Experiences with Smart System Integration and Validation

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1 Energy Vision and Smart Systems Role

Europe is charting a course towards a sustainable, secure, and competitive energy future with ambitious targets set for 2030[1] and 2050.[2] Central to these objectives is the integration of distributed renewable energy sources, which not only decarbonise the energy system but also modernise it to manage increasing complexity. The European Green Deal[3] and related policies underscore the need for a flexible, resilient, and intelligent energy ecosystem, transforming traditional power grids into sophisticated, cyber-physical networks.

[1] https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2030-climate-targets_en.
[2] https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en.
[3] https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

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This energy transition introduces significant challenges. The intermittent nature of renewable sources, rapid advancements in digital technologies, and the emergence of controllable loads—such as electric vehicles, heat pumps, and energy storage systems—necessitate a complete rethinking of grid planning, operation and management. Moreover, market liberalisation and evolving regulatory frameworks add further complexity. Addressing these challenges requires advanced design methodologies, innovative operational strategies, and intelligent automation to evolve current power systems into truly smart grids.

Smart systems are at the core of this transformation, integrating renewable energy sources, digital controls, and advanced communication networks to create more efficient and resilient power grids. Research and Technology Infrastructure (RTI) are essential in this context as they provide the experimental platforms necessary for testing, validating, and refining these smart systems. By integrating diverse elements—including electrical, communication and thermal networks, market dynamics, and regulatory considerations—RTIs create cohesive environments that simulate real-world conditions. This allows researchers and engineers to evaluate performance using standardised reference scenarios, interoperability benchmarks, and harmonised cyber-physical testing procedures, ultimately ensuring that smart energy solutions are robust, efficient, and secure before field deployment.

In this context, ERIGrid 2.0 plays a crucial role. It extends and enhances the capabilities of existing RTIs by integrating physical laboratories, simulation tools, and HIL systems throughout the development of novel tools and methodologies. This integration simplifies access to multi-domain experimental environments and standardises validation procedures across various testing facilities. By addressing critical gaps in current RTIs, ERIGrid 2.0 fosters collaborative innovation and supports the development of cutting-edge solutions aligned with Europe's strategic energy targets for 2030 and 2050.

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This chapter explores European energy targets and future scenarios, outlining the challenges and research objectives driving the energy transition. It specifically focuses on experiences with smart system integration and validation, drawing on feedback from Transnational Access (TA)—also called Lab Access—users and Key Performance Indicator (KPI) questionnaires. This feedback guided the development of the project tools (e.g., uAPI, configuration management tools, etc., see Chap. 6) and relative demonstrations. By learning from these experiences, RTI approaches have been refined, highlighting the advantages of integrated smart systems and documenting these benefits in forthcoming ERIGrid 2.0 reports [2]. Additionally, the chapter provides an overview of the demonstrations, showcasing the extended RTIs' capacities to deliver innovative new services.

2 User Needs and Experiences

Understanding user needs and experiences is essential for assessing the effectiveness of RTIs and ensuring that smart system integration and validation methodologies address real-world challenges. This section examines the feedback collected from TA users (see Sect. 2.1), highlighting how their insights have shaped the development of tools, methodologies, and experimental setups within ERIGrid 2.0. By systematically analysing responses from KPI questionnaires and laboratory surveys (see Sect. 2.2), it has been possible to identify key areas where improvements have been made and outline the impact of hosted projects on advancing smart energy systems. The findings presented here provide a foundation for evaluating the benefits of extended RTIs (see Sect. 3), refining future research directions, and aligning technological developments with user-driven requirements.

2.1 Experiences from Hosted User Projects

TA user projects hosted under ERIGrid 2.0 have been instrumental in testing and validating innovative technologies and methodologies for smart systems, including smart grids and electric power systems. These projects span a wide array of scientific domains, including power systems, smart grids, microgrids, energy management, electric vehicles, real-time simulation, control strategies, distributed energy resources, renewable energy integration, cybersecurity, anomaly detection, PHIL, and photovoltaic systems. A complete list is available on ERIGrid 2.0's Zenodo Community.[4] By addressing real-world challenges, these projects have not only informed the design of advanced methods and services within the extended RTIs but also underscored the critical importance of aligning technological developments with user needs.

[4] http://zenodo.org/communities/erigrid2.

Table 1 Overview of information collected for each user project

ID	Information requested per project
1	TA user project (UP) reference number
2	TA UP acronym
3	Brief technical summary of the project
4	User classification: Academy, Research Institute, Industry, Public Sector
5	Was this UP groundbreaking or significantly impactful for the host RTI? (Yes/No)
6	If yes, describe the new impact, development, or solution the UP helped achieve in your RTI
7	Is this an exemplary UP? (Yes/No)
8	If yes, describe what your RTI learned from the UP
9	What has the UP learned that could not have been achieved without the TA provisions?
10	What are the main outcomes or recommendations from hosting this UP in your RTI?
11	Which aspects of the TA provision process (before, during, and after UP access) worked particularly well? (Technical/Non-technical)
12	Which aspects of the TA provision process (before, during, and after UP access) did not work well? (Technical/Non-technical)

An internal survey was conducted among the RTI partners to evaluate the impact of the user projects hosted during ERIGrid 2.0. The survey collected detailed information for each project—including project reference number, acronym, a brief technical summary, user classification (Academy, Research Institute, Industry, or Public Sector), and assessments of whether the project was groundbreaking or exemplary. Table 1 summarises the information requested per project. This survey was designed to capture both technical and non-technical insights, assess the success of the TA process, and identify key outcomes and recommendations arising from the projects.

The analysis of the survey results reveals that several groundbreaking projects have made significant contributions to CPES innovation. For example, some projects have deepened the understanding and implementation of IoT-related concepts [2], while others have developed and tested new tools for upgrading microgrid SCADA systems using IoT elements [10]. Additionally, user projects have advanced decentralised energy technologies by investigating adaptive protection schemes and cyber-attack scenarios in microgrids [1]. Other notable achievements include the development of dynamic models for active distribution networks based on experimental measurements, a PHIL setup for testing grid-forming inverters with voltage-type amplifiers [7], the creation of a co-simulation framework enabling real-time data sharing between geographically distributed laboratories [6], and the expansion of blockchain applications for secure energy communications [15]. A clear tendency is the application of Artificial Intelligence (AI) and machine learning techniques to smart energy systems, ranging from cybersecurity assessments [3] to monitoring the health condition of substation instrument transformers. Furthermore, other projects have evaluated the impact of cyberattacks on control systems, developed effective detection mechanisms, tested remote control strategies for PV emulation setups [11], and analysed the impact of the RES integration in power distribution networks. Finally, the laboratory access activities entailed the accelerated validation of concrete tools such as voltage state estimators, net-load forecasting tools and grid condition prognostic platforms applicable to grids and microgrids within real-time simulation environments.

These findings highlight how user feedback and rigorous testing have driven methodological and technological advancements within ERIGrid 2.0. The insights gained from these projects not only validate the extended RTI approach but also provide a strong foundation for future research and development in smart grid integration and validation.

2.2 Laboratory Questionnaires

Within the ERIGrid 2.0 project, laboratory questionnaires have been developed as an essential evaluation tool to capture detailed feedback from researchers involved in various demonstration activities (see Sect. 3). As outlined in Chap. 2, these questionnaires were meticulously designed to systematically assess the performance and impact of the extended RTIs deployed throughout the project. They are structured into two distinct categories: The first set comprises *general questions* that evaluate management and operational aspects—key concerns for non-technical stakeholders, industrial clients, and academics—while the second addresses the *specific technical requirements* of each demonstration.

The primary purpose of these questionnaires is to gather comprehensive insights into KPIs, such as system stability, accuracy, scalability, and service enhancements. This structured feedback not only validates the experimental setups and the effectiveness of the integrated tools and methodologies but also drives iterative improvements and standardisation efforts across multiple domains. In essence, the questionnaires provide a critical feedback loop that supports the continuous refinement of the smart system integration and validation processes, ensuring that the extended RTIs meet both the immediate needs of the research community and the long-term European energy targets.

For example, the PHIL demonstration (see Sect. 3.1), addresses the challenge of extending the range of stable PHIL simulations. This need is driven by the limitations of existing interface algorithms that often suffer from instability at high impedance ratios or compromised accuracy-respondents. Thus, significant improvements in both system stability and measurement accuracy were reported. These enhancements translate into better performance and reliability in simulated environments. Overall, the assessments provide a comprehensive understanding of the flexibility, operational limits, and performance of the participating RTIs, confirming that an expanded stability region and reduced error margins are crucial for validating new interface algorithms.

Similarly, the questionnaires revealed that the innovative DDPG+LSTM algorithm (see Sect. 3.2) for time delay compensation in the GDRTS setup delivered noteworthy improvements in managing variable delays. This demonstration was designed to overcome the limitations of conventional time delay compensation methods, particularly in adapting to variable delays. The assessments provide a comprehensive overview of the feasibility, applicability, limitations, and benefits of both the conventional and the DDPG+LSTM-aided approaches within the participating RTIs. Laboratory researchers observed enhanced simulation accuracy and improved power synchronisation—vital for high operational efficiency in geographically distributed systems. Despite various challenges during the demonstration, the results indicate clear progress towards the project's objectives, with significant implications for advancing research, development, and the wider adoption of GDRTS techniques.

In the Accelerated Time-to-Experiment demonstration (see Sect. 3.3), the implementation of automated configuration tools—such as VILLASnode and the CM tool (detailed in Chap. 6)—received very positive feedback. The primary goal was to streamline the setup of multi-RTI scenarios involving CHIL and PHIL. A key challenge identified was the configuration of simulators, devices, and software modules (including lab coupling tools), a process that is not only tedious but also prone to human errors, which can cause delays or even damage equipment, leading to costly repairs or replacements. Moreover, the benefits of code reuse, enabled by a harmonisation layer in experiment communications, and reductions in administrative tasks (such as the implementation of firewall rules for inter-laboratory communication) further reduce the overall time-to-experiment. Participants noted that these tools substantially reduced setup times and minimised errors, thereby lowering operational costs and streamlining experimental processes. The advantages of code reuse and enhanced communication protocols were particularly emphasised, reflecting strong support for the methodologies employed.

Overall, the questionnaires provided a rich dataset of quantitative and qualitative feedback, enabling a comprehensive evaluation of the extended RTIs. The data confirms improvements in scalability, cost efficiency, and service extensions across multiple demonstrations while also guiding future refinements. These insights ensure that ERIGrid 2.0 tools and methodologies continue to meet the evolving needs of the research community and support broader European energy targets. The complete analysis is available in [12], and a summary of key quantitative metrics extracted from the KPI questionnaires is presented in Table 2.

3 Illustrative Demonstration Activities

To validate the methodologies and tools developed within ERIGrid 2.0 (see Chaps. 2–6), a series of illustrative demonstration activities were conducted across multiple RTIs. These demonstrations were designed to address critical challenges in smart grid validation, focusing on stability, interoperability, and automation in distributed energy systems.

The first demonstration investigated the VSI method to enhance stability and accuracy in PHIL simulations, overcoming limitations in traditional interface algo-

Table 2 Summary of quantitative metrics extracted from the KPI questionnaires

Demo	Preparation time (days)	Conduction time (days)	Improvement level (1–5)	Cost saving (1–5)	TRL
Improved Stability and Accuracy for PHIL	7	7	3	3	9
Time Delay Compensation for GDRTS	365	14	3	3	6
Accelerated Time-to-Experiment for Remote RTI Testing	168	12	3	3	∼5

rithms. The second demonstration focused on analysing time delays in a multi-RTI GDRTS setup and developing methodologies for effective compensation. The third demonstration aimed to streamline the setup of distributed experiments, leveraging automated configuration tools and real-time communication frameworks to improve scalability and efficiency.

These activities were not only technical evaluations but also an essential part of user-driven research through the TA programme. The experiences of TA users provided valuable feedback on the experimental methodologies, guiding refinements in both tools and validation frameworks. By incorporating real-world user perspectives, the demonstrations ensured that the solutions developed were practical, adaptable, and aligned with the evolving needs of the research and industry community.

3.1 Extended Range High-Fidelity PHIL Testing

As power systems become increasingly complex, integrating renewable energy sources, advanced control strategies, and novel power electronics technologies, the need for rigorous testing methodologies has never been greater. PHIL simulations have emerged as a critical tool for validating these modern energy systems under realistic conditions. However, PHIL setups are prone to stability and accuracy issues, primarily due to interface dynamics and delays introduced by power amplifiers. These limitations restrict the applicability of PHIL in assessing the real-world performance of CPES technologies.

This demonstration focuses on VSI, an advanced interface algorithm designed to improve the stability and accuracy of PHIL simulations. By effectively manipulating interface signals, VSI mitigates instability while preserving the fidelity of system responses, addressing key challenges in smart system integration and validation, as discussed in the broader scope of this chapter. The demonstration directly supports the ERIGrid 2.0 objectives by developing methodologies that enhance RTI capabilities, making PHIL testing more reliable and widely applicable in power and energy systems validation.

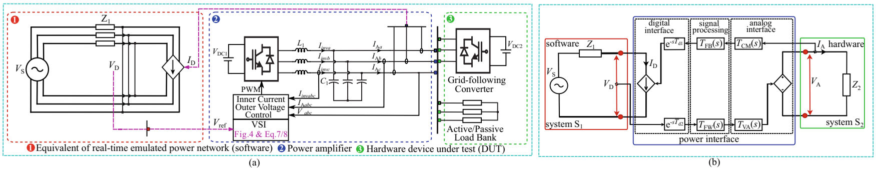

Fig. 1 **a** Schematic representation of the PHIL setup, and **b** equivalent model of the PHIL interface [9]

The experimental validation of VSI was conducted at two leading laboratories: The Power Networks Demonstration Centre and the Dynamic Power Systems Laboratory, both at the University of Strathclyde. These facilities provided the required infrastructure, including DRTS, bi-directional power amplifiers, and configurable passive load banks. The test system involved a real-time simulated power network interfaced with physical power devices through PHIL configurations. The objective was to assess how VSI enhances PHIL stability and accuracy compared to conventional methods like FBF. A schematic overview of the demonstration is presented in Fig. 1, with additional details available in [9].

The TA programme under ERIGrid 2.0 played a crucial role in shaping the development and validation of the VSI methodology. Through collaborative research projects hosted at both laboratories, visiting researchers and industry stakeholders had the opportunity to evaluate PHIL testing methodologies under real-world conditions, highlighting key challenges and areas for improvement.

Several TA users, particularly those working on renewable integration, power electronics, and microgrid control, reported frequent stability issues in PHIL experiments due to interface dynamics, latency, and amplifier-induced instabilities. Their feedback emphasized the trade-off between stability and accuracy in conventional PHIL approaches, particularly when employing LPF in FBF methods. This insight was instrumental in guiding the development of the VSI algorithm, as it directly addressed these concerns by improving stability margins while preserving system accuracy.

3.2 Time Delay Compensation for GDRTS

As modern power systems become increasingly complex and distributed, the need for accurate, real-time validation methods grows significantly. GDRTS has emerged as a powerful technique to enable collaborative experimentation across multiple RTIs. However, one of the critical challenges in GDRTS is the presence of time delays in signal exchange, which can significantly impact system stability and accuracy. This demonstration aimed to characterise and compensate for these time delays, ensuring reliable performance in geographically distributed validation environments.

The demonstration was designed to analyse time delays within a multi-RTI GDRTS setup and to develop methodologies for their compensation. The experimental setup involved multiple RTIs, where digital real-time simulators were interconnected over the internet through dedicated communication interfaces. The study focused on characterising the variability of time delays, assessing their impact on simulation accuracy, and implementing machine learning-aided compensation techniques.

The experiment employs a GDRTS framework, involving two research laboratories located approximately 3500 km apart: Dynamic Power Systems Laboratory, University of Strathclyde, and Electric Energy System Laboratory, National Technical University of Athens, as shown in Fig. 2.

To achieve these objectives, the experiment was divided into three key phases. *Time delay characterisation* involved a detailed assessment of time delays using statistical methods to evaluate their variability and uncertainty. Data was collected from multiple RTIs with measurements performed using Raspberry Pi devices deployed at different locations to monitor round-trip latency. *Accuracy analysis* and *stability assessment* focused on processing the collected time delay data to determine its distribution and impact on GDRTS fidelity. Probabilistic models quantified the likelihood of delay variations, revealing nonuniform and multimodal distributions, highlighting the need for advanced compensation strategies to mitigate their effects. Time delay compensation techniques were then developed, leveraging a machine learning-aided compensation scheme to adjust for variable yet deterministic delays in GDRTS setups. Predictive control algorithms were implemented to synchronise power signal exchanges across geographically distributed laboratories, ensuring accurate and stable real-time interactions.

User needs and experiences played a crucial role in shaping the experiment's design and execution. Feedback from previous TA projects highlighted the challenges posed by variable time delays in GDRTS. These insights underscored the

Fig. 2 Time delay measurements between geographically distributed RTIs: **a** DPSL-PNDC, **b** DPSL-ICCS [12]

necessity of developing an adaptive approach that could ensure stability and accuracy despite network-induced delays. The KPI questionnaires provided a structured evaluation of existing methods, revealing that conventional delay compensation techniques struggled to handle non-uniform and multimodal delay distributions effectively. This motivated the adoption of machine learning-based predictive control, allowing the system to anticipate and adjust for time delays dynamically.

3.3 Accelerated Time-to-Experiment for Remote RTI Testing

As distribution networks evolve into smart systems, they increasingly integrate power electronic devices, ICT infrastructure, and real-time control strategies to enhance efficiency and stability. However, this growing complexity presents new challenges for grid operators, device manufacturers, and regulatory bodies, particularly in coordinating control across DERs. Traditional testing environments struggle to capture the dynamic interactions between these elements fully, necessitating more advanced experimental approaches.

To address these challenges, this demonstration focuses on a GD-PHIL setup designed to evaluate voltage control strategies in a multi-RTI environment. The objective is to demonstrate how a CVC algorithm can manage voltage regulation devices across multiple RTIs while maintaining stability and efficiency. This aligns with the broader ERIGrid 2.0 objectives, particularly in developing tools that improve interoperability, automation, and the scalability of distributed testing environments. Concretely, voltage control is enabled directly via an OLTC or indirectly through active and reactive power injection using the PV and BESS resources.

The CVC algorithm is formulated as a constrained optimization problem. A weighted objective function minimizes the bus voltage deviation from the nominal value and the energy losses from transmission lines and penalizes the use of the OLTC to encourage the support from renewables. The problem is subject to equality and inequality constraints accounting for the energy balance, the grid elements' models, and the operational constraints. A detailed description of the CVC algorithm can be found in [8].

The GD-PHIL experiment intends to demonstrate a complex RTI integration scenario in which several participants contribute with a specific component of the grid. In addition, the main focus is on assessing the viability of the tools described in Chap. 6 to support and simplify the interoperability and automated configuration of distributed experiments.

As part of the ERIGrid 2.0 TA programme, visiting researchers participated in multi-RTI demonstrations, providing feedback on interoperability, experiment setup complexity, and system performance. The insights from these user experiences were critical in refining the automation and interoperability tools, ensuring their effectiveness in real-world applications.

4 Integration and System Validation

The integration and validation of smart energy systems require a rigorous testing approach that ensures the effectiveness, interoperability, and scalability of emerging technologies. Within ERIGrid 2.0, the conducted demonstration activities served as a foundation for evaluating key advancements in HIL methodologies, distributed control strategies, and automated experimental setups. This section presents the outcomes of these demonstrations, assessing their impact on grid stability, experimental efficiency, and the broader applicability of RTIs. Each subsection presents a comprehensive overview of the obtained outcomes, while further discussion can be found in related project results and relevant referenced papers.

4.1 Extended Range High-Fidelity PHIL Testing

A key objective of this study was to assess how the VSI methodology enhances the robustness and precision of PHIL setups while ensuring that experimental conditions closely replicate real-world power system behaviour. Beyond improving accuracy, this demonstration played a pivotal role in the integration of advanced control techniques into smart grid validation frameworks, aligning with ERIGrid 2.0's broader goal of developing standardised methodologies for RTIs to support next-generation grid technologies.

The Power Networks Demonstration Centre laboratory setup featured a DRTS from RTDS Technologies, a 270 kVA bi-directional power amplifier, and a 50 kVA passive load bank, providing a controlled yet flexible environment for validating the VSI approach. The passive load supported impedance variations between 3Ω and 100Ω, allowing for dynamic assessments of the stability margins. For the experimental analysis, an impedance ratio of $Z_1 = Z_2 = 12\Omega$ was selected to evaluate PHIL performance under realistic network conditions.

The second phase of the experiment at the Dynamic Power Systems Laboratory followed a similar setup, with modifications including a Triphase 90 kVA power amplifier and a 256-step passive load bank, extending the applicability of the VSI approach across different hardware configurations. The ability to integrate VSI within these distinct experimental environments underscored its versatility and scalability for broader research applications.

To rigorously test VSI's effectiveness, multiple scenarios were designed, comparing its performance against traditional FBF-based stabilisation methods. The study specifically focused on (i) voltage and current stability under steady-state conditions, (ii) transient response to sudden voltage fluctuations, and (iii) active and reactive power accuracy in PHIL simulations.

The experimental findings demonstrated a clear advantage of the VSI method over conventional techniques. In terms of stability improvement, while FBF methods required strict LPF with a 300 Hz cut-off to maintain marginal stability, the

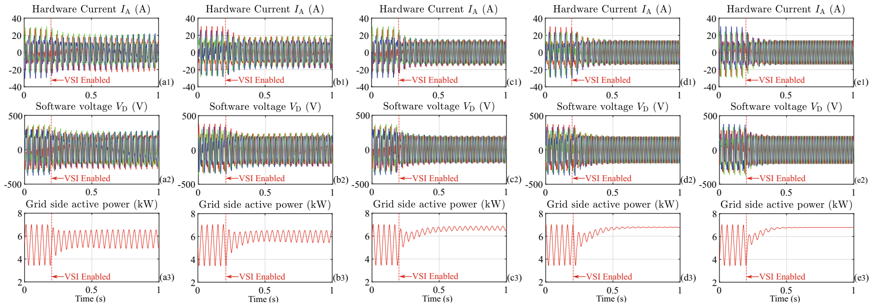

Fig. 3 PHIL experimental results comparing the FBF and VSI methods [9]

VSI approach enabled stable operation with an impedance shift of only 16%, offering a significantly wider stability region. Figure 3 presents the active and reactive power transfer with VSI. Regarding transient performance, VSI successfully maintained stable operation during an 8% voltage step change, validating its ability to enhance PHIL system resilience under dynamic conditions. In terms of accuracy enhancements, VSI significantly reduced active power oscillations and consistently exhibited greater precision compared to FBF, even when higher impedance shifting ratios (8.3% to 25%) were introduced.

This demonstration was not only a validation of VSI as a stability enhancement tool but also a critical step in integrating novel PHIL techniques into smart system RTIs. By demonstrating the applicability of VSI across different laboratory environments, this study confirmed that advanced interface algorithms can be seamlessly integrated into existing RTIs, reducing experimental uncertainties and broadening the scope of PHIL testing methodologies.

Furthermore, the results underscored the importance of structured validation frameworks for experimental research. The findings were evaluated against KPIs (see Sect. 2.2), ensuring that the method met quantifiable stability, accuracy, and scalability criteria. Additionally, TA feedback from researchers working with PHIL systems reinforced the relevance of developing standardised, interoperable validation methodologies for smart grid applications.

4.2 Time Delay Compensation for GDRTS

This demonstration was designed to evaluate the feasibility and effectiveness of a DRL-based time delay compensation method in GDRTS. Figure 4 illustrates the GDRTS delay between the Dynamic Power Systems Laboratory and Power Networks Demonstration Centre, based on 100,000 delay samples. By addressing the challenges posed by variable communication delays, the study aimed to validate the ability of an LSTM-DDPG-based approach to enhance power signal synchronisa-

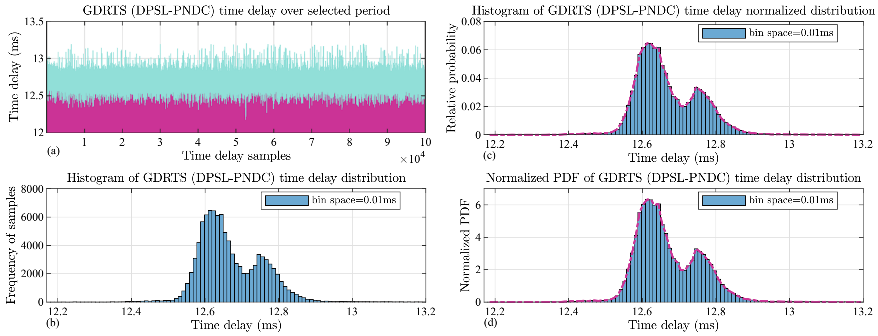

Fig. 4 Example implementation of asynchronous GDS showcasing voltage regulation in a distribution network [13]

tion and improve the stability of distributed energy systems. The experiment not only confirmed the potential of DRL for adaptive compensation but also highlighted the importance of standardised methodologies for integrating machine learning-based control strategies into multi-laboratory experimental frameworks.

The study was structured into multiple phases to systematically assess the performance of the DRL-aided delay compensation. The time delay characterisation phase involved collecting and analysing time delay data from geographically distributed RTIs, including the Dynamic Power Systems Laboratory and Power Networks Demonstration Centre, using Raspberry Pi-based latency monitoring. The accuracy analysis and stability assessment phase evaluated the impact of time delay variations on the fidelity of GDRTS by employing probabilistic models to quantify uncertainty and nonuniform distribution patterns. Finally, the time delay compensation evaluation phase tested the effectiveness of different DRL-based compensation strategies, including DDPG and an enhanced LSTM-DDPG model, in synchronising power signals across distributed laboratories.

To ensure robust validation, the experiment employed a voltage divider circuit to create a controlled testing environment for power tracking performance. The DRL agent was initially trained for fixed delays using historical delay data and then tested under both fixed and variable delay conditions. The results demonstrated that while the standard DDPG-based agent effectively compensated for static delays, it struggled with variable delays. In contrast, the LSTM-DDPG agent exhibited greater adaptability, learning to adjust dynamically to changing delays.

Key findings from the experiment include improvements in power tracking accuracy, with the LSTM-DDPG method significantly reducing active and reactive power errors compared to conventional fixed-delay compensation approaches. Phase alignment between voltage and current signals was also improved, ensuring better synchronisation of distributed power networks. Furthermore, the robustness of DRL-based compensation was demonstrated, confirming the feasibility of machine learning-based delay mitigation for geographically distributed real-time simulations. Further details can be found in related project reports [12] and Chap. 6. For the sake of brevity, plots and tabulated data are not included in this section.

These results underscore the potential of integrating artificial intelligence into real-time power system validation. By leveraging advanced reinforcement learning techniques, this study demonstrated the effectiveness of intelligent compensation methods for GDRTS, paving the way for further adoption of machine learning in distributed energy system validation.

4.3 Accelerated Time-to-Experiment for Remote RTI Testing

The integration of multiple geographically distributed RTIs was evaluated within the use case described in Sect. 3.3. A schematic representation of the laboratory setup is provided in Fig. 5. Several experiments were conducted across different RTIs in Europe, including RWTH Aachen, TECNALIA, DTU, UoS, SINTEF, and ICSS. Some of these experiments involved up to three RTIs simultaneously, utilizing various methodologies such as SIL and GD-PHIL.

A modified version of the CIGRE-MV benchmark [5] was implemented in the RTlab at RWTH. The CVC algorithm was executed in MATLAB with VILLASnode facilitating internal communication using UDP, while a Python script enabled connectivity to the JaNDER transport via the uAPI. The other participating RTIs connected to RTlab in a star topology, with those using VILLASnode employing WebRTC as the transport protocol. WebRTC streamlined connection establishment and mitigated challenges posed by restrictive firewall security policies, eliminating the need for additional tools such as VPNs and significantly reducing the setup time

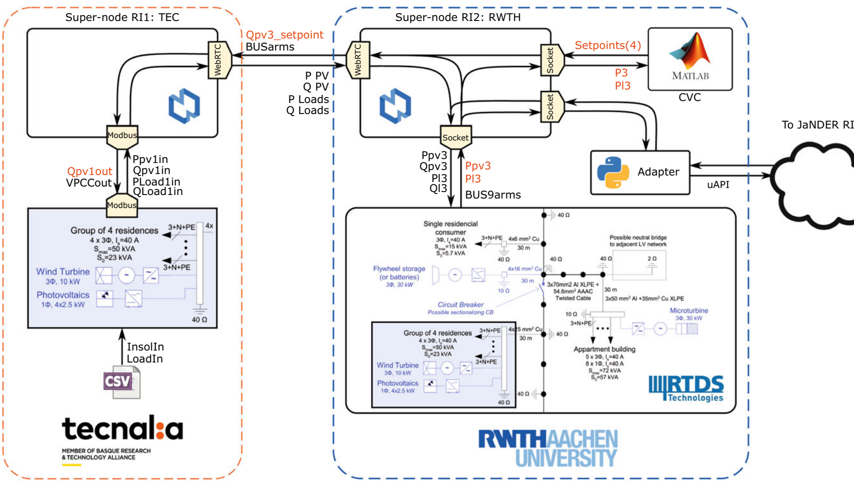

Fig. 5 Schematic representation of the GD-RTS setup between two RTIs [12]

for the distributed experiment. The only requirement for participants was the prior exchange of a session ID, which was included in the VILLASnode configuration file.

As depicted in Fig. 5, several buses of the benchmark network were designated as PCC. The corresponding RMS bus voltage was transmitted to participating RTIs following an asynchronous coupling scheme [14], under the assumption that the system frequency remained unaffected. Additionally, the voltage control setpoints computed by the CVC were transmitted, specifically the reactive power for buses with PV generation and the active/reactive power for the BESS. The participating RTIs reproduced the PCC bus voltage within their laboratories. For buses with loads, a predefined load profile was replicated. The control loop was completed by transmitting the active and reactive power values of PV and loads to RTlab, where they were routed to the RTDS. Finally, measurement signals related to active powers, PV, loads, and bus voltages were sent from the RTDS to MATLAB. As the number of participating RTIs increased beyond two, the complexity of planning, configuring, and coordinating the experiments increased significantly. To address these challenges, the CM tool (see Sect. 3.3) was deployed in a simplified version of the experiment and demonstrated in a live session [4]. The implementation of the CM tool improved the experimental setup by reducing the number of lines of code required to prepare the configuration, minimizing human errors, and streamlining verification processes.

The insights gained from this demonstration reinforce the importance of cross-laboratory collaboration in smart grid validation and demonstrate how advanced configuration management tools can enhance the feasibility and efficiency of multi-RTI experiments. These results not only validate the CVC approach in a real-world setting but also establish a framework for future scalable, automated CPES testing environments.

5 Closing Remarks

This chapter has explored the integration and validation of smart energy systems within the ERIGrid 2.0 project, highlighting the role of distributed RTIs in advancing testing methodologies and experimental validation. Through TA experiences and KPIs, the demonstrations presented here addressed critical challenges in power system stability, interoperability, and real-time control validation.

User feedback from TA experiences played a pivotal role in shaping the experimental setups, refining test scenarios, and guiding the development of tools such as uAPI, CM, and RTI adapters. These tools facilitated seamless data exchange, improved protocol compatibility, and streamlined multi-RTI experiment configuration. The lessons learned from user engagement confirmed that integrating practical feedback into the research process enhances the relevance and applicability of experimental methodologies, ensuring that RTIs remain valuable resources for advancing smart grid innovation.

Future research should continue enhancing RTI interoperability, refining experimental frameworks, and addressing remaining challenges in scalability and automation, ensuring that RTIs remain at the forefront of CPES innovation.

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