system equivalent for real-time digital power system simulators," *IEEE Trans. Power Syst.*, vol. 24, no. 1, pp. 237–249, Feb. 2009.

[58] M. La Scala, M. De Benedictis, S. Bruno, A. Grobovoy, N. Bondareva, N. Borodina, D. Denisova, A. J. Germond, and R. Cherkaoui, "Development of applications in WAMS and WACS: An international cooperation experience," in *Proc. IEEE Power Eng. Soc. Gen. Meeting*, Jun. 2006, p. 10.

[59] T. Becejac, C. Eppinger, A. Ashok, U. Agrawal, and J. O'Brien, "PRIME: A real-time cyber-physical systems testbed: From wide-area monitoring, protection, and control prototyping to operator training and beyond," *IET Cyber-Phys. Syst., Theory Appl.*, vol. 5, no. 2, pp. 186–195, Jun. 2020.

[60] S. Bruno, M. De Benedictis, and M. La Scala, "Integrating dynamic optimization methodologies with WAMS technologies," in *Proc. IEEE Power Eng. Soc. Gen. Meeting*, Jun. 2007, pp. 1–8.

[61] J. R. L. Gutiérrez, P. Ponce, and A. Molina, "Real-time power electronics laboratory to strengthen distance learning engineering education on smart grids and microgrids," *Future Internet*, vol. 13, no. 9, p. 237, Sep. 2021.

[62] T. Strasser, M. Stifter, F. Andrén, and P. Palensky, "Co-simulation training platform for smart grids," *IEEE Trans. Power Syst.*, vol. 29, no. 4, pp. 1989–1997, Jul. 2014.

[63] M. Čech, M. Goubej, J. Sobota, and A. Visioli, "Model-based system engineering in control education using HIL simulators," *IFAC-PapersOnLine*, vol. 53, no. 2, pp. 17302–17307, 2020.

[64] C. Dufour, S. Abourida, J. Belanger, and V. Lapointe, "InfiniBand-based real-time simulation of HVDC, STATCOM, and SVC devices with commercial-off-the-shelf PCs and FPGAs," in *Proc. 32nd Annu. Conf. IEEE Ind. Electron. (IECON)*, Paris, France, Nov. 2006, pp. 5325–5331.

[65] M. Daryabak, S. Filizadeh, J. Jatskevich, A. Davoudi, M. Saeedifard, V. K. Sood, J. A. Martinez, D. Aliprantis, J. Cano, and A. Mehrizi-Sani, "Modeling of LCC-HVDC systems using dynamic phasors," *IEEE Trans. Power Del.*, vol. 29, no. 4, pp. 1989–1998, Aug. 2014.

[66] N. Lin and V. Dinavahi, "Detailed device-level electrothermal modeling of the proactive hybrid HVDC breaker for real-time hardware-in-the-loop simulation of DC grids," *IEEE Trans. Power Electron.*, vol. 33, no. 2, pp. 1118–1134, Feb. 2018.

[67] P. Mitra and T. Larsson, "ABB'S HVDC grid simulation center: A powerful tool for real-time research of DC grids," in *Proc. EWEA Annu. Event*, Barcelona, Spain, 2014, pp. 1–10.

[68] P. Mitra et al., "First real-time implementation of DC grid protection strategy," Tech. Rep., 2015.

[69] H. Horii, Y. Kida, T. Ooishi, G. Managaki, F. Saito, and K. Takahashi, "Closed-loop test of HVDC control system using real-time digital simulator," in *Proc. Int. Conf. Electr. Eng. (ICEE)*, 2008.

[70] S. D'Arco, T. D. Duong, and J. Are Suul, "P-HiL evaluation of virtual inertia support to the Nordic power system by an HVDC terminal," in *Proc. IEEE PES Innov. Smart Grid Technol. Eur. (ISGT-Europe)*, Oct. 2020, pp. 176–180.

[71] R. Li, L. Xu, and D. Guo, "Accelerated switching function model of hybrid MMCs for HVDC system simulation," *IET Power Electron.*, vol. 10, no. 15, pp. 2199–2207, Dec. 2017.

[72] O. Venjakob, S. Kubera, R. Hibberts-Caswell, P. A. Forsyth, and T. L. Maguire, "Setup and performance of the real-time simulator used for hardware-in-loop-tests of a VSC-based HVDC scheme for offshore applications," in *Proc. Int. Conf. Power Syst. Transients (IPST)*, 2013, pp. 18–20.

[73] M. Lemaire, P. Sicard, and J. Belanger, "Prototyping and testing power electronics systems using controller hardware-in-the-loop (HIL) and power hardware-in-the-loop (PHIL) simulations," in *Proc. IEEE Vehicle Power Propuls. Conf. (VPPC)*, Oct. 2015, pp. 1–6.

[74] W. Li and J. Bélanger, "An equivalent circuit method for modelling and simulation of modular multilevel converters in real-time HIL test bench," *IEEE Trans. Power Del.*, vol. 31, no. 5, pp. 2401–2409, Oct. 2016.

[75] J. P. Farwell and R. Rohozinski, "Stuxnet and the future of cyber war," *Survival*, vol. 53, no. 1, pp. 23–40, Feb. 2011.

[76] J. Choi, D. Narayanasamy, B. Ahn, S. Ahmad, J. Zeng, and T. Kim, "A real-time hardware-in-the-loop (HIL) cybersecurity testbed for power electronics devices and systems in cyber-physical environments," in *Proc. IEEE 12th Int. Symp. Power Electron. for Distrib. Gener. Syst. (PEDG)*, Jun. 2021, pp. 1–5.

[77] S. Bruno, G. Giannoccaro, C. Iurlaro, M. L. Scala, and C. Rodio, "A low-cost controller to enable synthetic inertia response of distributed energy resources," in *Proc. IEEE Int. Conf. Environ. Electr. Eng. IEEE Ind. Commercial Power Syst. Eur. (EEEIC/I&CPS Europe)*, Jun. 2020, pp. 1–6.

[78] S. Bruno, G. Giannoccaro, C. Iurlaro, M. L. Scala, M. Menga, C. Rodio, and R. Sbrizzai, "Fast frequency support through LED street lighting in small non-synchronous power systems," *IEEE Trans. Ind. Appl.*, vol. 59, no. 2, pp. 2277–2287, Mar. 2023.

[79] M. Vogt, F. Marten, and M. Braun, "A survey and statistical analysis of smart grid co-simulations," *Appl. Energy*, vol. 222, pp. 67–78, Jul. 2018.

[80] R. Todd, H. J. Uppal, T. Feehally, A. J. Forsyth, and A. M. Pavan, "A power hardware-in-the-loop simulation facility for testing grid-connected storage systems," in *Proc. IEEE Power Energy Soc. Innov. Smart Grid Technol. Conf. (ISGT)*, Feb. 2019, pp. 1–5.

[81] P. Imris, M. Bradley, G. Taylor, and Y. Li, "Validation of dynamic GB transmission system models with PMU data for hardware-in-the-loop studies," in *Proc. 15th Int. Conf. Develop. Power Syst. Protection (DPSP)*. Edison, NJ, USA: IET, Mar. 2020, pp. 1–6.

[82] G. Di Lembo, V. Agnetta, and G. Fiorenza, "Integration of DSO control systems and tso automatic load shedding system to improve the security of the national grid," in *Proc. 20th Int. Conf. Exhib. Electr. Distrib. (CIRED)*, Prague, Czech Republic, Jun. 2009, pp. 1–4.

[83] S. Abdelwahid, A. Babiker, A. Eltom, and G. Kobet, "Hardware implementation of an automatic adaptive centralized underfrequency load shedding scheme," *IEEE Trans. Power Del.*, vol. 29, no. 6, pp. 2664–2673, Dec. 2014.

[84] S. Bruno, C. Iurlaro, M. La Scala, M. Menga, and M. Semeraro, "A dynamic model of the favignana island non-synchronous power system for power hardware-in-the-loop tests," in *Proc. Workshop Blockchain for Renew. Integr. (BLORIN)*, Sep. 2022, pp. 107–112.

[85] S. Bruno, G. Giannoccaro, M. M. Islam, C. Iurlaro, M. La Scala, M. Menga, and C. Rodio, "Control and power hardware-in-the-loop tests for low-inertia power systems," in *Proc. AEIT Int. Annu. Conf. (AEIT)*, Oct. 2022, pp. 1–6.

[86] K. Kawal, Q. Hong, S. Paladhi, D. Liu, P. N. Papadopoulos, S. Blair, and C. Booth, "Vulnerability assessment of line current differential protection in converter–dominated power systems," in *Proc. 16th Int. Conf. Develop. Power Syst. Protection (DPSP)*, vol. 2022, Mar. 2022, pp. 362–367.

[87] C. Wei, C. Tu, A. Wen, and W. Song, "Tie line fault ride-through method of photovoltaic station based on cooperative strategy of energy storage, relay protection and photovoltaic inverters," *IET Gener., Transmiss. Distrib.*, vol. 17, no. 7, pp. 1613–1623, Apr. 2023.

[88] P. Forsyth et al., "A real-time environment for closed-loop testing of PMU-based WACS schemes," in *Proc. CIGRE*, 2013.

[89] A. T. Al-Hammouri, L. Nordström, M. Chenine, L. Vanfretti, N. Honeth, and R. Leelaruji, "Virtualization of synchronized phasor measurement units within real-time simulators for smart grid applications," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2012, pp. 1–7.

[90] R. Majumder, B. C. Pal, C. Dufour, and P. Korba, "Design and real-time implementation of robust FACTS controller for damping inter-area oscillation," *IEEE Trans. Power Syst.*, vol. 21, no. 2, pp. 809–816, May 2006.

[91] Y. Liu, Z. Xi, Z. Liang, W. Song, S. Bhattacharya, A. Huang, J. Langston, M. Steurer, W. Litzenberger, L. Anderson, R. Adapa, and A. Sundaram, "Controller hardware-in-the-loop validation for a 10 MVA ETO-based STATCOM for wind farm application," in *Proc. IEEE Energy Convers. Congr. Expo.*, Sep. 2009, pp. 1398–1403.

[92] A. S. Musleh, S. M. Muyeen, A. Al-Durra, and I. Kamwa, "Testing and validation of wide-area control of STATCOM using real-time digital simulator with hybrid HIL–SIL configuration," *IET Gener., Transmiss. Distrib.*, vol. 11, no. 12, pp. 3039–3049, Aug. 2017.

[93] S. Su and A. Auld-Hill, "Santiago synchronous condenser replica controller HIL setup for apparatus training and operational support," GE Autom., Nayak Corp., RTDS Tech., Southern California Edison, Rosemead, CA, USA, Tech. Rep., 2014.

[94] J. Jia, G. Yang, A. H. Nielsen, and P. Rønne-Hansen, "Hardware-in-the-loop tests on reverse power and over-frequency protection for synchronous condensers," in *Proc. Int. Symp. CIGRE Aalborg*, 2019, p. 104.

[95] M. S. Almas, M. Baudette, and L. Vanfretti, "Utilizing synchrophasor-based supplementary damping control signals in conventional generator excitation systems," *Electric Power Syst. Res.*, vol. 157, pp. 157–167, Apr. 2018.

[96] S. Li, L. Zhang, J.-N. Paquin, J. Bélanger, and L. Vanfretti, "Hardware-in-the-loop use cases for synchrophasor applications," in *Proc. Int. Conf. Smart Grid Synchronized Meas. Anal. (SGSMA)*, May 2019, pp. 1–8.

[97] P. Castello, G. Gallus, P. A. Pegoraro, and S. Sulis, "Measurement platform for latency characterization of wide area monitoring, protection and control systems," *IEEE Trans. Instrum. Meas.*, vol. 73, pp. 1–12, 2024.

[98] F. Zhang, Y. Sun, L. Cheng, X. Li, J. H. Chow, and W. Zhao, "Measurement and modeling of delays in wide-area closed-loop control systems," *IEEE Trans. Power Syst.*, vol. 30, no. 5, pp. 2426–2433, Sep. 2015.

[99] D. Baltensperger, S. Sanchez, S. D'Arco, and K. Uhlen, "Assessing hardware in the loop approaches for wide-area monitoring control and protection devices," *IEEE Trans. Power Del.*, vol. 38, no. 4, pp. 2724–2734, Aug. 2023.

[100] A. C. Adewole and R. Tzoneva, "Co-simulation platform for integrated real-time power system emulation and wide area communication," *IET Gener., Transmiss. Distrib.*, vol. 11, no. 12, pp. 3019–3029, Aug. 2017.

[101] L. Kumar, S. Ahmed, L. Vanfretti, and N. Kishor, "Real-time testing of synchrophasor-based wide-area monitoring system applications acknowledging the potential use of a prototyping software toolchain," *Int. Trans. Electr. Energy Syst.*, vol. 2022, Jul. 2022.

[102] H. Georg, S. C. Müller, N. Dorsch, C. Rehtanz, and C. Wietfeld, "INSPIRE: Integrated co-simulation of power and ICT systems for real-time evaluation," in *Proc. IEEE Int. Conf. Smart Grid Commun. (SmartGridComm)*, Oct. 2013, pp. 576–581.

[103] V. P. Tran, S. Kamalasadan, and J. Enslin, "Real-time modeling and model validation of synchronous generator using synchrophasor measurements," in *Proc. North Amer. Power Symp. (NAPS)*, Sep. 2013, pp. 1–5.

[104] C. B. Vellaithurai, S. S. Biswas, and A. K. Srivastava, "Development and application of a real-time test bed for cyber–physical system," *IEEE Syst. J.*, vol. 11, no. 4, pp. 2192–2203, Dec. 2017.

[105] A. Chakrabortty and Y. Xin, "Hardware-in-the-loop simulations and verifications of smart power systems over an exo-GENI testbed," in *Proc. 2nd GENI Res. Educ. Exp. Workshop*, Mar. 2013, pp. 16–19.

[106] A. Grobovoy, N. Bondareva, N. Borodina, D. Denisova, A. Germond, R. Cherkaoui, M. La Scala, S. Bruno, and M. De Benedictis, "Full-scale tests of the AC transmission system to examine the new SPS complexes," in *Proc. 8th IEE Int. Conf. AC DC Power Transmiss. (ACDC)*. Edison, NJ, USA: IET, 2006, pp. 4–8.

[107] M. S. Almas, L. Vanfretti, R. S. Singh, and G. M. Jonsdottir, ''Vulnerability of synchrophasor-based WAMPAC applications' to time synchronization spoofing,'' *IEEE Trans. Smart Grid*, vol. 9, no. 5, pp. 4601–4612, Sep. 2018.

[108] K. Popovici and P. Mosterman, *Real-Time Simulation Technologies: Principles, Methodologies, and Applications* (Computational Analysis, Synthesis, and Design of Dynamic Systems). Boca Raton, FL, USA: CRC Press, 2017. [Online]. Available: https://books.google.it/books?id=GvlzMPbuZqAC

[109] M. Vogt, F. Marten, L. Löwer, D. Horst, K. Brauns, D. Fetzer, J.-H. Menke, M. Troncia, J. Hegemann, C. Töbermann, and M. Braun, ''Evaluation of interactions between multiple grid operators based on sparse grid knowledge in context of a smart grid co-simulation environment,'' in *Proc. IEEE Eindhoven PowerTech*, Jun. 2015, pp. 1–6.

[110] S. Bruno et al., ''Co-simulazione multi-sito e cooperazione tra laboratori,'' in *Proc. COVID*, 2020.

[111] M. Stevic, A. Estebsari, S. Vogel, E. Pons, E. Bompard, M. Masera, and A. Monti, ''Multi-site European framework for real-time co-simulation of power systems,'' *IET Gener., Transmiss. Distrib.*, vol. 11, no. 17, pp. 4126–4135, Nov. 2017.

[112] F. Xie, C. McEntee, M. Zhang, N. Lu, X. Ke, M. R. Vallem, and N. Samaan, ''Networked HIL simulation system for modeling large-scale power systems,'' in *Proc. 52nd North Amer. Power Symp. (NAPS)*, Apr. 2021, pp. 1–6.

[113] International Energy Agency, Paris, France. (2023). *Renewable Analysis and Forecasts to 2028*. [Online]. Available: https://www.iea.org/reports/renewables-2023

[114] K. Shanmugam, M. Filippone, P. Almaleck, and P. Serra, ''Real time modelling and hardware-in-loop validation of smart AC microgrid with BESS,'' in *Proc. IEEE 12th Int. Symp. Power Electron. Distrib. Gener. Syst. (PEDG)*, Jun. 2021, pp. 1–8.

[115] E. Tara, S. Filizadeh, and E. Dirks, ''Battery-in-the-loop simulation of a planetary-gear-based hybrid electric vehicle,'' *IEEE Trans. Veh. Technol.*, vol. 62, no. 2, pp. 573–581, Feb. 2013.

[116] E. Tara, S. Filizadeh, J. Jatskevich, E. Dirks, A. Davoudi, M. Saeedifard, K. Strunz, and V. K. Sood, ''Dynamic average-value modeling of hybrid-electric vehicular power systems,'' *IEEE Trans. Power Del.*, vol. 27, no. 1, pp. 430–438, Jan. 2012.

[117] S. Bruno, G. Giannoccaro, C. Iurlaro, M. La Scala, and C. Rodio, ''Power hardware-in-the-loop test of a low-cost synthetic inertia controller for battery energy storage system,'' *Energies*, vol. 15, no. 9, p. 3016, Apr. 2022.

[118] A. Hoke, P. Koralewicz, R. W. Kenyon, B. Wang, L. Yu, K. Kawamura, and J. Tan, ''Stabilizing inverter-based transmission systems: Power hardware-in-the-loop experiments with a megawatt-scale grid-forming inverter,'' *IEEE Electrific. Mag.*, vol. 10, no. 3, pp. 32–44, Sep. 2022.

[119] H. T. Reda, B. Ray, P. Peidaee, A. Anwar, A. Mahmood, A. Kalam, and N. Islam, ''Vulnerability and impact analysis of the IEC 61850 GOOSE protocol in the smart grid,'' *Sensors*, vol. 21, no. 4, p. 1554, Feb. 2021.

[120] V. S. Rajkumar, M. Tealane, A. Stefanov, A. Presekal, and P. Palensky, ''Cyber attacks on power system automation and protection and impact analysis,'' in *Proc. IEEE PES Innov. Smart Grid Technol. Eur. (ISGT-Europe)*, Oct. 2020, pp. 247–254.

[121] A. A. Memon and K. Kauhaniemi, ''Real-time hardware-in-the-loop testing of IEC 61850 GOOSE-based logically selective adaptive protection of AC microgrid,'' *IEEE Access*, vol. 9, pp. 154612–154639, 2021.

[122] Y. Yang, H.-Q. Xu, L. Gao, Y.-B. Yuan, K. McLaughlin, and S. Sezer, ''Multidimensional intrusion detection system for IEC 61850-based SCADA networks,'' *IEEE Trans. Power Del.*, vol. 32, no. 2, pp. 1068–1078, Apr. 2017.

[123] M. Hemmati, H. Palahalli, G. Gruosso, and S. Grillo, ''Interoperability analysis of IEC61850 protocol using an emulated IED in a HIL microgrid testbed,'' in *Proc. IEEE Int. Conf. Commun., Control, Comput. Technol. for Smart Grids (SmartGridComm)*, Oct. 2021, pp. 152–157.

[124] J. Hong, R. Karnati, C.-W. Ten, S. Lee, and S. Choi, ''Implementation of secure sampled value (SeSV) messages in substation automation system,'' *IEEE Trans. Power Del.*, vol. 37, no. 1, pp. 405–414, Feb. 2022.

[125] M. Hemmati, M. H. Palahalli, G. Storti Gajani, and G. Gruosso, ''Impact and vulnerability analysis of IEC61850 in smartgrids using multiple HIL real-time testbeds,'' *IEEE Access*, vol. 10, pp. 103275–103285, 2022.

[126] (2022). *Typhoon HIL*. Accessed: Jan. 2022. [Online]. Available: https://www.typhoon-hil.com/

[127] S. Li, D. Hilbrich, A. Bonetti, J.-N. Paquin, ''Evolution to model-based testing of protection systems and the publication of the IEC 60255–121 standard,'' in *Proc. 8th PAC World Conf.*, Wrocław, Poland, 2017, pp. 26–29.

[128] *Measuring Relays and Protection Equipment—Part 121: Functional Requirements for Distance Protection*, Standard IEC-60255-121, IEC Standard Press, 2014. [Online]. Available: https://books.google.it/books?id=GvlzMPbuZqAC

[129] V. Raveendran, M. Andresen, G. Buticchi, and M. Liserre, ''Thermal stress based power routing of smart transformer with CHB and DAB converters,'' *IEEE Trans. Power Electron.*, vol. 35, no. 4, pp. 4205–4215, Apr. 2020.

[130] C. Rehtanz and X. Guillaud, ''Real-time and co-simulations for the development of power system monitoring, control and protection,'' in *Proc. Power Syst. Comput. Conf. (PSCC)*, Jun. 2016, pp. 1–20.

[131] X. Sun, Y. Chen, J. Liu, and S. Huang, ''A co-simulation platform for smart grid considering interaction between information and power systems,'' in *Proc. ISGT*, Feb. 2014, pp. 1–6.

[132] K. Luo, X. Chen, H. Zheng, and Z. Shi, ''A review of deep learning approach to predicting the state of health and state of charge of lithium-ion batteries,'' *J. Energy Chem.*, vol. 74, pp. 159–173, Nov. 2022.

[133] O. Tremblay, D. Rimorov, R. Gagnon, and H. Fortin-Blanchette, ''A multi-time-step transmission line interface for power hardware-in-the-loop simulators,'' *IEEE Trans. Energy Convers.*, vol. 35, no. 1, pp. 539–548, Mar. 2020.

[134] O. Tremblay and L.-A. Dessaint, ''Experimental validation of a battery dynamic model for EV applications,'' *World Electr. Vehicle J.*, vol. 3, no. 2, pp. 289–298, Jun. 2009.

[135] A. Spina, O. Pohl, U. Häger, and C. Rehtanz, ''A power hardware-in-the-loop setup for testing distributed series reactors,'' in *Proc. AEIT Int. Annu. Conf. (AEIT)*, Sep. 2020, pp. 1–6.

[136] OPAL-RT Technologies. (2021). *Versatile Real-time Digital Simulator*. [Online]. Available: https://www.opal-rt.com/simulator-platform-op5600/

[137] M. H. McKinney, J. C. Fox, E. R. Collins, K. Bulgakov, and T. E. Salem, ''Design, development, and commissioning of a multimegawatt test facility for renewable energy research,'' *IEEE Trans. Ind. Appl.*, vol. 52, no. 1, pp. 11–17, Jan. 2016.

[138] A. von Jouanne, E. Agamloh, and A. Yokochi, ''Power hardware-in-the-loop (PHIL): A review to advance smart inverter-based grid-edge solutions,'' *Energies*, vol. 16, no. 2, p. 916, Jan. 2023.

[139] L. Vanfretti, M. Chenine, M. S. Almas, R. Leelaruji, L. Ängquist, and L. Nordström, ''SmarTS lab —A laboratory for developing applications for WAMPAC systems,'' in *Proc. IEEE Power Energy Soc. Gen. Meeting*, Jul. 2012, pp. 1–8.

[140] G. Benedetto, A. Mazza, E. Pons, E. Bompard, A. De Paola, D. Thomas, E. Kotsakis, G. Fulli, S. Vogel, A. Monti, S. Bruno, G. Giannoccaro, M. L. Scala, A. Bonfiglio, M. Invernizzi, M. Rossi, F. De Caro, and D. Villacci, ''Supporting a 'glocal' energy transition: From local energy communities to global simulation networks,'' in *Proc. Int. Conf. Smart Energy Syst. Technol. (SEST)*, Sep. 2023, pp. 1–6.

[141] S. Bruno, G. Giannoccaro, C. Iurlaro, M. L. Scala, C. Rodio, and R. Sbrizzai, ''Fast frequency regulation support by LED street lighting control,'' in *Proc. IEEE Int. Conf. Environ. Electr. Eng. IEEE Ind. Commercial Power Syst. Eur. (EEEIC/I&CPS Europe)*, Sep. 2021, pp. 1–6.

[142] V. Hoa Nguyen, Y. Besanger, Q. Tuan Tran, T. L. Nguyen, C. Boudinet, R. Brandl, F. Marten, A. Markou, P. Kotsampopoulos, A. A. van der Meer, E. Guillo-Sansano, G. Lauss, T. I. Strasser, and K. Heussen, ''Real-time simulation and hardware-in-the-loop approaches for integrating renewable energy sources into smart grids: Challenges & actions,'' 2017, *arXiv:1710.02306*.

[143] Z. Liu, Q. Wang, and Y. Tang, ''Design of a cosimulation platform with hardware-in-the-loop for cyber-attacks on cyber-physical power systems,'' *IEEE Access*, vol. 8, pp. 95997–96005, 2020.

[144] M. Nikkhoo, M. R. Nasab, and A. Hosseini, ''An innovative shielding strategy for stray loss reduction of neutral grounding reactor,'' *IEEE Trans. Magn.*, vol. 58, no. 8, pp. 1–9, Aug. 2022.

[145] C. M. Franck, ''HVDC circuit breakers: A review identifying future research needs,'' *IEEE Trans. Power Del.*, vol. 26, no. 2, pp. 998–1007, Apr. 2011.

[146] G. F. Lauss, M. O. Faruque, K. Schoder, C. Dufour, A. Viehweider, and J. Langston, ''Characteristics and design of power hardware-in-the-loop simulations for electrical power systems,'' *IEEE Trans. Ind. Electron.*, vol. 63, no. 1, pp. 406–417, Jan. 2016.

[147] Z. Jin, Y. Wu, S. Wang, and B. Zhang, "FPGA-based real-time simulation of dual-port submodule MMC–HVDC system," *Energies*, vol. 15, no. 13, p. 4624, Jun. 2022.

[148] R. Li, D. Li, Y. Gao, C. Gu, X. Sun, and L. Fan, "FPGA-based real-time simulation of LCC-HVDC systems with C-NAM method," *J. Power Electron.*, vol. 23, no. 6, pp. 913–922, Jun. 2023.

[149] Z. Shen, F. Arraño-Vargas, H. R. Wickramasinghe, and G. Konstantinou, "Distributed real-time simulations of power systems: A review," in *Proc. IEEE PES 14th Asia–Pacific Power Energy Eng. Conf. (APPEEC)*, Nov. 2022, pp. 1–6.

[150] M. Barnes, D. S. Vilchis-Rodriguez, X. Pei, R. Shuttleworth, O. Cwikowski, and A. C. Smith, "HVDC circuit breakers—A review," *IEEE Access*, vol. 8, pp. 211829–211848, 2020.

[151] P. S. Hosseinian, S. Ebrahimi, and J. Jatskevich, "Hybrid parametric average-value/detailed modeling of classic HVDC systems," in *Proc. Int. Conf. Electr., Comput. Energy Technol. (ICECET)*, Jul. 2022, pp. 1–6.

[152] A. Shetgaonkar, S. Liu, and M. Popov, "Comparative analysis of a detailed and an average VARC DCCB model in MTDC systems," in *Proc. IEEE Power Energy Soc. Gen. Meeting (PESGM)*, Jul. 2022, pp. 1–5.

[153] S. S. H. Yazdi, K. Rouzbehi, M. J. Carrizosa, A. Heidary, and M. Bagheri, "Modeling, control, and operation of an M-DAB DC–DC converter for interconnection of HVDC grids," *IEEE Syst. J.*, vol. 17, no. 2, pp. 2652–2663, Jun. 2023.

[154] H. Kikusato, T. S. Ustun, J. Hashimoto, K. Otani, T. Nagakura, Y. Yoshioka, R. Maeda, and K. Mori, "Developing power hardware-in-the-loop based testing environment for volt-var and frequency-watt functions of 500 kW photovoltaic smart inverter," *IEEE Access*, vol. 8, pp. 224135–224144, 2020.

[155] M. Kurtoğlu, F. Eroğlu, A. O. Arslan, and A. M. Vural, "Recent contributions and future prospects of the modular multilevel converters: A comprehensive review," *Int. Trans. Electr. Energy Syst.*, vol. 29, no. 3, p. 2763, Mar. 2019.

[156] A. Alassi, S. Bañales, O. Ellabban, G. Adam, and C. MacIver, "HVDC transmission: Technology review, market trends and future outlook," *Renew. Sustain. Energy Rev.*, vol. 112, pp. 530–554, Sep. 2019.

MOHAMMAD RAJABI NASAB (Graduate Student Member, IEEE) was born in Shahrood, Iran. He received the M.Sc. degree (Hons.) in electrical engineering, with a specialization in power systems from Semnan University, Semnan, Iran, in 2019. He is currently pursuing the Ph.D. degree with the Department of Electrical and Information Engineering, Polytechnic University of Bari, Bari, Italy. He is also a Research Fellow with the Polytechnic University of Bari. His research interests include smart grids, grid flexibility, power system transients, power hardware-in-the-loop, and real-time simulation.

ROBERTO COMETA (Graduate Student Member, IEEE) was born in Putignano, Italy, in 1996. He received the B.Sc. and M.Sc. (cum laude) degrees in electrical engineering from the Politecnico di Bari, Bari, in 2020 and 2022, respectively, where he is currently pursuing a Ph.D. degree in electrical engineering in the power systems field. His research interests include electric transmission and distribution systems, with an emphasis on static and dynamic security analysis and the optimal use of grid assets by system's operators. His current studies encompass optimization algorithms from electricity market applications to the identification of optimal operating maneuvers for improving the security and reliability of power systems, and simulations of dynamic systems using remote-power hardware in-the-loop techniques.

SERGIO BRUNO (Member, IEEE) received the master's and Ph.D. degrees in electrical engineering from the Politecnico di Bari, Bari, Italy, in 2000 and 2004, respectively. He has been involved as a Senior Scientist in several research and development projects in the field of smart grids and energy systems. He is currently an Associate Professor with the Politecnico di Bari, where he holds courses in power system automation and power quality, and manages the operational activities of the laboratory LabZERO. He is the Vice-Chair of the IEEE Italy Section Chapter PE31. His current studies deal with power system automation, smart distribution systems, microgrids, energy services, power hardware-in-the-loop, and geographically distributed real-time simulation.

GIOVANNI GIANNOCCARO was born in Fasano, Italy, in 1980. He received the degree in electronic engineering, with a specialization in microelectronics and the Ph.D. degree in electrical and information engineering on the topic of energy saving and distributed microgeneration from the Politecnico di Bari, in 2011 and 2016, respectively. In 2017, he was a Research Fellow on several industrial research and development projects. He is currently a Researcher in power systems with the Università degli studi di Napoli Federico II. His research interests include demand response, microgrid optimization and control, integration of energy infrastructures and innovation on devices, and services for energy utilization management.

MASSIMO LA SCALA (Life Fellow, IEEE) is currently a Full Professor of electrical energy systems with the Politecnico di Bari, Bari, Italy; and the Scientific Director of the Laboratory on Smart Grids and Energy Efficiency LabZERO. He is an active Researcher involved as a Principal Investigator in several projects about smart grids and energy systems. He is with the Panel of Experts of the Italian Ministry of the University and a Research in Charge of issuing the Program of Scientific Research, from 2021 to 2027. He is with Consultative Group to support the joint IEA-Italy Project: Smarter Digital Power Infrastructure to enhance energy efficiency, resilient systems, and energy transition.

• • •

Open Access funding provided by 'Politecnico di Bari' within the CRUI CARE Agreement