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High-Fidelity Validation with Smart Grid Modelling Complexity: Considerations on Emerging Solutions

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***Abstract*—The continued integration of increased volumes of distributed energy resources and flexibility services into power networks across the world is introducing increasing complexity into system operations. With the growing number and dimensions of complexity, modelling of smart grids for simulation is becoming more demanding. In particular, achieving high-fidelity validation of such complex cyber-physical systems is growing in importance and in scale of challenge. Coordinated real-time simulation across multiple platforms, termed geographically distributed simulations (GDS), paves a new pathway for high-fidelity validation of large-scale smart grids. Furthermore, the integration of cloud solutions enables efficient initialization of simulations and ensures secure data communications among GDS participants. This paper provides a comprehensive overview of different types of real-time simulation concepts and explains how they can best be utilized to realize GDS with enhanced computational capability. Subsequently, this paper summarizes the applicability of GDS, specifically emphasizing on cloud-based GDS, to facilitate high-fidelity validation of complex smart grids.**

***Index Terms*—Cloud-edge simulation, geographically distributed simulation, modelling complexity, smart grid, validation.**

I. INTRODUCTION

Power networks were initially developed to supply customers with energy from large fossil fueled power stations. Electricity distribution networks have undergone evolution spanning almost a century. For instance, even in the 1960s, UK homes predominantly used gas or solid fuel for heating and used less than half the number of electric appliances that they do at the present time. The drive for carbon-neutral energy networks and a decrease in the price of renewable energy technologies have greatly increased both power generation within distribution networks and the pace of change itself. This increased distributed generation, from wind and solar power relies on asynchronous inverter-based technologies. In order to address the resulting requirement for grid flexibility and reduction in system inertia, energy storage technologies such as electrochemical batteries and hydrogen storage are being integrated into the distribution network. The increase in electric vehicles and electric heating is also influencing peak demand scale and time, calling for increased attention to demand-side management. All these changes are altering the way power flows within electricity distribution networks. Thus, continuous changes in the operation, commercial, and regulatory aspects of electric power systems are required [1]. Moreover, increasing monitoring and control functions and associated communications are becoming essential features at the grid edges. The emergent cyber-physical nature of the smart grid brings additional complexities when it comes to the validation of proposed control, protection schemes and the integration of new control variables into power system management. As power systems become more complex, the need for high-fidelity mathematical modeling is growing in importance to validate the smart grid system for accurate prediction and operational planning [2].

Section II of the paper highlights the major complexities of the power system as the smart grid development continues. The importance of high-fidelity validation for aiding the energy transition towards net zero is described in Section III, before a critical review of prior work in digital real-time simulation (DRTS) and geographically distributed simulation (GDS). Section IV gives an overview of cloud-based simulations and discusses the applicability of cloud solutions and GDS in the smart grid domain. Section V concludes this paper.

II. GROWING COMPLEXITIES IN POWER SYSTEMS

As smart grid schemes continue to be deployed, and integrated to form holistic smart grids, increasing complexity is emerging through developments such as sector coupling, ubiquity of decentralized generation in renewable-rich power grids, new interconnected control architectures, DSO services, converter advances to name a few. This transition results in growing complexity in power system operations from various perspectives, including but not limited to the following:

A. Maintaining Power Balance

Power systems maintain balance between supply and demand to ensure a reliable and efficient supply of energy to consumers. This is achieved through the use of the balancing mechanisms and ancillary services, which enable the optimal dispatch of controllable generations during each trading period. However, Distributed Energy Resources(DERs) that rely on highly variable and weather-dependent energy sources like solar and wind make balancing the system during periods of low demand in particular increasingly challenging. The balancing mechanism and ancillary services are generally based on the condition of the transmission system. Distributed generations connected to the distribution network are not included in the calculation of short-term dispatch of the electricity market. On the contrary, generation from DERs decrease the projected demand in real-time [3], [4]. This places strain on the stability of the system, resulting in potentially problematic frequency deviations for the distribution network operators (DNO). So, it is essential to have effective management of the integrated energy system to limit the detrimental effect on system frequency or voltage [5]. Unlike conventional generation units, renewable energy sources are coupled to the grid using power converter interfaces, which do not inherently contribute to system inertia. These changes are already being reflected in higher rates of change of frequency (RoCoF) during power imbalance in the Great Britain (GB) grid. GB protection schemes operate when RoCoF is greater than 0.125 Hz/s, which can trip DERs even after the original fault is cleared. Since it can cause disconnection of more inverter controlled connections than planned, the power system is prone to greater risk. Therefore, protection devices with less sensitivity are required for low inertia systems [4].

With the presence of distributed generators, lower power flows across the network increases reactive gain however, at the same time fewer generators are available to provide voltage support. DERs may be expected to provide grid ancillary services, such as voltage control, according to the requirement of emerging distribution system operators (DSOs), which requires improved monitoring of DER conditions [4], [6]. The transition from DNO to DSO involves the use of virtual power plants (VPPs) as a functional component that can manage dispatch within the distribution network, while the DNO retains usual network ownership [7]. VPPs have the potential for better control integration among all energy stakeholders, increasing flexibility and controllability of distributed and demand variable DERs [8]. Establishing the new concept of VPP requires the integration of real-time data of the complete distribution network and an accurate model of the system. Therefore, high fidelity modelling with integration of DERs would allow better control and power balance in the power system.

B. System-Wide Smart Grid Technology Integration

Advanced sensors, communication networks, and control systems to better monitor and manage power flow in real-time are increasingly featured in grid scheme. While these technologies offer many benefits, their integration requires significant changes to the existing infrastructure, which can create new vulnerabilities in the system. Energy management systems (EMS) play a crucial part in system operation and control as DNOs are gradually transitioning to become DSOs. EMS hosts several network computation functions such as static state estimation (SSE), optimal power flow, and contingency analysis. However, SSE is not suitable for real-time monitoring and control of time-critical dynamics in the system due to slow update rates. To address this limitation, supervisory control and data acquisition (SCADA) systems are used in EMS. The modern wide area monitoring system (WAMS) uses the data from phasor measurement units (PMU) to monitor critical areas of the power system as PMUs have the capability of processing detailed snapshots of network conditions at higher reporting rates [9]. This is achieved by strategically placing the sensors in critical areas of the system [10]. The measurements from the WAMS are utilized by wide-area control system to control transient and oscillatory dynamics of system voltage and frequency [11]. When designing controllers for such applications, the variability of local controllers and their impacts on the system must be considered. The increased reliance on real-time data needs greater observability of networks for dynamic state estimation and efficient data management. The consequence of cyber attacks also increases as digital technology is utilized more extensively in electric power networks. The system requires safeguarding against malicious attacks, which needs reliable security measures and continuous monitoring [12]. Such cyber-physical energy systems integrating multiple energy domains, communications and automation technologies require sophisticated testing frameworks for holistic validation [10], [13].

C. Establishing Holistic Communications and Data

The lack of consistent protocols for collecting data from DERs in grids means information about the amount and type of DER in different parts of the network tends to be incomplete [7]. Industry would benefit from adopting standard message protocols [14]. The UK has been reportedly slow to adopt such standards compared to other European countries. Different levels of control are required in the smart grid, i.e. system level deals with operation strategies like load balancing, the subsystem level deals with DER management and the component level deals with enhancing the local power electronics control behavior. To meet the flexibility, adaptability, scalability, and autonomy required of smart grid, interoperability and open interfaces are necessary to enable coordinating functions at different levels of the grid. This remains a challenge. Consequently, for these cyber-physical systems, a holistic standard-based protocol for data recording and communication is required to enable reliable and secure grid operations [13], [15].

III. HIGH FIDELITY VALIDATION

Smart grids are increasingly complex, and the implementation of their validation framework poses significant challenges such as ensuring that it accurately represents the interdependence and integrity of subsystems across different domains. High fidelity validation is the proving of system behaviour with simulators, emulators and testing rigs that produce realistic images of the physical system. Power system modelling falls into two broad categories: modelling for planning purposes and modelling for operational management, with functions across different time scales. Currently, different types of software are used at different levels of the network for analysis supporting decision-making, control, and monitoring purposes, but interoperability is limited and analytical capabilities vary extensively.

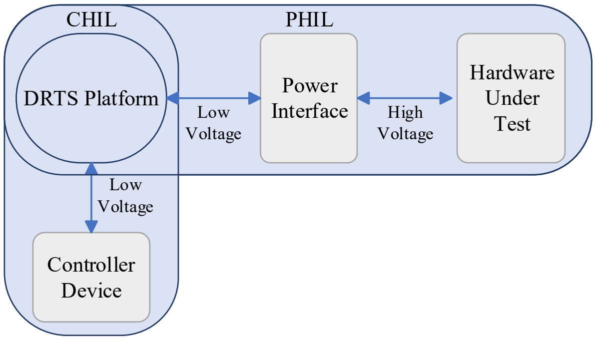

Fig. 1: A representation of different types of HIL.

For instance, software tools such as DIGSILENT, IPSA, ETAP are mostly used for steady state, transient and harmonic analysis of the network. Several other software are used for electromagnetic transient (EMT) analysis (eg. PSCAD), multi-domain analysis (e.g. MATLAB, DYMOLA), real-time simulation and hybrid simulation [8]. For real time study, simulators like RTDS, Opal-RT, Typhoon, dSPACE, etc are typically used [16]. For holistic high-fidelity validation, the integration of data from multiple sources with varying formats needs to be harmonized and made interoperable, either through cosimulation or platform coupling. References [13] and [17] presented a conceptual integrated framework combining models for a holistic assessment of power system flexibility requirements across all timescales. In addition to addressing the issue of interoperability of multiple software, accurate temporal and spatial representation of the grid in the working model is another critical concern for ensuring high-fidelity validation of the system. Creating models of the aggregated dynamic responses of the DERs and addressing the uncertainty related to their availability and level of response are two of the most significant challenges in this arena. Advanced state estimation can be utilized with the increasing amount of real-time data received from PMUs to improve system observability by creating an accurate representation of the system [8]. The optimal placement of PMUs is a crucial factor for getting the exact grid image with minimal investment [10]. Digital twins based on an accurate model and real-time data can also contribute to improving network operators' capacity to model and foresee potential threatening situations [18]. Therefore, high fidelity representation of the power system can be used to validate any major change in the system before it goes live.

A. Digital Real Time Simulation at the Core

The core requirement for the validation of any system is to have an accurate model for the simulation of possible scenarios that may arise in the system. Digital real-time simulations (DRTS) are simulations where the time required by the simulator to reproduce a state is equal to the actual wall-clock time. DRTS is useful for detailed analysis of power systems particularly in validation and optimization of control algorithms as it permits emulation of real-time operational effects. It also allows comprehensive analysis and performance validation of dynamic power electronics-based systems [19]. Most DRTS platforms are available as dedicated hardware consisting of powerful processors and software supporting the modelling and simulation functions. As in [16], the 4 key components of DRTS platforms are:

- Real-time simulations on parallel connected processors.
- Host computers for offline model preparation, loading to processors, and monitoring real-time simulation results.
- I/O terminals to interface with external hardware.
- Communication network for data exchange between processors and a separate communication link between host computer and the processor cluster.

Along with using commercial DRTS platforms, efforts had been devoted to integrating real-time simulation using programming languages and other simulation tools. References [20] and [21] demonstrated the feasibility of equation-based object-oriented modelling and modelica language for the modelling and simulation of power grids even though it was done on a small scale. Studies have also been conducted for developing EMT based real-time model using HYPERSIM software, from a RMS-based PSS/E model of the simplified Australian 14-Generator power system [22].

B. Hardware-in-the-Loop Testing

Validation experiments can be carried out as independent simulation in the DRTS platform. DRTS can also be coupled with external hardware at its I/O terminal to perform hardware-in-the-loop (HIL) testing [23], which allows the validation and extensive analysis of the hardware under various simulated operating conditions. HIL Testing can be further classified based on the coupled hardware, which can be either a low voltage controller referred to as controller hardware-in-the-loop (CHIL) or a high-voltage power device referred to as power hardware-in-the-loop (PHIL) as shown in Fig. 1. CHIL and PHIL real-time simulations paved a new pathway in investigating the interactions between the physical power components (or physical controller-based control algorithms) and the real-time simulated power systems. Both of these have been extensively exploited for the prototyping of power apparatus [24]–[26], validation of novel control schemes [26], [27], black start testing of grid-forming converter [25], [26], etc. In addition, advanced HIL technique has also been used for testing and verification of PMU-based linear state estimator, supporting a simulated system of over 1,500 buses and 2,800 branches which has been modeled in OPAL-RT [28]. Furthermore, HIL technique has been leveraged to successfully realise a test bed for testing and validation of cyber physical system consisting of physical power system, power system monitoring, energy management system and communication layers of smart gird [29]. These HIL validation approaches significantly de-risk the testing and minimize the expense and time-to-market of research and development in the renewable energy and smart grid context [24]–[30].

C. Geographically Distributed Simulation (GDS)

The extent to which the modelling of smart grid can be implemented in a single DRTS platform is constrained by the computational limit of the platform. Each DRTS platform has

Fig. 2: Basic GDS Schematic.

a limit on the number of nodes that it can support in the model and the time step it takes to solve the model to produce results of the system transients [16]. Co-Simulation of the same model segregated into subsystems would allow simulation of even complex networks. This has encouraged the development and establishment of the concept of geographically distributed simulation (GDS), which utilizes computational resources across numerous geographically distributed facilities. As summarized in [31], some of the advantages of GDS are:

- Interconnection of multiple laboratories to test interconnectivity concepts for facilitating interaction and communication validation between remote smart grid components.
- Utilizing services developed by partner laboratories, so time and effort is not wasted recreating the same service.
- Collaboration with industrial partners is facilitated by eliminating the need to share detailed sensitive models.
- Makes prototype testing logistically convenient as bulky equipment is not always needed on site.

To have the subsystems of GDS working together, each DRTS platform needs to communicate with other associated DRTS, which is achieved with the aid of communication interfaces and communication network. A communication interface conditions the data exchanged between individual DRTS to make it compatible with the selected protocol of the network and address communication delays. The communication network provides the connection between the communication interfaces of the associated DRTS through the internet. Fig. 2 shows the basic schematic for GDS.

For high-fidelity representation of smart grids different simulators based on different languages and specializing in different domains need to be in synchronism. To ensure the proper functioning of the overall simulation, all associated simulators must have coordinated initialization values at the start of the simulation [32]. Data transferred between simulators should also be time synchronized to ensure that data loss due to delays in communication between remote components does not affect its performance.

The points within the overall GDS system where the whole model is decoupled into subsystems hosted in different simulators are important factors for consideration. The sections connected with fewer tie lines are the best points of separation within the simulated system as it reduces the number of exchange variables that need to be transferred. It is also preferable to have the minimum number of subsystems in the model as it simplifies the task of time delay compensation [19]. DRTS platforms can be coupled synchronously or asynchronously. Both coupling methods of GDS have been established between two locations [33], [34]. The preferred coupling method depends on the requirement of the experiment. A comprehensive study of the existing use cases of GDS has been published in [35]. The development of a 'Global Real-time Super Lab' across eight locations using three different simulators is a notable milestone experiment, demonstrating the VILLAS framework providing seamless integration of distributed simulators [31].

In analogy to the HIL experiments [23], [36], [37], the stability and accuracy of GDS closed-loop setups had also been well analyzed in [38], [39]. A high-fidelity test environment has been created by syncing the measurement and output of two subsystems of GDS in every single simulation timestep synchronizing the assets at both locations. It allowed the hardware under test (HUT) to interact in real-time with a simulation demonstrating GDS's applicability in future hardware testing [40]. In another experiment it is observed that when a system operator sends a control signal to adjust the reactive power generated by a microgrid, the on-load tap changers installed with transformers in substations also react to it; thus minimizing the effect of the control action. This auto-adjusting nature needs to be considered when designing holistic control of smart grid components. It also imitates interactions of subsystems on different hierarchical levels and operational time frames with minimal loss of data and delays, showcasing the applicability of GDS for smart grid studies [41].

Each of the techniques mentioned earlier has the potential to analyze dynamic responses in real-time. However, they have individual unique characteristics that make them better suited for specific validation studies. A summarized comparison of these three real-time simulation techniques is presented in Table 1. DRTS has the shortest developmental time and the least amount of error. However, its scope is limited to the digital domain, and simulation size and details are capped by the capacity of the DRTS platform. HIL opens up the scope for testing hardware in real-time, providing better fidelity, but its usage is also constrained by the same DRTS computational limitation. Additional complexities stemming from the signal conversion and interface algorithms need to be addressed to maintain a low level of error for testing of PMUs, converters, etc. GDS is the most complex of all three as it needs to handle communication protocols and time delay adjustment in addition to the complexities associated with HIL. GDS allows the validation of large systems, making it useful for validating the operations of VPPs, which addresses the challenge of maintaining power balance within DER-enriched smart grids. Furthermore, it also lays the foundation for investigating the interoperability and holistic protocol for data and communication. It would address the data management and continuous monitoring challenges that come with system-wide technology integration in smart grid. Hence, GDS is a feasible approach for the validation study of interactions and coordination between smart grid components.

TABLE I: Comparison of different real-time simulation techniques

ATTRIBUTE	Digital Real-Time Simulation DRTS	Hardware-in-the-Loop Simulation HIL	Geographically Distributed Simulation GDS
Summary	Digital simulators based real-time system simulation	Couples hardware with DRTS and allows hardware testing in real-time	Combines several DRTS and/or HIL for large-scale real-time simulation
Fidelity	Medium	High	High
Error Scope	Low	Medium	High
Simulation Scale	Small	Small	Large
Developmental Speed	Fast	Slow	Slow

IV. Cloud Computing Resources Aided GDS

A. Cloud Based GDS Implementations

GDS implementation can be realised between locations connected via optical fiber. However, most GDS implementations have been done over the internet using User Datagram Protocol (UDP) with a direct VPN connection between DRTS platforms [19], [32]–[34]. This is the preferred choice of connection since DRTS platforms associated with GDS are usually dispersed across the globe. Neither of the above connections is classed within the cloud computing domain as they don't provide the key virtualization or scalability function of cloud computing for either modelling or interconnection of the GDS components [42]. GDS can broadly be classified into two types of cloud implementation:

- Cloud-edge simulation: Model hosted at distributed DRTS platforms but remote connection is possible via cloud infrastructures.
- Cloud simulation: Model hosted in a cloud and can be accessed from any computer.

Commercial DRTS platforms (e.g., OPAL-RT and RTDS), host the simulation model within its hardware for analyzing the model. So, they are categorized as cloud-edge simulations due to such hardware-based computing mechanisms. Establishing communication and initializing simulation in GDS is a complicated task as it requires coordination between associated DRTS platforms and relies on specialized devices, drivers, compilers, and complex configurations. Frameworks for easy initialization and communication between GDS subsystems are being explored within the research community. VILLAS framework allows direct communication between different types of DRTS platforms as its gateway supports communication in different protocols and interfacing with commercial DRTS platforms [43]. Edge computing technology has been implemented for multi-agent consensus dispatch in distributed power networks. A multi-access edge computing (MEC) and multi-agent system (MAS) based consensus dispatch model computes data processing and storage to the edge node. It reduces both time for dispatch and network transmission cost compared to central consensus dispatch models [44].

Cloud Simulations may be considered more user-friendly as simulation can be started by simply logging in or connecting to the simulator without any complex configuration. CloudPSS platform, for instance, is a cloud simulator based on virtualization techniques. It is composed of three subsystems: a web-based workspace, a platform for exchanging data, and an engine for parallel simulation. All three components. are hosted in third-party cloud service providers allowing flexibility and scalability [43]. General transient simulator (GTS) is another individually developed cloud simulator that uses EMT simulation in high-performance automatic parallel computing technology. GTS has been used to simulate the Fujian power grid of China with AC power system above 10 kV [45].

PSS/E software is heavily used by the energy industry for planning and analysis of networks. Pilot deployment of PSS/E in public cloud infrastructure showed improved computing efficiency and considerable cost reduction [46]. Siemens has recently launched its PSS/E Cloud solution that has industry-level dynamic analysis capability with additional scalable computation power, secure collaboration possibility, and remote access to the simulator [47]. Even though PSS/E Cloud does not have direct real-time simulation capability, it has the potential of being integrated with an EMT based real-time model since it is based on PSS/E infrastructure [22].

B. Applicability of Cloud Solutions in the Smart Grid Domain

The scalability and distributed control options of growing smart grids are important areas of consideration with the advancement of data-intensive controllable IoT devices in the power network. Cloud computing has the potential of managing the overwhelming information generated in the smart grid. A cloud-based framework has been developed for acquiring and storing big data for smart grids by integrating Labview and Microsoft SQL Server [48]; Another framework for information management and big data analysis has been proposed which involves setting up cloud computing centers at three hierarchical levels: top, regional, and end-user. It also addressed security issues by including identity-based encryption in its framework [49].

Smart grids also have accelerating levels of interaction between multiple domains like electricity, heat, transport, etc. Hence, Multi-Domain Simulation is needed for the validation of the future smart grid. Experts from several fields in the energy, ICT, social, economic, and political sectors need to collaborate to analyze these complex multi-domain systems. Although multi-domain simulation has enormous potential in performance assessment and system-level validation, its applicability is subject to concern. That is because models in different platforms need to be modified or even reformed to make them compatible with the overall simulation architecture. It would take enormous effort to bring the modelling and analysis capability of so many disciplines into a single platform. To overcome this challenge, the GDS approach has been adopted to integrate pre-existing domain-specific simulators into a single environment. Co-simulation frameworks like Mosaik and HELICS have been developed to simplify the integration procedure [50]. The separation of the modelling and simulation processes is the primary advantage of integrating into a single environment. It allows simulations portraying different domains to be constructed and utilized at different organizations without violating intellectual property issues. Before the simulations are integrated into a single environment, it is essential to modify them into a functional mock-up model for exchange. The functional model is a common schema that can be interacted with irrespective of the platform-specific model it is based on. A functional mock-up interface (FMI) can then integrate all the different Functional Models together to create a single environment thus making it possible to investigate the dynamics of a 'System of Systems' [51]. Here again, comes the need for adhering to holistic data and communication protocol, as simulation platforms incompatible with the FMI can not be integrated with the 'System of Systems' simulation.

As a stepping stone for creating the simulation of a 'System of Systems', large-scale GDS could be tested out by the integration of research institutions (RI). Laboratory setups consisting of different components could be virtualized and made available in the cloud to be used as 'Simulation as a Service'. The virtual model could always contribute to the overall simulation model allowing associated RIs to connect to it even when the host institution is conducting its own experiment. Its practical demonstration had limitations in modelling dynamics that are not compatible with its communication interface [52].

V. Conclusions

With careful design and implementation of abstract techniques, high fidelity and trusted validation of smart grids including the effect of increasing complexity can be realised. In doing so, increasing penetration of DERs and complex decentralized control and management schemes can be confidently assessed, and operational risks mitigated before deployment. Substantial cost reduction and time-saving are therefore possible through identifying unfeasible infrastructure choices. Potential unforeseen issues can thus be mitigated to prevent significant disruption within energy system. Real-time simulation of the complete system could increase grid observability and controllability of DERs. Since current state-of-the-art real-time simulations are limited by the computational capability within individual organizations, collaboration through geographically distributed infrastructures towards holistic system testing could contribute to enhance the validation of complex systems. However, holistic approaches for analyzing and validating multi-domain cyber-physical systems like smart grids remain less than comprehensive. Addressing the issues arising from the integration and interoperability of various DRTS platforms and communications solutions into a holistic scheme remains a work in progress.

Additionally, incorporating the reproduction of the performance of the grid-edge and cloud based operational functions, together with utilization of cloud based tools in realising trusted GDS based validation, are worthy of dedicated investigation. Challenges remain and are shared including interoperability and holistic data sharing. The contribution of cloud based applications to consistently performing GDS and overcoming sensitive model sharing concerns are deserving of rigorous study. Ongoing work will investigate functional mock-up models, sensitive data masking and 'Simulation as a Service' for differing stakeholders. In this way, the security of supply for emerging energy systems will remain a priority as complexity-rich smart grids emerge.

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