IEEE Open Journal of
Power Electronics

Received 15 February 2024; revised 23 March 2024; accepted 2 April 2024. Date of publication 8 April 2024; date of current version 25 April 2024. The review of this article was arranged by Associate Editor Zhixiang Zou.

Digital Object Identifier 10.1109/OJPEL.2024.3386198

UNSW Sydney's Real-Time Simulations Laboratory (RTS@UNSW): Supporting Power Electronics Defined Power Systems, Down Under

FELIPE ARRAÑO-VARGAS [1] (Member, IEEE), VASSILIOS G. AGELIDIS [2] (Fellow, IEEE), AND GEORGIOS KONSTANTINOU [1] (Senior Member, IEEE)

[1]School of Electrical Engineering and Telecommunications, The University of New South Wales (UNSW Sydney), Sydney, NSW 2052, Australia
[2]Department of Electrical and Computer Engineering, Democritus University of Thrace, 671 00 Xanthi, Greece

CORRESPONDING AUTHOR: GEORGIOS KONSTANTINOU (e-mail: g.konstantinou@unsw.edu.au)

ABSTRACT Real-time simulations (RTS) and hardware-in-the-loop (HiL) testing are becoming increasingly vital to the power industry in order to support the pace of the ongoing energy transition. Such methods enable the optimization of power systems and validation of solutions, applications and components under realistic operational conditions while minimizing associated risks. The Real-Time Simulations Laboratory at The University of New South Wales, in Sydney Australia (RTS@UNSW) is a dedicated research facility built with a focus on enabling and advancing the use of RTS and HiL in Australia. The lab is equipped with state-of-the-art simulators and testing equipment supporting integration of power electronics at scale and the development and deployment of power electronics defined power systems. This paper will provide a brief introduction to the Australian context related to the energy transition, an overview of the available facilities, and some of the key research and industry-related projects that it supports.

INDEX TERMS Co-simulation, engineering education, hardware-in-the-loop (HiL) testing, large-scale modeling, rapid control prototyping (RCP), real-time digital simulation (RTS), RTS@UNSW.

I. INTRODUCTION

Australia's transition to net-zero emissions energy systems has accelerated over the past few decades, driven by ambitious environmental targets, federal and state policies, technological advancements, cost reductions and public expectations for emissions reductions. To reach a net-zero National Electricity Market (NEM – Australia's eastern interconnected power system) by 2050, the Australian Energy Market Operator (AEMO) is proposing a strategy that calls for investment that would [1]: *i)* add 10,000 km of new and upgraded transmission lines, *ii)* triple grid-scale variable renewable generation by 2030 (57 GW) and increase it seven-fold by 2050 (126 GW), *iii)* add 74 GW of firming capacity from dispatchable storage, hydro and gas-power plants, and *iv)* support a four-fold increase in distributed solar photovoltaic (DPV) of 72 GW by 2050.

This transformational challenge comes in addition to operating a network with very unique characteristics: isolated, weakly interconnected, and extremely thin and long. Adapting the grid to emerging technologies and increasing prosumer participation have unfolded unprecedented operational challenges, including: *i)* new instability phenomena, *ii)* deficiency of essential grid services, *iii)* lack of understanding of proprietary software-based controller technologies, and *iv)* poor operational visibility and controllability of distributed resources.

Operating a significantly more complex and dynamic NEM, alongside with the South West Interconnected System (SWIS) and other remote power systems, all while ensuring an effective and just energy transition, necessitate innovative solutions. These solutions must integrate old and new technologies, supported by data-driven strategies and an evolving toolkit for system and market *i)* planning, *ii)* management, *iii)* operation, and *iv)* analysis. Effective deployment requires leveraging technological advancements, developing models, and algorithms, collecting and analyzing copious amount of data, and conducting tests to continue delivering secure, reliable, sustainable, and low-cost electricity services.

This problem is not new. The initial growth in small-scale distributed energy resources (DER) in the early 2000 s and the deployment of the first large-scale renewable energy projects in the 2010 s demonstrated that a more comprehensive understanding of power system planning and operation was essential. Availability of a dedicated facility can significantly enhance the industry and system operators' ability to swiftly adapt to changing energy system conditions, optimize resource use, and effectively anticipate and address challenges. The early development of utility-scale solar farms was supported by the Solar Flagships Program [2], an initiative by the Australian Government, to accelerate the commercialization of new solar technologies including both photovoltaic (PV) and concentrated solar power (CSP) technologies.

A component of the broader investment in innovation and infrastructure linked to the renewable energy sector was the Education Investment Fund (EIF). It facilitated the establishment of state-of-the-art research facilities, laboratories, and educational spaces. Among these initiatives was the construction of a laboratory at The University of New South Wales (UNSW Sydney) aimed at advancing research in renewable energy integration into power systems. This effort culminated with the establishment of the Real-Time Simulations Laboratory at UNSW (RTS@UNSW Lab), marking Australia's first large-scale RTS laboratory. The RTS@UNSW Lab was developed as a powerful simulation platform for fast and accurate modeling of energy systems that incorporate characteristics of power electronics technologies at a sufficiently detailed level to meet the needs of a power system that is increasingly dependent on conversion technologies. Given the importance of real-time simulation in validating theoretical models and ensuring the practical applicability of research findings, RTS@UNSW serves as a crucial resource for both academic research and industry collaboration, facilitating the development of solutions to current and future challenges in the energy sector.

In this paper, we discuss the motivations driving research at RTS@UNSW, detail the available infrastructure, and explore case studies from various research projects alongside learning and teaching initiatives.

II. RESEARCH MOTIVATIONS FUELING RTS@UNSW LAB'S WORK

The primary research motivation at the RTS@UNSW Lab is to support a secure and reliable energy transition and the pathway towards power electronics defined power systems. The distinctive Australian landscape and the challenges faced in its electricity grids further drive the research using innovative methods, techniques, equipment, and tools. This section summarizes these key motivations.

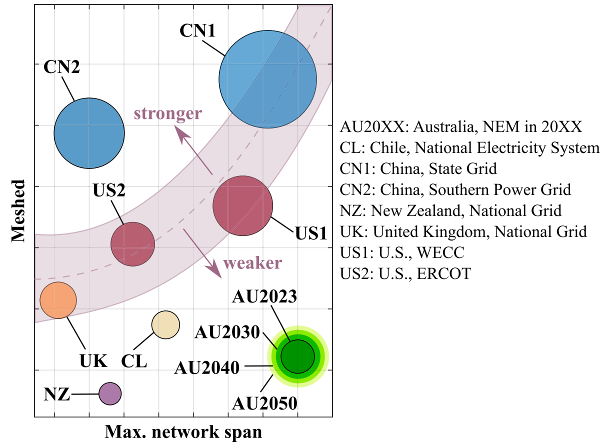

FIGURE 1. Most grids are substantially stronger and more robust compared to the long, thin, and weak Australian NEM [3].

A. THE DISTINCTIVENESS OF AUSTRALIAN GRIDS

The ongoing transformation of the power system presents challenges that extend beyond Australia. In fact, numerous other countries are dealing with the energy trilemma: balancing security, sustainability and affordability while managing decarbonization, decentralization, and digitization as the three pillars that define the future power system. Yet, the distinct topological characteristics of the Australian network [3], evaluated across multiple metrics, separate the National Electricity Market (NEM)—and the South West Interconnected System (SWIS) to a similar extent—from every other network in the world (Fig. 1). Comparing Australia's maximum network span and meshed level with other major power systems (which directly influence research agendas and aims) highlights complications that need to be addressed with regards to remoteness of locations, coordination of resources, system stability, security, and strength [4]. Furthermore, the inherent variability and uncertainty of renewable energy resources are disproportionately affecting systems such as Australia's, due to the reduced number of interconnections, as experienced most notably in the 2016 South Australian blackout [5].

Considering the current and projected levels of renewable energy in Australia (shown by bubble size in Fig. 1) highlights the need for targeted research and development. Such efforts should be shaped by Australia's unique energy landscape, ongoing experience and tailored to meet the specific requirements of the NEM and SWIS [6].

B. CHALLENGES OF TIMESCALES IN AN EVOLVING POWER SYSTEM AND THE VALUE OF RTS

Speed is necessary for responding but also proactively managing the continuous evolution of power systems. Speed is also critical due to the technical nature of the problems that need to be addressed in modern power systems which feature a mix of *i)* lower inertia networks leading to faster dynamics [7], *ii)* highly variable, highly volatile generation (i.e., solar, wind) [8], *iii)* fast control through power electronics converters [9], and *v)* faster observations of the changes that occur

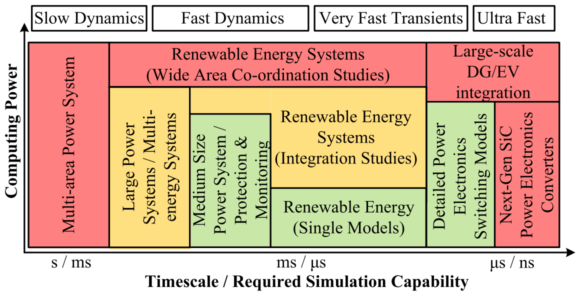

FIGURE 2. Timescale challenges and current capacity in areas of research.

in the network [10]. Compounding this complexity, modern power converters respond in "microseconds," contrasting with the "seconds" level of electromechanical responses, and the minutes needed for market driven responses. Fig. 2 highlights the sophisticated simulation capabilities necessary to address the system behaviors across multiple timescales and domains.

Furthermore, fundamental changes are taking place in the monitoring, control, and protection of modern power grids where an increasing amount of renewable energy sources, both distributed and large-scale, is progressively connected. Integration of renewable energy into existing grids at scale, requires specific control processes and availability of new technologies [11]. Consequently, power systems are becoming more complex, dominated by power electronics [12]. In this context, there is a pressing need for high-performing real-time simulation tools capable of quantifying the dynamic behavior of these complex systems for studying, developing, and testing new solutions for the monitoring, control, and protection of modern power grids [13].

Real-time simulation offers a state-of-the art, robust platform for designing, developing, iterating, and validating solutions for complex power systems dominated by power electronics [14]. However, real-time simulation capability comes at a substantial cost. Hardware required to complete extensive tests is expensive, in terms of initial investment and continuous update. Considering inflexible equipment allocation to projects and suboptimal utilization of resources, these costs become prohibitive for a single institution if not supported by external funding initiatives. These costs have hindered the deployment of real-time simulation capabilities at most Australian universities and allow only handling of simplified, unrepresentative cases at any one time, limiting the impact of research outcomes. This precludes, for example, modeling complex, system-wide dynamics such as the ones experienced during the 2018 or 2021 network separation events [15], in a reasonable timescale or with external hardware as part of the post-event analysis.

C. THE IMPORTANCE OF DETAILED, LARGE MODELS FOR POWER ELECTRONICS DEFINED POWER SYSTEMS

The use of single-machine infinite bus (SMIB) and small-scale network models has been, up to now, very common in R&D projects (especially in academia and to the same extent in demonstation and commercial projects). However, such simplifications are reaching a limit, as these models no longer appropriately capture the topology, size, nor the complexity of modern power systems. Basic network equivalent models cannot be used to identify complex network-wide instabilities and oscillations, and average-model power electronics representations fail to capture small-signal stability requirements [16]. For instance, Fig. 3 shows that in simulations of a fault within the Australian NEM, the RMS-equivalent model fails to predict the commutation failure and subsequent disconnection of a line-commutated converter (LCC) HVDC link. The consequences of such event is, nevertheless, predicted when using an EMT-based model of the system [17].

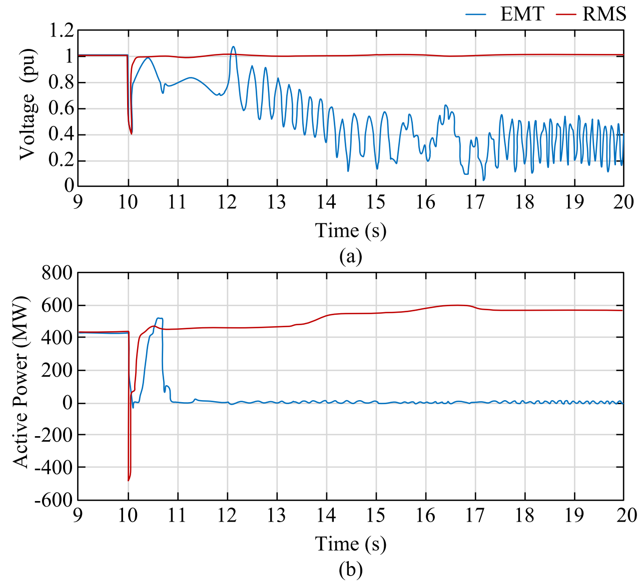

FIGURE 3. Different model assumptions (and sizes) may change the overall response of the system. A commutation failure is observed in an LCC-HVDC link when using an EMT-based model of the Australian NEM, this is not observed when using the RMS-equivalent model [17].

There is a critical need to shift towards using larger, more realistic network representations with fully modeled power system components and considering higher penetration of inverter-based resources (IBR), in order to accurately reflect the current reality and future expectations of power system transformation [18]. This requirement has been broadly identified in the power industry (e.g., Hydro-Québec [19] and China Southern Grid [20]) which sees benefits in detailed, large-scale RTS models to improve planning and operation of their respective grids. In Australia, TasNetworks has implemented a similar modeling approach to the Tasmanian network as part of a new HVDC interconnector to the mainland and the addition of new wind farms in the island [21].

III. RTS@UNSW INFRASTRUCTURE

RTS@UNSW, shown in Fig. 4, is a dedicated real-time digital simulation laboratory in Australia, which is used for education, training, and research, fostering innovation and

FIGURE 4. Real-time simulations laboratory (RTS@UNSW Lab).

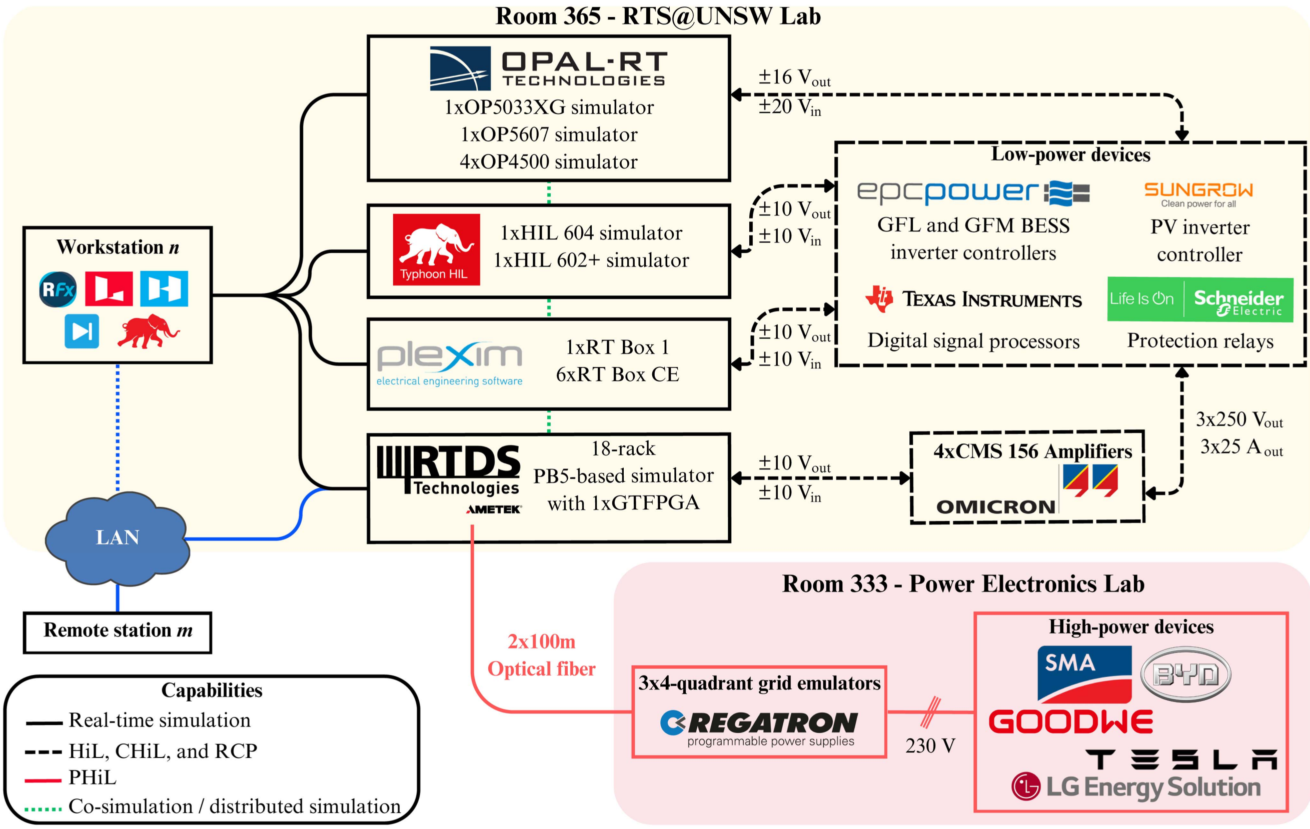

FIGURE 5. Power and data schematic of the capabilities of the real-time simulations laboratory (RTS@UNSW Lab).

sustainable solutions for the energy sector. With a comprehensive range of simulators, RTS@UNSW provides unique simulation capabilities when compared to other existing real-time simulation laboratories, including: *i)* capacity to simulate in real-time 2x5,000 electrical nodes (phasor) and more than 800 three-phase (or more than 2,500 single-phase) electrical nodes (EMT), *ii)* multiple high-resolution digital and analog input/output cards for hardware-in-the-loop (HiL) testing and rapid control prototyping (RPC), *iii)* FPGA-based power electronics toolboxes for the modeling and simulation of high-frequency switching converters, and *iv)* compact and entry-level simulators for educational and training purposes. A high-level schematic of the RTS@UNSW Lab, including the connections between the simulators for co-simulation purposes, is shown in Fig. 5. Features of each simulator can be found in Table 1 of the Appendix.

The laboratory is also connected, via two optical fiber links, with the Power Electronics Research Laboratory also located in the same building. This connection facilitates power hardware-in-the-loop (PHiL) testing of physical equipment, including residential PV and battery inverters, through REGATRON four-quadrant grid emulators. It also enables interfacing real-time simulators with a wide range of multi-level converters (MMC) and a local microgrid. Table 2 of the

Appendix provides the main specifications of the equipment that can be interfaced with the simulators.

IV. IMPACT-DRIVEN RESEARCH AT RTS@UNSW LAB: CASE STUDIES

This section provides an overview of relevant real-world case studies and projects carried out at the RTS@UNSW Lab.

A. CONTROL HARDWARE-IN-THE-LOOP TESTING: GRID-FORMING INVERTERS

Real-time digital simulation testing offers additional features beyond those available to conventional offline EMT simulations. Through HiL testing, it is possible to validate the performance of actual controllers, protection relays, or even power electronics converters in conditions that replicate field operation. Some of the successful applications performed at RTS@UNSW include the testing of distance and series compensation protection relays as well as solar and battery energy storage controllers. The devices under test were subject to a variety of scenarios and conditions in order to verify their correct operation before their deployment to the actual grid.

Of particular interest is the case of AGL's Broken Hill Battery Energy Storage System (BH BESS) [23]. The BH BESS is a 50 MW/100 MWh battery connected in the remote town of Broken Hill in New South Wales. Beyond providing local storage to the network and minimizing curtailment of local generation, the project objectives also included field demonstration of the potential of large-scale batteries with grid-forming (GFM) capabilities, in providing grid support and ancillary services in weak areas of power systems. As an emerging solution in Australian networks and an alternative to the widely used grid-following (GFL) inverters, the capabilities and suitability of GFM controls/inverters had to be analyzed and demonstrated. In the first stage of the project, RTS@UNSW collaborated with AGL to demonstrate, via detailed real-time modeling and simulations, the technical feasibility of the solution, including: *i)* the GFM control strategy (based on virtual synchronous machine, VSM [24]), *ii)* its suitability to increase system strength while mitigating voltage oscillations in weak areas (as such voltage oscillations were commonly experienced in the wider West Murray Zone [22]), and *iii)* the potential increase of renewable hosting capacity. For instance, Fig. 6 shows the successful damping of 17 Hz voltage oscillations when the proposed GFM control strategy is enabled in the generic model of the BESS. These oscillations are accentuated if a traditional GFL strategy is implemented.

In the second stage of the project, RTS@UNSW provided additional control HiL (CHiL) tests to demonstrate the performance of the controller under different scenarios and fault conditions (yellow setup in Fig. 7). By closely collaborating with industry partners, this project accelerated the research and knowledge sharing in the critical area of grid-scale, GFM batteries, disseminating information about emerging technologies to manufacturers, transmission system operators,

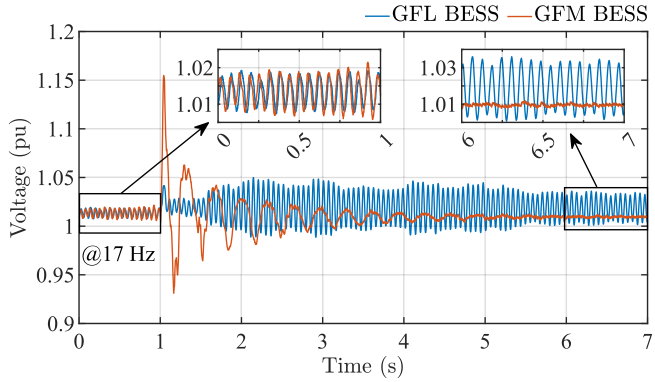

FIGURE 6. Impact of BH BESS connection at $t = 1$ s over sub-synchronous oscillations in the West Murray Zone. GFM functionalities show the damping of oscillations [22].

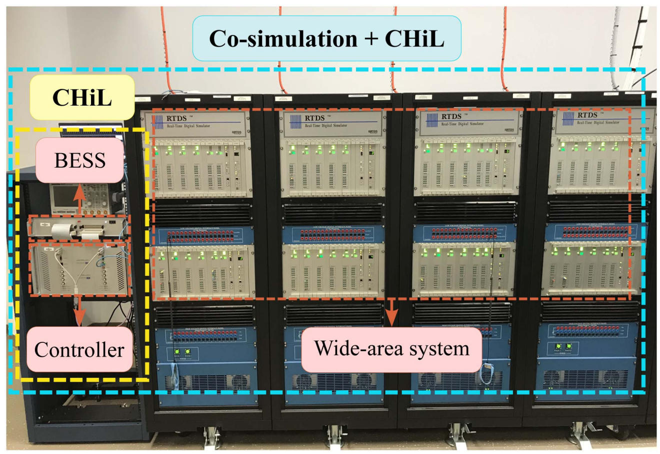

FIGURE 7. Control hardware-in-the-loop and co-simulation setups for the integration of grid-forming battery energy storage systems [22].

and the broader industry, as well as to the research community [22], [25].

B. REAL-TIME CO-SIMULATION: BATTERY ENERGY STORAGE INTEGRATION

As the generation pool diversifies and new grid issues emerge (e.g., resonance and control driven stability [10]), the use of traditional SMIB models and/or current injection tests is not sufficient for assessing new connections and their impact on the grid. During the BH BESS connection application process, and to properly represent the dynamics of the system (in particular voltage oscillations), it was necessary to consider a much broader area of the adjacent network and not only local buses. However, real-time simulations of modern grids require significant computational capacity, and thus simulation of detailed, large models is limited by availability and access to hardware. Real-time co-simulations provide the capability to integrate different types of real-time simulation hardware to perform complex and large-scale simulations, combining unique capabilities of different simulators while alleviating issues related to computation capacity [26]. By

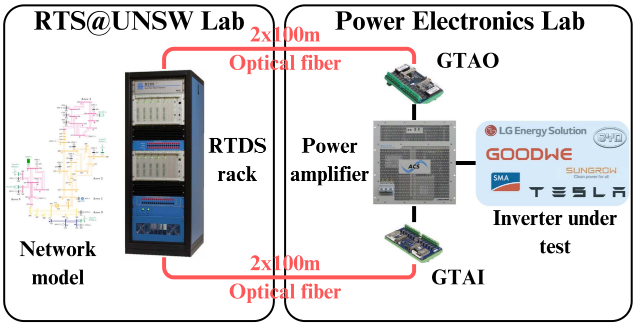

FIGURE 8. Power hardware-in-the-loop setup for distributed inverter-based generation [28].

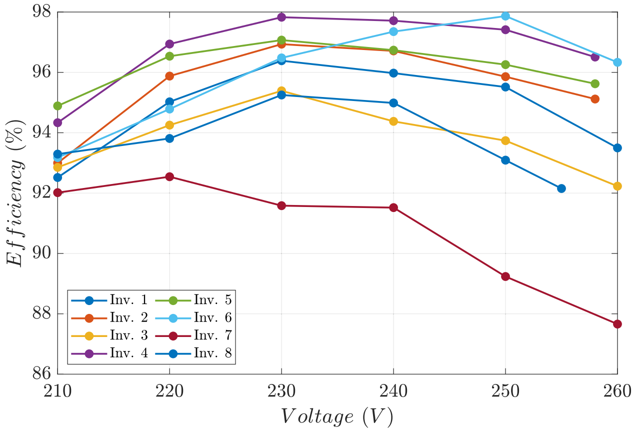

FIGURE 9. Efficiency curves of PV inverters as a function of grid voltage [32].

interfacing two different simulators (i.e., a Typhoon HIL 604 and a PB5-based RTDS, light blue setup in Fig. 7) through 10 V 20 kHz analog inputs/outputs and the ideal transformer model (ITM) [27], it was possible to overcome modeling limitations of the BH BESS and its surrounding area. In these tests, the grid with its corresponding IBRs (e.g., wind farms and solar farms connected to the vicinity of Broken Hill) were modeled and simulated in the RTDS while the BH BESS was modeled in the Typhoon simulator, which at the same time was connected with the actual controller in the Typhoon HIL Connect. Co-simulation with CHiL capabilities further demonstrated the value of the proposed GFM BH BESS and its suitability in very weak power systems when compared to GFL implementations.

C. POWER HARDWARE-IN-THE-LOOP TESTING: INTEGRATION OF DISTRIBUTED SOLAR PV SYSTEMS

Australia represents one of the largest solar PV markets in the world–especially for rooftop systems. More than 3.5 million installations of DPV systems on households and businesses, connected to the grid through inverters, typically in the 2–50 kW range can be found across the NEM for a total Australian rooftop solar capacity of more than 20.5 GW [29].

The number and geographical distribution of solar PV systems can no longer be considered negligible for the safe operation of the network [30]. Instances of solar DPV "shake-off" in distribution feeders is observed following faults even at transmission level. In order to better understand PV performance and support increased installation volumes it is critical to evaluate PV inverter behavior. However, there is a great variety of PV inverter manufacturers and even greater range of DPV inverter models currently installed across Australian networks. Although all inverters comply with local standards (AS/NZS 4777 [31]), grid faults rarely match the prescriptive tests defined in them.

Bench-testing of DPV inverters provides useful insights for their response under a broad range of disturbances including voltage and frequency disturbances. Their performance can be validated through PHiL testing (Fig. 8). This assessment allows to [28], [32]: *i)* test at different levels of solar PV penetrations in feeders, *ii)* coordinate testing of multiple inverters in the same feeder, and *iii)* test for multiple feeders (urban, suburban, rural etc.). Fig. 9 shows the efficiency of eight PV inverters under different irradiance and power levels. The measured efficiency presents observable variations across the voltage range, leading to the clear need of updating efficiency curves in inverter datasheets as a function of grid voltage.

D. LARGE-SCALE MODELING: BENCHMARK MODELS AND SYNTHETIC GRIDS

Existing real-time benchmark models are few, not openly available, and confined to libraries of real-time simulator companies. Moreover, longitudinal power systems (LPS), such as the ones in Australia, Chile, and New Zealand, are not typically included in any power system libraries [3]. This gap was identified by researchers at the RTS@UNSW, who then adapted and developed benchmark models for LPS that are suitable for real-time EMT simulations, making them also available to public.

The *Simplified Australian 14-Generator* power system was first adapted for RTDS (RSCAD) and OPAL-RT (HYPERSIM) real-time simulators [33], [34], and then it was expanded to include a variety of IBR resources [35], representing modern grids. By incorporating such a model into additional libraries, it becomes possible to test new applications and algorithms with a focus on LPS. For instance, the benchmark model has been later used for: *i)* testing new algorithms for decoupling models for distributed simulations [36], *ii)* developing adaptive power reserve control strategies for PV plants [37], and *iii)* demonstrating a virtual testbed for digital twin applications [38]. In addition, simulations and results using the *Simplified Australian 14-Generator* can be cross-verified along various software and platforms [39].

With the intention of representing the appropriate size, complex topology and dynamic behavior of the existing Australian NEM, the first-of-its-kind synthetic grid with longitudinal structure, the *S-NEM2300*, was developed [18]. The model, containing more than 2,300 three-phase electrical nodes, has enabled researchers and engineers to perform

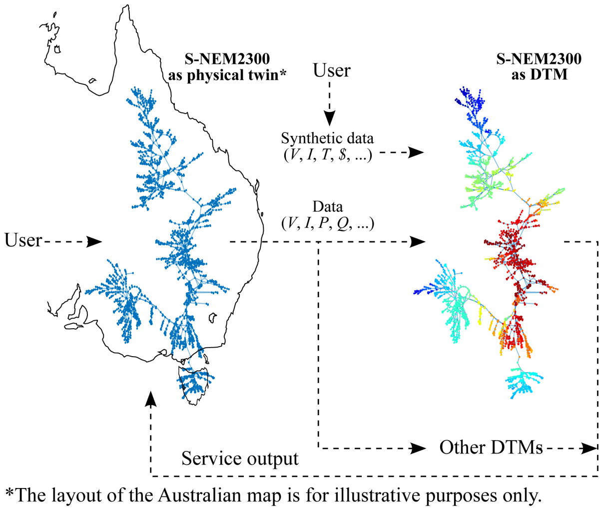

FIGURE 10. ***S-NEM2300*** **as the core of power system digital twin tests.**

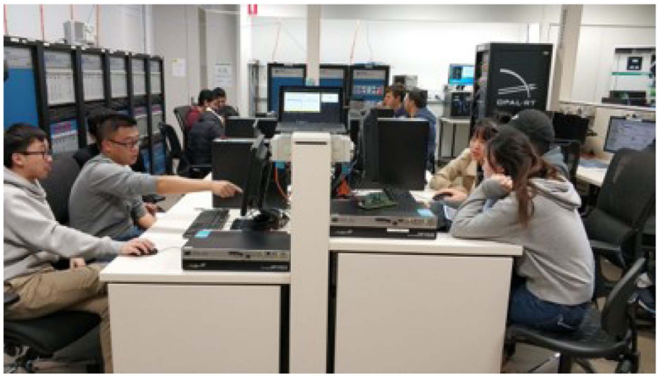

FIGURE 11. Dedicated hands-on course on real-time digital simulations and hardware-in-the-loop testing.

power system analyses in a more realistic network case. Since the release of the *S-NEM2300*, it has been adapted and expanded by different research institutes (e.g., CSIRO in Australia and EPRI in the U.S.). Furthermore, it has been used by OPAL-RT Technologies to demonstrate the proof-of-concept of the high-performance power system simulator requested by AEMO [40].

The *S-NEM2300* is also envisioned to serve as a basic unit for power system digital twins (PSDT), a research area with growing interest and considerable potential [41]. For instance, integrating the *S-NEM2300* with real-time and historical data and artificial intelligence in the OP5033XG can form a testbed system that could be used by the research community to study digital twins, test digital twin applications, or as a prototype for an industrial PSDT [42]. Fig. 10 illustrates the role of the *S-NEM2300* as the physical twin of a grid, which could be used for the training of application and services, and as a digital twin module (DTM) where applications can be executed.

V. RTS@UNSW AND ENGINEERING EDUCATION

The integration of RTS and HiL throughout the power engineering curriculum offers an excellent opportunity to bridge theoretical knowledge with practical applications and hands-on student experiences. Such educational approaches allow us to maintain the relevance of training programs for legacy power systems. Furthermore, it equips tomorrow's workforce with the necessary skills to drive the energy transition and manage future power systems. Having access to large RTS facilities, like the RTS@UNSW Laboratory, is essential, in offering a comprehensive learning experience. It also fulfills multiple educational objectives: reinforcing theoretical knowledge, sparking interest in emerging power technologies, and demonstrating the links between virtual, physical and cyber-physical systems. These objectives are attainable from undergraduate programs up to continuous professional development for working professionals. The following describes opportunities and the use of RTS@UNSW Laboratory for education and training.

A. UNDERGRADUATE EDUCATION

Currently in electrical engineering undergraduate curriculum, RTS and HiL serve as educational tools within a structured framework. Students can interact with predefined models and experiments, which enables them to engage with complex concepts through practical, hands-on experience. These simulations or experiments are guided, with students exploring close-ended questions that lead to clear, predefined learning outcomes. For instance, a CHiL test bench to introduce PV systems and concepts like maximum power point tracking using the OPAL-RT OP4500 simulator was developed in [43]. This approach reinforces theoretical knowledge and creates an environment where students can observe the direct implications of power engineering principles in close to real-world scenarios.

Undergraduate students also have the opportunity to delve deeper into the practical applications of RTS and HiL through their capstone or thesis projects supervised by RTS@UNSW academics. Thesis projects are typically linked with model development, coding, or the utilization of existing experimental setups, while offering a platform for independent but supervised research. Exposure to RTS facilities and methods at an undergraduate level equips students with the preliminary experiences and knowledge necessary to appreciate the benefits, advantages, and challenges associated with RTS and HiL testing enhancing their technical proficiency and encouraging them to consider these advanced methods as options in their future power engineering careers. Integration of RTS and HiL into undergraduate studies, lays the necessary groundwork for developing engineers who are well-versed in modern technologies and who are prepared to address the complexities of future energy systems.

B. POSTGRADUATE EDUCATION

The value of RTS and HiL extends significantly beyond foundational learning in postgraduate programs. Students are encouraged to tackle more open-ended questions. Smaller classes and a more open access to the laboratories allows for broader and tailored educational outcomes, more closely

TABLE 1 Summary of Salient Features of RTS@UNSW Lab Simulators and Their Applications

Manufacturer	Hardware†	Software/Toolbox	Modeling	Application*
RTDS	90xPB5 cards (180 processors @ 1.7 GHz)	RSCAD	EMT (+800 3-ph)	PSDT, PHiL, education
OPAL-RT	OP5033XG (7 cores @ 3.3 GHz)	HYPERSIM	EMT (+700 3-ph)	Power systems
	OP5607 (1 core @ 3.47 GHz)	RT-LAB: ePHASORSIM	RMS (+10,000 1-ph)	Power systems
	OP5607 (FPGA)	RT-LAB: eHS	FPGA (344 states)	Power electronics, CHiL
	OP5607 (2 cores @ 3.47 GHz)	RT-LAB: ARTEMiS	EMT (1e6 states)	Power electronics
	OP5607 (FPGA)	RT-LAB: XSG	FPGA (6x100 MMC cells)	Power electronics
	4xOP4500 (2 cores @ 3.3 GHz)	RT-LAB: ARTEMiS	FPGA (1e6 states)	Power electronics, RCP
	4xOP4500 (FPGA)	RT-LAB: XSG	FPGA (6x100 MMC cells)	Power electronics, RCP
Typhoon HIL	HIL 604 (8 FPGA + 2 cores)	Schematic Editor	EMT (8 converters)	CHiL, co-simulation
	HIL 602+ (6 FPGA)	Schematic Editor	EMT (6 converters)	Power electronics
PLEXIM	RT Box 1 (2 cores @ 1 GHz)	PLECS	EMT (2 converters)	Power electronics, RCP
	6xRT Box CE (2 cores @ 1 GHz)	PLECS	EMT (2 converters)	RCP, education

† Real-time enabled capacity.
* These are just examples of the applications given to each simulator in the RTS@UNSW Lab, each simulator can have several more.

linked to the capabilities and research interests of each individual student. This advanced level of study allows students to delve deeper into the theory of modeling and simulations specific to RTS and HiL [44], equipping students with a comprehensive skill-set that includes both development and application of these technologies starting from essentially a blank canvas, fostering a deeper understanding of the intricacies involved in RTS and HiL testing.

To this extent, at UNSW Sydney we offer Australia's first and only course dedicated to real-time simulations (Fig. 11). An internationally leading laboratory-based course on modeling and development of real-time simulations for both power systems and power electronics, offers students a unique educational experience with several hands-on activities with state-of-the-art equipment. The course covers a broad spectrum of topics, including protection HiL for power systems and control HiL for power electronics, and integrates recent research trends, publications, and simulation models into its curriculum. By doing so, it ensures that students develop advanced knowledge and problem-solving skills linked to current industry needs while keeping abreast with the latest research developments in the field. Through focused and advanced training, postgraduate students are well positioned to contribute valuable insights and solutions to the power engineering community.

C. PROFESSIONAL DEVELOPMENT

Use of RTS and HiL is no longer confined to R&D laboratories but is becoming more mainstream for general power engineering applications and the power industry as a whole. As an example, requirements for RTS and HiL testing have been recently introduced by AEMO as prerequisites for new original equipment manufacturers (OEM) and developers that wish to connect large-scale projects to Australian networks [45]. Such prerequisites underscore the importance of continuous professional development (CPD) for engineers. Moreover, the substantial interest from the power industry on the concept of digital twins [42] has further accentuated the need for upskilling in the RTS and HiL domains for those already in the industry. As such, professional short-course training programs offered by RTS@UNSW Lab that focus on RTS and HiL are crucial for equipping engineers with the skills and knowledge to ensure their expertise meets the evolving demands of the Australian power engineering sector.

VI. CONCLUSION

The role of real-time digital simulations is becoming more indispensable for industries, utilities, and research groups. The testing performed with these simulators brings solutions to the ever challenging operation and expansion of modern power systems with high levels of inverter-based resources. The RTS@UNSW Lab, one of the most comprehensive real-time simulation facilities, provides a versatile and flexible environment with multiple resources that allows to perform high-fidelity test, including pure real-time simulations and hardware-in-the-loop testing. Furthermore, by combining and interfacing multiple vendor simulators together (either co-simulation or distributed simulation), it is possible to further leverage each individual resource, enabling more detailed and accurate tests to support Australia's transition to net-zero emissions energy systems.

APPENDIX

Tables 1 and 2 provide further details of the simulators and equipment introduced in Section III as part of the RTS@UNSW infrastructure.

TABLE 2 Main Specifications of Equipment Used for HiL, CHiL, and PHiL Testing

Equipment	Specification
HIL Connect	1xGFM and 1xGFL EPC Power inverter controller for BESS
Easergy (Schneider) Relays	1xP3L30 line protection and 1xP3F30 feeder protection
OMICRON Amplifier	4xCMS 156 (3x250 V, 3x25 A)
Half MMC Converter	Power MOSFET (10 kVA, 400 V_{dc}, 200 V_{ac}), 4 submodules per arm (100 V, 5.93 mF), arm inductance 3 mH
Full MMC Converter	IXFB210N30P3 (20 kVA, 800 V_{dc}, 400 V_{ac}), 8 submodules per arm (100 V, 5.93 mF), arm inductance 6 mH
REGATRON Grid Emulator	3xTopCon TC.ACS.50.480.400 full 4-quadrant 3-ph ac power source (up to 280 V and 50 kVA, 16–1000 Hz)
REGATRON dc Supply	2xTC.GSS biderectional dc power supplies (1000 V, 10 and 16 kW)
PV and Battery Inverters	+50 inverters (1.5–8 kV, 350–600 V_{dc})
Microgrid	5xDanfoss FC302 VLT (5.5 kW, 400 V) + 1 wind turbine emulator

REFERENCES

[1] Australian Energy Market Operator (AEMO), "Draft 2024 integrated system plan," AEMO, Melbourne, VIC, Australia, Jan. 2024.

[2] International Energy Agency (IEA), "Solar flagships program," IEA, Paris, France, Sep. 2020. Accessed: Feb. 14, 2024. [Online]. Available: https://www.iea.org/policies/4870-solar-flagships-program

[3] F. Arraño-Vargas and G. Konstantinou, "Longitudinal power systems for modern and future grid studies: A graph theory analysis," *Sustain. Energy, Grids Netw.*, vol. 35, Sep. 2023, Art. no. 101132.

[4] Australian Energy Market Operator (AEMO), "Fact sheet: The National Electricity Market," AEMO, Melbourne, VIC, Australia, Dec. 2021.

[5] Australian Energy Market Operator (AEMO), "Black system South Australia 28 Sep. 2016," AEMO, Melbourne, VIC, Australia, Mar. 2017.

[6] F. Arraño-Vargas, Z. Shen, S. Jiang, J. Fletcher, and G. Konstantinou, "Challenges and mitigation measures in power systems with high share of renewables—The Australian experience," *Energies*, vol. 15, no. 2, Jan. 2022, Art. no. 429.

[7] F. Milano, F. Dörfler, G. Hug, D. J. Hill, and G. Verbič, "Foundations and challenges of low-inertia systems," in *Proc. IEEE Power Syst. Computation Conf.*, 2018, pp. 1–25.

[8] M. Khalid, R. P. Aguilera, A. V. Savkin, and V. G. Agelidis, "On maximizing profit of wind-battery supported power station based on wind power and energy price forecasting," *Appl. Energy*, vol. 211, pp. 764–773, Feb. 2018.

[9] H. D. Tafti et al., "Extended functionalities of photovoltaic systems with flexible power point tracking: Recent advances," *IEEE Trans. Power Electron.*, vol. 35, no. 9, pp. 9342–9356, Sep. 2020.

[10] Power System Dynamic Performance Committee (PSDP), "Stability definitions and characterization of dynamic behavior in systems with high penetration of power electronic interfaced technologies," IEEE PES, Tech. Rep. PS-TR77, Apr. 2020.

[11] N. Modi, B. Badrzadeh, A. Halley, A. Louis, and A. Jalali, "Operational manifestation of low system strength conditions - Australian experience," in *Proc. CIGRE Centennial Session*, 2021, pp. 1–11.

[12] B. Kroposki et al., "Achieving a 100% renewable grid: Operating electric power systems with extremely high levels of variable renewable energy," *IEEE Power Energy Mag.*, vol. 15, no. 2, pp. 61–73, Mar./Apr. 2017.

[13] X. Guillaud et al., "Applications of real-time simulation technologies in power and energy systems," *IEEE Power Energy Technol. Syst. J.*, vol. 2, no. 3, pp. 103–115, Sep. 2015.

[14] M. O. Faruque et al., "Real-time simulation technologies for power systems design, testing, and analysis," *IEEE Power Energy Technol. Syst. J.*, vol. 2, no. 2, pp. 63–73, Jun. 2015.

[15] Australian Energy Market Operator, "Queensland and South Australia system separation on 25 Aug. 2018," AEMO, Melbourne, VIC, Australia, Final Rep., Jan. 2019.

[16] L. Fan and Z. Miao, "Admittance-based stability analysis: Bode plots, Nyquist diagrams or eigenvalue analysis?," *IEEE Trans. Power Syst.*, vol. 35, no. 4, pp. 3312–3315, Jul. 2020.

[17] Australian Energy Market Operator (AEMO), "System strength workshop," AEMO, Melbourne, VIC, Australia, Aug. 2020. Accessed: Oct. 11, 2021. [Online]. Available: https://aemo.com.au/en/learn/energy-explained

[18] F. Arraño-Vargas and G. Konstantinou, "Synthetic grid modeling for real-time simulations," in *Proc. IEEE PES Innov. Smart Grid Technol. - Asia*, 2021, pp. 1–5.

[19] R. Gagnon et al., "Large-scale real-time simulation of wind power plants into hydro-Québec power system," in *Proc. 9th Int. Workshop Large-Scale Integration Wind Power Power Syst. Transmiss. Netw. Offshore Wind Power Plants*, 2010, pp. 1–8.

[20] S. Zhang, Y. Zhu, K. Ou, Q. Guo, Y. Hu, and W. Li, "A practical real-time hybrid simulator for modern large HVAC/DC power systems interfacing RTDS and external transient program," in *Proc. IEEE Power Energy Soc. Gen. Meeting*, 2016, pp. 1–5.

[21] M. Davies, "Preparing for the future power system - now," in *Proc. Aust. User's Group Meeting*, 2019, pp. 1–16.

[22] F. Arraño-Vargas, S. Jiang, B. Bennett, and G. Konstantinou, "Mitigation of power system oscillations in weak grids with battery energy storage systems: A real-world case study," *Energy*, vol. 283, Nov. 2023, Art. no. 128648.

[23] AGL, "Broken hill battery energy storage system," AGL, Sydney, NSW, Australia,2022. Accessed: Aug. 19, 2022. [Online]. Available: https://www.agl.com.au/about-agl/how-we-source-energy/broken-hill-battery-energy-storage-system

[24] H.-P. Beck and R. Hesse, "Virtual synchronous machine," in *Proc. IEEE 9th Int. Conf. Elect. Power Qual. Utilisation*, 2007, pp. 1–6.

[25] S. Jiang and G. Konstantinou, "Impedance-based stability analysis: Nodal admittance or bus admittance?," *IEEE Trans. Power Syst.*, vol. 39, no. 1, pp. 2327–2340, Jan. 2024.

[26] R. F. Espinoza, G. Justino, R. B. Otto, and R. Ramos, "Real-time RMS-EMT co-simulation and its application in HIL testing of protective relays," *Electric Power Syst. Res.*, vol. 197, Aug. 2021, Art. no. 107326.

[27] X. Wu and A. Monti, "Methods for partitioning the system and performance evaluation in power-hardware-in-the-loop simulations. Part I," in *Proc. IEEE 31th Annu. Conf. Ind. Electron. Soc.*, 2005, pp. 1–6.

[28] K. Ndirangu, H. D. Tafti, J. E. Fletcher, and G. Konstantinou, "Validation of solar photovoltaic inverter behavior to grid disturbances through power-hardware-in-the-loop testing," in *Proc. IEEE 12th Energy Convers. Congr. Expo. - Asia*, 2021, pp. 250–255.

[29] Australian PV Institute, "Australian PV market since Apr. 2001," Australian PV Institute, Sydney, NSW, Australia, Dec. 2023. Accessed: Dec. 13, 2023. [Online]. Available: https://pv-map.apvi.org.au/analyses

[30] N. Stringer, N. Haghdadi, A. Bruce, J. Riesz, and I. MacGill, "Observed behavior of distributed photovoltaic systems during major voltage disturbances and implications for power system security," *Appl. Energy*, vol. 260, Feb. 2020, Art. no. 114283.

[31] "Grid connection of energy systems via inverters, Part 2: Inverter requirements," AS/NZS Standard 4777.2:2020, 2020.

[32] K. Ndirangu, H. D. Tafti, J. E. Fletcher, and G. Konstantinou, "Impact of grid voltage and grid-supporting functions on efficiency of single-phase photovoltaic inverters," *IEEE J. Photovolt.*, vol. 12, no. 1, pp. 421–428, Jan. 2022.

[33] F. Arraño-Vargas and G. Konstantinou, "Development of real-time benchmark models for integration studies of advanced energy conversion systems," *IEEE Trans. Energy Convers.*, vol. 35, no. 1, pp. 497–507, Mar. 2020.

[34] M. Gao, F. Arraño-Vargas, and G. Konstantinou, "Real-time model of the simplified Australian 14-generator system in HYPERSIM," in *Proc. IEEE Int. Conf. Smart Grids Energy Syst.*, 2020, pp. 789–794.

[35] F. Arraño-Vargas and G. Konstantinou, "Real-time models of advanced energy conversion systems for large-scale integration studies," in *Proc. IEEE 10th Int. Symp. Power Electron. Distrib. Gener. Syst.*, 2019, pp. 756–761.

[36] Z. Shen, F. Arraño-Vargas, H. R. Wickramasinghe, and G. Konstantinou, "Development of power system models for distributed real-time simulations," *IEEE Access*, vol. 10, pp. 119706–119721, 2022.

[37] Q. Lei, F. Arraño-Vargas, and G. Konstantinou, "Adaptive power reserve control for photovoltaic power plants based on local inertia in low-inertia power systems," *IEEE J. Emerg. Sel. Topics Ind. Electron.*, vol. 4, no. 3, pp. 781–790, Jul. 2023.

[38] Z. Shen, F. Arraño-Vargas, and G. Konstantinou, "Virtual testbed for development and evaluation of power system digital twins and their applications," *Sustain. Energy, Grids Netw.*, vol. 38, Jun. 2024, Art. no. 101331.

[39] F. Arraño-Vargas and G. Konstantinou, "Expanding power system benchmark models to support real-time simulations," in *Proc. IEEE Int. Conf. Energy Technol. Future Grids*, 2023, pp. 1–5.

[40] Australian Energy Market Operator (AEMO), "AEMO power system simulator moves to implementation phase," AEMO, Melbourne, VIC, Australia, Jul. 2021. Accessed: Dec. 14, 2021. [Online]. Available: https://aemo.com.au/newsroom/news-updates/aemo-power-system-simulator-moves-to-implementation

[41] Z. Shen, F. Arraño-Vargas, and G. Konstantinou, "Artificial intelligence and digital twins in power systems: Trends, synergies and opportunities," *Digit. Twin*, vol. 2, no. 11, pp. 1–29, Mar. 2023.

[42] F. Arraño-Vargas and G. Konstantinou, "Modular design and real-time simulators toward power system digital twins implementation," *IEEE Trans. Ind. Inform.*, vol. 19, no. 1, pp. 52–61, Jan. 2023.

[43] Z. Jiang, G. Konstantinou, Z. Zhong, and P. Acuna, "Real-time digital simulation based laboratory test-bench development for research and education on solar PV systems," in *Proc. IEEE Australas. Universities Power Eng. Conf.*, 2017, pp. 1–6.

[44] A. Monti and A. Benigni, *Modeling and Simulation of Complex Power Systems*, 1st ed. London, U.K.: Ins. Eng. Technol., 2022.

[45] Australian Energy Market Operator (AEMO), "Dynamic model acceptance test guideline," AEMO, Melbourne, VIC, Australia, Nov. 2021.