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A Digital Framework for Locally and Geographically Distributed Simulation of Power Grids

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The power system sector is expected to contribute significantly to addressing the global climate change challenge through solutions such as the integration of distributed energy resources with low carbon emissions and demand side management as part of the flexibility solutions. However, the transformations in the power grids necessitate additional solutions to ensure the stable and reliable operation of the grids. Such novel solutions require detailed studies in laboratories before implementation in real grids. Power systems simulations combined with power-hardware-in-the-loop (P-HIL) experiments provide a reliable form of conducting such studies. The current article introduces the Energy Grids Simulations and Analysis Laboratory of the Energy Lab 2.0 as a digital framework enabling local and distributed analysis of power grids. The outstanding feature of the laboratory is its ability to connect the simulation of validated networks directly to the real hardware of the Energy Lab 2.0 in form of P-HIL setups and virtually to distant energy research infrastructures, thus enabling geographically distributed experimental studies. Results of the benchmark case studies show that the communication methods available in the simulation laboratory can be used to accurately set up locally and geographically distributed simulations, as well as for reliably interfacing physical hardware components to real-time simulations.

1. Introduction

The power grid is a fundamental block in the operation of nearly all critical areas in society and industry. This level of importance places high requirements on the security of the grid, in terms of system stability and reliability of operation. In the current environment, network operators rely on state-of-the-art simulation tools to carry out system-wide studies to analyze different grid states during normal and extreme operating conditions. Such studies, together with experience, are always used as an aid by operators in making decisions during critical grid conditions.

Recent studies, however, show that a reliable and affordable future supply of power will tremendously rely on renewable energy sources (RES), especially photovoltaic and wind power generation. This is further supported by the recent trend in the installation of renewable energy sources on local and global scales as reported in Ref. [1,2] as a contribution to the inter-sectoral efforts required to address the global climate change challenge. However, due to the intermittent nature of the generated power from renewable energy sources, solutions such as energy storage systems and demand side management are increasingly considered together with the RES to replace large generation sources heavily dependent on fossil fuels.

The integration of RES, and distributed energy resources in particular, has led to a huge ongoing transformation in the power grid structure. As a result, the following challenges arise in the operation of power systems: First, the primary energy sources, i.e., wind and sun, are weather dependent and therefore highly variable. This results in continuous variation and mismatch between generation and consumption,[3,4] thus causing pressure on system stability in form of frequency deviations. Second, renewable energy sources are connected to the existing power grid through power converter interfaces, unlike the traditional grid dominated by synchronous machines.[5,6] From the operation point of view, synchronous machines are the main source of inertia, and thus contribute enormously to the system damping which determines the rate of change of frequency (RoCoF) during critical operating conditions. This service is not naturally provided by the power electronic converters interfacing the renewable energy sources to the grid and therefore leaves the power system vulnerable to sudden disturbances.[7] Third, the integration of distributed energy resources (DER) introduces bidirectional power flows in the network, whereby power flow is experienced from distribution networks to transmission networks, in addition to the conventional flow from the high-voltage transmission to low-voltage distribution networks. This results in a challenge for operators in

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dealing with voltage stability, especially since the connection points of most renewable energy sources are on the distribution level.[8] In addition, the power system has experienced a tremendous increase in complexity due to the operation of large interconnected networks in the current grids and an increase in electricity demand resulting from electric vehicles[9] and heat pumps,[10] among others.

The smart grid concept has gained momentum in research and industry as a possible solution for managing the newly distributed energy resources and the evolving power grid.[11] The fundamental idea is to integrate the different grid components in form of intelligent electronic devices, advanced metering infrastructure, together with information and communication technologies for efficient, economical, and secure delivery of electricity.[12] In other words, the smart grid has the capability of addressing the bi-directional flow of electricity and control information in an automated and advanced power grid. Several research and development projects have been reported in the literature analyzing the viability of the smart grid concept in future power grids with DER.[12,13] This shift from the traditional power grid to the smart grid concept results in a change in the underlying computational problem and complexity in the tools used for operational planning and assessment of system stability. As a result, the simulation tools and analysis techniques have to be revised in research and industry to cope with the changes in the environment characterized by a large share of RES in the smart grid context.

Extensive research has been carried out to develop new tools that will reliably evolve with the changing power system environment. The result has been power system analysis tools for individual applications ranging from power flow analysis, electromechanical transients simulations, and electromagnetic transient (EMT) simulations. The class of simulations most relevant to the current power grids is the EMT simulations that can be used for detailed analysis of the power-electronic-based generation sources. EMT simulations use very small time steps, in the range of microseconds, to achieve the computational accuracy required for the detailed analysis. Furthermore, EMT simulations usually require specialized hardware to handle the computational effort in real-time simulations. However, theoretical considerations alone cannot account for the huge amount of work required to implement innovative solutions for future grids. Extensive testing and experimentation of the solutions are indispensable and should also be taken into account in a setting close to the real power systems. Since experiments cannot be carried out in public grids, smart grid experimental laboratories offer such a platform for testing innovative hardware and software solutions for future grids.

A number of smart grid experimental laboratories have been set up in research and industry in order to conduct investigations on innovative solutions for future grids.[14,15] Among such projects is the Energy Lab 2.0 platform of the Helmholtz Association. The Energy Lab 2.0 platform offers state-of-the-art experimental infrastructure for studying the interaction between new components including generation, energy storage, and conversion systems in future power grids, as well as testing new hardware and software solutions necessary for a successful energy transition. The central components of the Energy Lab 2.0 infrastructure are the Smart Energy System Control Laboratory (SESCL), the Energy Grids Simulation and Analysis Laboratory (EGSAL), the Control, Monitoring and Visualization Center, Living Lab Energy Campus experimental buildings, Security Lab Energy, and the Power Hardware-in-the-Loop Laboratory.[16]

Due to the critical nature of the power grid and safety reasons, there is no direct access to public grids to carry out experiments to test innovative solutions. The Energy Grids Simulation and Analysis Laboratory (EGSAL) is a framework for modeling, simulation, analysis, and visualization of energy grids for experimental purposes as part of the Energy Lab 2.0 infrastructure. EGSAL forms a link between the simulation environment and the experimental hardware within Energy Lab 2.0. The aim of EGSAL is to provide digital representations of energy grid models and a simulation framework that can be used for testing software and hardware solutions for future grids in collaboration with other laboratories in energy research. With the virtual connection of research infrastructures, EGSAL allows sharing of expensive simulation and experimental hardware among research and industrial partners. The corresponding research topics within the scope of the EGSAL laboratory include: power grid modeling and analysis; geographically distributed real-time simulations; distributed co-simulation for multi-physics-based energy systems integration; high-performance computing for parallel grid simulations; development of simulation and analysis software framework; time-series data measurement and analysis for network model verification.

The main contributions of the current article are: Description of the hardware and software composition of the EGSAL digital framework that can be used for experiments and testing; Description of a validated campus network model for application in experimental tests; Simulation scenarios within the EGSAL scope demonstrating locally and geographically distributed real-time simulations; and description of the interface between the simulated networks and real experimental hardware in the Energy Lab 2.0 context. The rest of the current article is structured as follows: Section 2 gives an overview of other smart grid laboratories in relation to EGSAL and the Energy Lab 2.0 infrastructure. The software and hardware composition of the EGSAL infrastructure are described in Section 3. In Section 4, key use cases are presented to show the potential of the digital framework. Finally, Section 5 concludes the paper with an outlook on future work.

2. Related Work

In view of the challenges introduced in the analysis process of power systems, research efforts have been devoted to developing additional solutions to cope with the grid transformation and enable a smooth energy transition. Such novel promising theoretical approaches, however, require detailed analysis and validation before being applied in real power grids. For this purpose, large-scale smart grid experimental laboratories have been set up to test such solutions for future power systems in both simulation and experimental aspects, as reported in Ref. [14,15] The reports list a number of categories as the main research topics at the different smart grid centers. One of the identified predominant categories is grid management, which deals with grid monitoring and investigations regarding the integration of components into the transmission and distribution system.[15] Such studies are mainly facilitated by real-time simulations, combined with (power) hardware-in-the-loop (P-HIL) experiments. The grid

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simulation features and capabilities of different smart grid laboratories are summarized below.

At the Smart Electricity Systems and Technologies Laboratory (SmartEST) of the Austrian Institute of Technology, real-time simulation of complex power grids and components is carried out. These simulations are coupled with grid simulators implemented using laboratory hardware in a form of HIL setup.[17] The real-time simulation hardware in the laboratory is an Opal-RT with several cores that can be used for real-time PHIL simulations.

The Norwegian National Smart Grids Laboratory is a state-of-the-art smart energy systems experimental facility for demonstration, verification, and testing of a wide range of smart grid scenarios. Specifically, the laboratory provides the opportunity to integrate real-time simulations and physical power system hardware as a HIL setup. The Opal-RT system is available for real-time digital simulations, HIL testing, and rapid control prototyping.[18]

At the Technical University Dortmund, the Smart Grid Technology Laboratory provides a multifunctional research and testing infrastructure for the development of future low-voltage networks and electromobility. The simulation part of the laboratory consists of Opal-RT as the real-time digital simulator and an interface to an Egston power amplifier to complete the PHIL setup.[19]

An emulation center for networked energy systems (NESTEC) has been developed at the German Aerospace Center (DLR) in Oldenburg for emulating miniaturized city districts with buildings, networks, and charging stations. NESTEC provides a research platform for representing complex distribution grid structures with real dimensions.[20]

Another example of a smart grid infrastructure is the PREDIS laboratory developed at the Grenoble Institute of Technology. PREDIS provides an emulated distribution network platform in the form of reduced-scale models of real medium-voltage networks.[21] The HIL system can be set up by connecting the emulated distribution network to real-time simulators through power amplifiers.

Other research laboratories dealing with real-time simulations include: Real-Time experimental Laboratory RTX-Lab at the University of Alberta Canada with a cluster-based, parallel real-time digital simulator for power engineering research[22]; the Center for Advanced Power Systems (CAPS) at Florida State University in the USA with an established and advanced simulation and experimental facility with the capability of performing HIL, real-time power system simulation[23]; the Institute for Automation of Complex Power Systems (ACSs) at RWTH Aachen University, Germany; the laboratory of Energy Department (DENERG) at PoliTO, Italy; SINTEF Energy Lab in Norway; the Idaho National Laboratory (INL), USA; Sandia National Laboratories in New Mexico; the Energy Systems Integration Facility (ESIF) by the National Renewable Energy Laboratory.

Furthermore, a number of additional smart grid experimental laboratories have also been set up in the industry to directly experiment with innovative solutions in real power systems. Such laboratories include: the Flex Power Grid Lab (FPGLab) in the Netherlands and the Concept Grid by Électricité de France (EDF), among others.

Real-time simulations have also been extended beyond single and isolated research infrastructures through the concept of geographically distributed simulations. Such an approach makes sharing of experimental resources between laboratories possible. This is especially beneficial for the simulation of large-scale networks that require a large amount of computation power and can be split into suitable sub-networks. In Ref. [24,25], a geographically distributed real-time simulation is presented combining the real-time digital simulators (RTDS) simulator at CAPS and Opal-RT at the RTX-Lab via an asynchronous link using TCP/IP and UDP protocols for application in an electric ship simulation. With further advancement in interface methodologies, an internet-distributed simulation platform integrating two remote real-time digital Opal-RT simulators at the University of South Carolina, USA, and at RWTH Aachen University, Germany is presented in Ref. [26]. Other implementations of geographically distributed simulations between two research infrastructures are reported in Ref. [27–29]. In a further step,[30] presents a virtual interconnection of real-time simulations and HIL experiments at eight geographically distributed infrastructures.

The research infrastructures presented above show experimental setups with simplified grids and a variety of standard test networks. In EGSAL, a further step is taken to include validated real power grid models in real-time simulations, providing a step towards an accurate digital representation of the networks. The benchmark network in this case is the KIT Campus North 20 kV network, with detailed network plans, component parameters, and planned integration of measurement data from the substations. A direct connection exists between EGSAL and the four laboratories within the Energy Labs 2.0 framework, which extends the application of the digital networks to the experiments in the laboratories in form of HIL or PHIL experiments. With this direct connection, the simulation laboratory is therefore complemented by the unique feature of Energy Lab 2.0 with the ability to set up topologically variable microgrid experiments using real power system components.[31] This establishes a digital simulation framework with test possibilities in the areas of automation, energy management, data processing, and *P*-HIL experiments using near real-world networks.

In addition, analysis of the different simulation infrastructures shows that the real-time digital simulators considered by the other research infrastructures are from three major vendors RTDS Technologies, Opal-RT Technologies, and in some cases Typhoon HIL. The aim of the EGSAL distributed real-time simulation infrastructure is to incorporate all vendor technologies in the digital-signals-based interconnection. This creates a wider distributed simulation infrastructure with the ability to connect a large number of industrial and research laboratory infrastructures not only to combine the simulation computing power for larger networks, but also to share experimental hardware resources.

The real-time simulations within EGSAL are complemented by offline simulation and analysis tools together with the application of high-performance computing for efficient grid studies.[32,33] Furthermore, the co-simulation of multi-modal energy systems is a major topic of research within EGSAL to extend the analysis to coupled power, gas, and heat grids.[34,35] The coupling of such grids will play a significant role in achieving a smooth energy transition and reliable operation of future grids.

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3. EGSAL Infrastructure

The EGSAL infrastructure is divided into the following components: the simulation hardware and software, the digital power grid models, and the communication methods for distributed real-time simulations. In the following sections, the three components introduced above are described in detail.

3.1. Hardware and Software Components

The scope of application of the hardware and software components within EGSAL ranges from offline and parallel grid simulations to real-time simulations as described in the following sections.

3.1.1. RTDS

The main hardware components for the simulations in EGSAL are the RTDS[https://www.rtds.com/technology/] for the real-time simulation of electrical networks. Currently, the laboratory consists of two RTDS systems each with the full computation power of 10 CPU cores. In addition, a third RTDS machine as part of the cluster with full computation power is mainly used for experiments and tests, but can be connected to the simulation cluster within EGSAL. The special hardware used for interfacing the different machines to exchange synchronization signals is the Global Bus Hub (GBH). The GBH can directly interface up to 36 RTDS NovaCor chassis via fiber optic transmitter/receiver cables.

The interface between the simulator and external devices is realized through the GTNETx2 card real-time communication link via Ethernet using different standard network protocols depending on the application. In EGSAL, the protocols installed for data exchange include: TCP/UDP Sockets (SKT), MODBUS, IEC 61 850-9-2/IEC61869-9 Sampled Values (SV), IEC 61 850 GOOSE Messaging (GSE), COMTRADE/ASCII, DNP3, IEC 60 870-5-104, and IEC/IEEE-60 255-118-1 PMU Playback [https://knowledge.rtds.com/hc/en-us/articles/360034788593-GTNETx2-The-RTDS-Simulator-s-Network-Interface-Card]. However, the GTNETx2 card has only two processor modules with each running only one network protocol at a given time, thus a total of two protocols simultaneously. The link between the simulation and the GTNETx2 card is realized via an optical fiber cable. Four GT fiber I/O ports on the Novacor are reserved for interfacing external equipment via Aurora communication. Two machines in the EGSAL framework are activated with Aurora licenses.

3.1.2. VILLAS Framework

The simulation cluster available to EGSAL can be extended using virtual interconnection to external simulators through a server running VILLASnode for geographically distributed real-time simulations. VILLASnode is a gateway application that is specifically designed to handle intercommunication among real-time simulators.[36] In such a setup, the infrastructures participating in the distributed simulation form the simulation subsystems. These subsystems are coupled through the respective VILLASnode instances, which provide the platform for data exchange between the respective distributed real-time simulations. The coupling method applied in the VILLASnode communication is based on the ideal transformer model (ITM) using dynamic phasors as described in Section 3.3.2.[26]

Time synchronization is critical for accuracy during distributed real-time simulations. The simulations of the different subsystems are synchronized to each other in terms of time and clock pulse using a GPS-controlled high-precision clock. This, therefore, allows the exact superimposition of signals at the coupling points of the simulated networks, which is important during the analysis of the exchanged signals.

3.1.3. Simulation and Computing Infrastructure

Additional computing infrastructure is available mainly for offline simulation and analysis, and testing software under development. These include: a GPU-enhanced power workstation – 2 Intel Xeon(R) Platinum 8176M CPU @2.1 GHz with 28 cores per CPU and 2 threads per core, 1.5 TB RAM, and an NVIDIA Quadro GV100 GPU – is used for offline simulation and modeling work using commercial simulation software and the in-house developed *e*ASiMOV framework;[37] a sector-coupling server – 2 CPU-Intel Xeon Platinum 8170 @2.1 GHz with 26 cores per CPU and 2 threads per core, 512 GB of RAM – applied for development work of a co-simulation framework for the simulation of multi-modal energy systems.[34] In addition, the high-performance computing (HPC) cluster of the Karlsruhe Institute of Technology at the Steinbuch Center for Computing (SCC) is also used for accelerated parallel and distributed simulations with the goal of achieving online stability analysis in power grids. The HoreKa[http://www.nhr.kit.edu/userdocs/horeka/hardware/] computing cluster consists of 769 compute nodes, 2 Intel Xeon Platinum 8368, each with 76 cores, 152 threads, and 256 GB (512 GB for high memory node and accelerator nodes) of RAM. Interconnection between the nodes is realized through a 200 Gbit s^{-1} InfiniBand 4X HDR Interconnect link.

3.1.4. Simulation Software

A number of simulation software packages are used in the simulation and analysis process within EGSAL for comparison purposes during the network modeling process and to validate the simulation results based on the standard software tools. These include DIgSILENT PowerFactory, NEPLAN, PSCAD, PSS/E, Dymola, MATLAB/Simulink, and OpenModelica. In addition, the in-house software framework *e*ASiMOV (for energy grids Analysis, Simulation, Modeling, Optimization, and Visualization)[37,38] is also part of the EGSAL toolkit. As part of the ongoing work, a software module is under development that will combine the different simulation packages in a co-simulation environment. Furthermore, the framework will enable automatic model conversion to facilitate easy model exchange between the different simulation software packages.

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3.2. Grid Models

Power grids of different sizes are considered in the scope of the EGSAL simulations. These include low-voltage distribution networks like the KIT Campus North 20 kV power grid, distribution and transmission networks, for example, Karlsruhe city network, Baden-Württemberg 380/220/110 kV network, the Germany 380/220 kV network, as well as the interconnected central European transmission 380/220 kV grid. In addition, standard IEEE test networks are used for testing, validation, and comparison of software developed within EGSAL.

The benchmark model applied for detailed real-time simulations is the KIT Campus North 20 kV network as described in Ref. [39]. A basic form of model exchange between different software packages is realized through automatic model conversion, thus forming a modeling pipeline from DIgSILENT PowerFactory, PSS/E, and finally to RSCAD for the real-time simulation. **Figure 1** shows the logical representation of the KIT Campus North network in DIgSILENT PowerFactory simulation software. The network consists of 43 20 kV-buses, 87 transformers, and 86 loads connected to the 400 V level. In terms of internal generation, the network consists of four generators and one 1.0 MW peak solar PV generation. Further details of the campus network and structural representation are given in Ref. [39].

3.3. Simulator Coupling Methods

The limitation of the real-time simulators is that only a limited number of grid nodes can be accommodated by a 10-core RTDS Novacor chassis for real-time simulations. This implies that the network size simulated in real-time is limited by the processing power of the simulator. To simulate larger networks, the network can be split and distributed among the available simulators, and the different simulators interconnected to combine the processing power during the simulation. Within the EGSAL framework, a number of interface methodologies for simulator coupling have been tested and are described in the following.

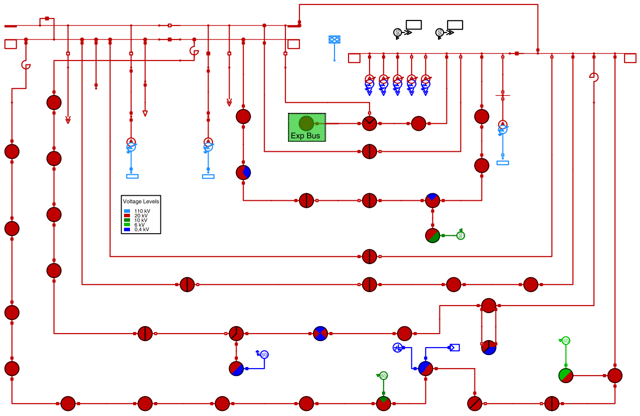

Figure 1. KIT Campus North 20 kV electrical network in PowerFactory. The coupling point of the experiment hall to the campus network is the Exp Bus (green highlighted block).

3.3.1. Inter-Rack Communication (IRC)

This form of communication is a direct link between different simulators to form a large-scale simulation cluster. Each RTDS rack has six IRC connections. This implies that a maximum of seven rack interconnections can be supported by the internal IRC channels. To accommodate a larger number of racks, an IRC switch is required, which is a high-speed switch augmenting the IRC connections for inter-rack communication with up to 144 racks in the system. The connection between the IRC connections is via a fiber optic cable.

For splitting the simulated network, the main method depends on the transmission line model (TLM), which uses the properties of the traveling electromagnetic wave in comparison to the step size. The network is decoupled in such a way that, if the traveling time is greater than the simulation step size, the changes at the sending end of the transmission line do not affect the receiving end (and vice versa) in the same time step. However, a simulation step size of 50 μs mainly applied for real-time simulations would require a minimum transmission line length of 15 km to achieve the required calculation accuracy. The minimum length for cables is ≈5 km, since the large shunt capacitance in cables slows down the propagating signals. Therefore, the decoupling points need to be selected accordingly.

3.3.2. GTNETx2 Interface

The GTNETx2 card provides a communication link between the simulator and external devices. If one or several racks are considered external devices, the GTNETx2 can be used as a communication link between the main simulator and the secondary simulators using the standard communication protocols.

Application of the GTNETx2 card communication method to distributed real-time simulation requires specific interface methods for the split network as defined in the literature. The most common interface method is the ideal transformer model (ITM).[40] The method is based on representing the decoupled network subsystems as controlled current and voltage sources in the opposite subsystem. **Figure 2** illustrates the ITM interface method. In this case, subsystem 1 is represented as a controlled voltage source in subsystem 2, whereas subsystem 2 is represented as a controlled current source is subsystem 1. During the simulation, a voltage signal is measured in subsystem 1 and sent to subsystem 2 via the communication network. In contrast, a current signal is measured in subsystem 2 and sent to subsystem 1. The communication bandwidth depends on the applied network protocol, e.g., the GTNET-SKT protocol supports 300 input and output data points (each with 4 bytes) per packet

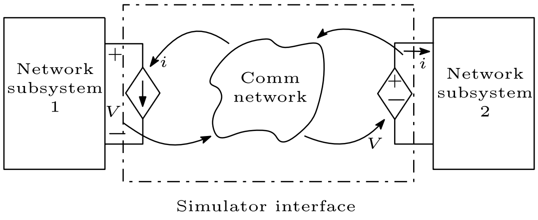

Figure 2. Ideal transformer model interface method.

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and 5000 packets per second[https://knowledge.rtds.com/hc/en-us/articles/360034788593-GTNETx2-The-RTDS-Simulator-s-Network-Interface-Card].

However, the ITM method is known to be sensitive to delays and phase shifts between the measured voltage and current signals in the interfaced subsystems. Stevic et al.[26] propose a modification of the ITM method by applying dynamic phasors to the exchanged signals. Dynamic phasors represent the measured fast varying time-domain instantaneous voltage and current signals as a series of slow varying Fourier coefficients in a specific time window.[41] The resulting phasors are the values exchanged between the simulators. The received dynamic phasors (DP) are converted back to time-domain (TD) representation in the respective network subsystems. The modified representation of the ITM method with dynamic phasors transformation is shown in **Figure 3**.

3.3.3. Virtual Connection via VILLASnode

The coupling methods described above directly connect simulators to extend the simulation cluster. However, real-time simulations usually require expensive equipment set up at experimental infrastructures. These infrastructures are usually located in geographically distant locations, thereby rendering a direct connection impossible. VILLASnode as described in Section 3.1.2 provides a virtual interface for fast data exchange between individual geographically distant simulated networks through specified connection nodes.[42] The interface method used in the VILLASnode is based on the ideal transformer model with dynamic phasors as the exchanged values between simulators (cf. Figure 3). The initial steps of setting up the virtual interconnection of the EGSAL hardware (KIT) with the partner institutes via the VILLASnode are implemented as part of the Energy System Design project of the Helmholtz Association.

3.3.4. Link Layer Communication via Aurora Protocol

The RTDS simulator provides the option of interfacing external devices using the Aurora 8B/10B protocol[https://docs.xilinx.com/v/u/en-US/aurora_8b10b_protocol_spec_sp002]. The Aurora protocol is a high-speed digital interface to the simulator via GT fiber cable. As mentioned in Section 3.1.1, four GT I/O ports are reserved on each NovaCor specifically for Aurora communication, thereby enabling simultaneous communication via four channels[https://knowledge.rtds.com/hc/en-us/articles/4415386203927-Aurora-Protocol]. The split network subsystems in this case are interconnected using the ITM interface method via the Aurora communication protocol.

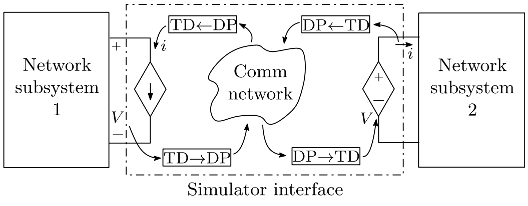

Figure 3. Ideal transformer model with dynamic phasors interface method.

4. Evaluation of Coupling Methods

In the following section, the different rack coupling methods available in EGSAL are evaluated. For this, the KIT Campus North network is used together with a simple experimental setup using real hardware in the Energy Lab 2.0 experimentation hall SESCL. For purposes of testing, the point of coupling between the detailed network and the experiment is assumed to be through a 5.25 km long cable to the 20 kV side of the transformer to which the SESCL laboratory is connected in the KIT Campus North 20 kV network. In the first case, the test is based on simulations using locally distributed simulators, i.e., RTDS–RTDS experiment, between the KIT campus network and the experimental load on separate RTDS systems. The second case includes a P-HIL setup through the Opal-RT hardware, i.e., RTDS–Opal-RT–PHIL. The aim of the experiments is to evaluate the accuracy of the simulator coupling methods and to analyze the time delay and their effects on the simulation accuracy.

4.1. Locally Distributed Simulations

In this scenario, the KIT campus network is simulated on one RTDS system (subsystem 1 – main subsystem) and the experimental load is simulated on a second RTDS system (subsystem 2). The simulator coupling methods are evaluated by a sudden increase in the load by 1 MW in the subsystem representing the simple experimental setup. The load change is triggered by sending a trigger signal from subsystem 1 to the experimental load in subsystem 2 at 2 ms. The following five coupling modes are tested in this part of the experiment: monolithic mode (benchmark mode)—where the KIT network and the experiment are simulated as a single system on one RTDS system; TLM mode—the setup consists of two subsystems coupled using the transmission line model method; ITM-Fiber mode—whereby the subsystems are directly coupled using fiber cables and the ideal transformer model as the interface method; ITM-Aurora—uses the ITM method as the interface technique whereas the communication is through the Aurora links; ITM-DP—uses the ITM method and dynamic phasors with a virtual connection through the GTNETx2 ethernet connection.

4.1.1. Voltage

Figure 4 shows the comparison of the root mean square (RMS) voltages at the coupling point in the main subsystem (subsystem 1) considering the five coupling modes. Important to note in this case is the voltage transition after the load change is triggered at 2 ms. It can be observed that the responses of the direct coupling methods (TLM, ITM-Fiber, ITM-Aurora) during the transition differ only slightly, whereby the TLM response matches the monolithic mode, whereas the two ITM modes show a small delay of about one time step (50 μs). However, the ITM-DP mode responds with a delay of about 2 ms, which corresponds to twice the delay in exchanging values between the subsystems using the virtual interface via the GTNETx2 connection. Nevertheless, the

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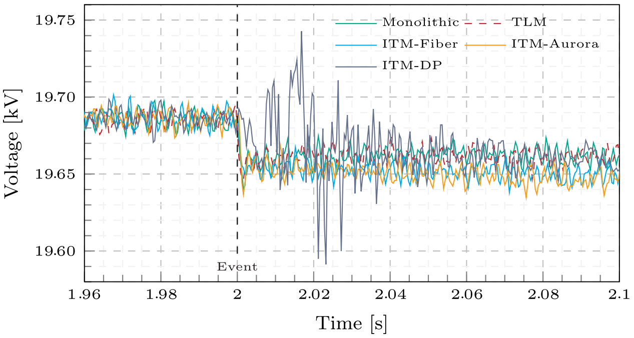

Figure 4. Root mean square (RMS) voltage at the coupling point for the different coupling modes compared to the benchmark monolithic mode.

steady-state voltage value attained after the load change is similar in all interface modes.

4.1.2. Current

The responses of the measured current at the coupling point are shown in **Figure 5** and **6** for the instantaneous and RMS currents of one of the phases (Phase A), respectively. It can be observed in Figure 5 that the response of the TLM mode is similar to the benchmark monolithic mode. However, a slight phase shift is observed in the responses of the ITM modes, where the ITM-Fiber is similar to the ITM-Aurora response. The ITM-DP mode however shows a significant delay in response to the load change.

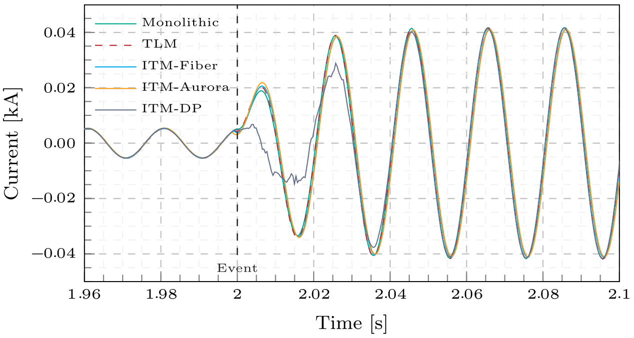

Figure 5. Phase-A instantaneous current at the coupling point.

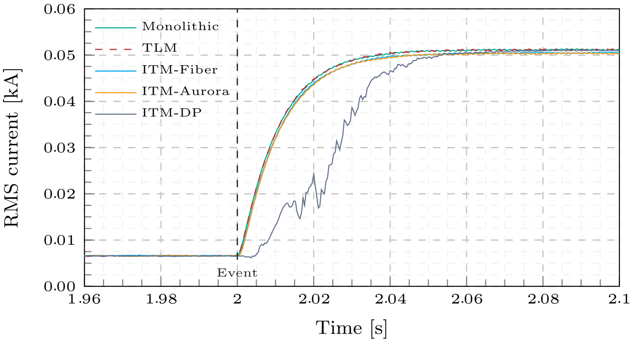

Figure 6. Phase-A RMS current at the coupling point.

This can be clearly observed in Figure 6, where the response to the event is delayed by about 2 ms for the ITM-DP mode compared to the other interface modes. The steady-state RMS current for the TLM-mode and ITM-DP mode is similar to the benchmark monolithic mode, unlike the ITM-Fiber and ITM-Aurora modes, which show are slight offset in the RMS current value compared to the benchmark case. It can be further observed that, although the change in the ITM-DP mode is delayed by only 2 ms, the response and steady state are delayed by up to 20 ms.

4.1.3. Active and Reactive Power

Figure 7 shows the injected real power into subsystem 2. In this case, a negative value indicates power flow from subsystem 1 to subsystem 2. As expected, the active power drawn by subsystem 2 increases from 0 to 1 MW as observed in all the investigated cases. However, there are differences in the responses during the transition to the new steady-state active power value. The direct coupling modes show a response closely similar to the benchmark monolithic mode. In contrast, the ITM-DP mode shows a significant delay in the response, but reaches the same steady state value as the other modes.

The response of the injected reactive power is shown in **Figure 8**, whereby negative indicates power injection from subsystem 1 to subsystem 2 at the coupling point. Important to note here is that the load reactive power remains zero for the simulated case. The positive value of the reactive power is a result of the net injection of reactive power due low loading

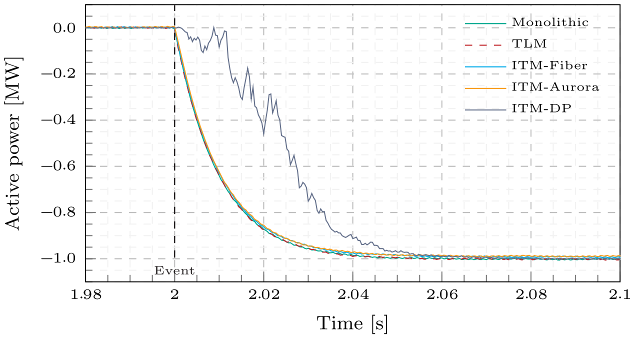

Figure 7. Active power injection into the experimental subsystem seen from the grid side at the coupling point.

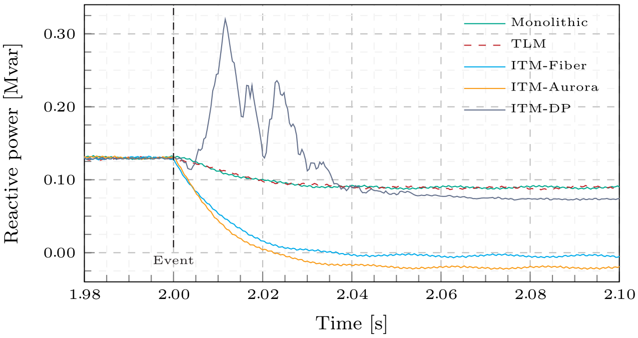

Figure 8. Reactive power injection into the experimental subsystem seen from the grid side at the coupling point.

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of the coupling cable. As can be observed in Figure 8, the net injection decreases when the additional 1 MW load is connected. However, the steady-state values of the ITM (-Fiber, -Aurora, -DP) modes deviate significantly compared to the benchmark monolithic mode. This could be attributed to the instability of the ITM method due to its sensitivity to delays and phase shifts when using fast varying time-domain instantaneous signals as mentioned in Ref. [26]. Further investigations are, however, necessary to determine the cause of the offset. The effect of modification of the instantaneous signals to dynamic phasors can be observed by the improved steady-state reactive power value of the ITM-DP mode. This response can be further improved by increasing the rate of exchange of dynamic phasors between the subsystems and by utilizing the time information and rotating the phasors accordingly.

4.2. P-HIL Preliminary Use Case: Low Latency Opal-RT RTDS Interface

The experiment described in this section illustrates the coupling of the simulation part and the experimental hardware within the Energy Lab 2.0 infrastructure. The aim of these coupled parts is to test new solutions, both from the software and hardware perspectives. The setup consists of two digital real-time simulators, i.e., RTDS and Opal-RT with a direct high-performance interface using the Aurora protocol, connected to experimental hardware. This constitutes the hardware-in-the-loop setup as shown in **Figure 9**. The experimental hardware is connected to the power grid through the Opal-RT P–HIL setup. The hardware in this case is a variable resistive load (*R-load*) which represents a daily load profile of a "Dentist's Alley" [The term refers to a street where several residents install, for example, high-power charging equipment and may want to use the equipment at the same time.] with a peak load of 80 kVA. The point of coupling of the two systems is at the 400 V-bus to which the SESCL laboratory is physically connected in the KIT Campus North 20 kV network via the Microgrid-Under-Test environment provided by SESCL.

The aim of the experiment is to analyze the total delay in the setup and evaluate how the delay influences the accuracy of such an experimental setup.

4.2.1. Benchmark Test Case

In the first step, the minimum delay between the simulations is tested by sending a signal from the RTDS simulator (Sent) to the Opal-RT simulator, which is then looped back to the RTDS simulator (Loopback). This serves as the benchmark for delay measurements in the experiment case set up between the two simulators. **Figure 10** shows the two signals as recorded on the RTDS simulator. It can be observed that the delay in the closed loop signal transmission is 100 μs as shown in Figure 10, which corresponds to two simulation time steps of 50 μs, i.e., one time step to send the signal from RTDS to Opal-RT and one time step to loopback the signal from Opal-RT to RTDS. The result of this benchmark test case confirms that the link layer communication delay via the Aurora protocol has negligible influence, and the resulting delay depends only on the simulation sampling time.

4.2.2. Closed-Loop Test Case

In this simulation scenario, the communication between the campus network on the RTDS system and experimental

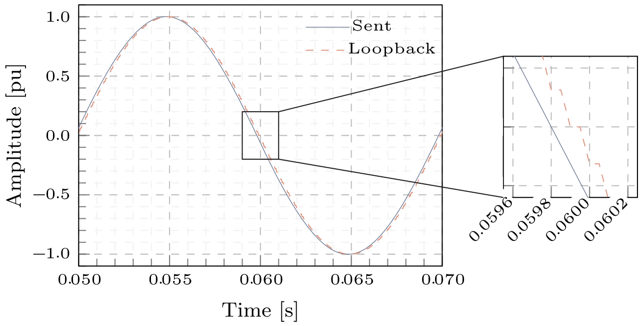

Figure 10. Benchmark delay measurement; Comparison of sent signal from RTDS to loopback signal from Opal-RT.

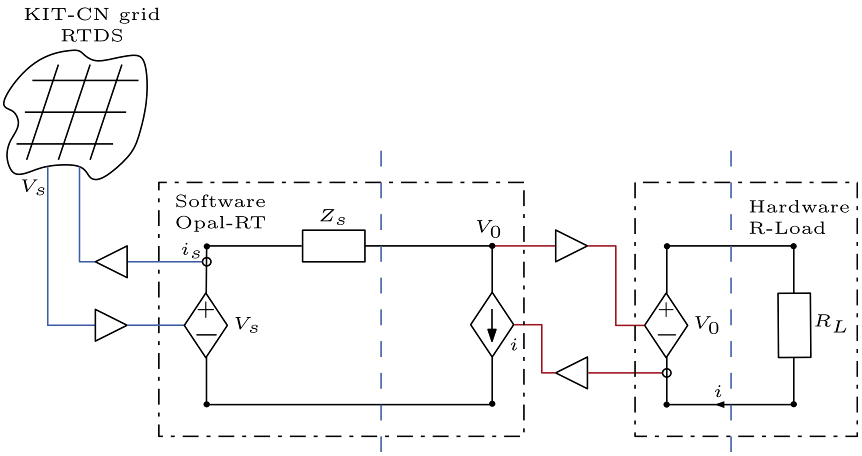

Figure 9. Schematic representation of experiment setup; KIT campus electrical grid in real-time digital simulators (RTDS) and OpalRT- power-hardware-in-the-loop (P-HIL) experiment.

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hardware via the Opal-RT simulator is tested in a closed-loop connection. Two scenarios are considered in this case; 1). Simulation with an experimental load set to 0 kW, 2). Simulation with an experimental load of 60 kW. In both scenarios, a delay in the communication is measured by initiating an abrupt increase in the load of 1 MW on the campus network side, and recording the voltage response at the coupling point of the two subsystems, i.e., voltage sent from the campus side (Sent), and the voltage measured on the experiment side (Measured).

Figure 11 shows the RMS voltage at the coupling point in response to an abrupt increase in load on the campus network side with no load on the experiment side. The increase of load in the campus network causes a voltage droop, which acts as a setpoint for the power amplifier as a coupling device between the simulators and the real power hardware. The response with a 60 kW load is shown in **Figure 12**. Important to observe is the difference in the communication delay compared to the benchmark test case without connection to real hardware. In the first scenario shown in Figure 11, a delay of 20 ms is observed, whereas the delay in the second scenario in Figure 12 is about 25 ms. This is due to the fact that additional time is required for the communication between the Opal-RT system and the real hardware. The settling time to steady state voltage is also different in the two cases, since the power electronics of the experimental hardware setup require different time duration to change to the new setpoint resulting from the voltage change under different loading conditions. In addition, the scenario with a 60 kW load shows an offset of 0.1% in the RMS voltage magnitude measured on the experiment side as shown in Figure 12. This difference can be explained by the fact that the RMS calculation block, in this case, only considers the fundamental components of the voltage signal. The measurement contains a non-zero share of other frequencies due to the real power electronic components used as well as measurement noise, whereas the signal from the real-time simulator carries only the fundamental frequency.

4.3. Discussion

The results presented in the current article evaluate the benefits of the different coupling methods implemented in the digital simulation framework. In the simulator-simulator coupling, the monolithic model is used as the benchmark case for comparing the accuracy of the four coupling methods. It is shown that the TLM method is the most accurate, since it considers the traveling electromagnetic wave properties in the signal exchange. However, the application of the method is limited to coupling subsystems via transmission lines or cables with a length of

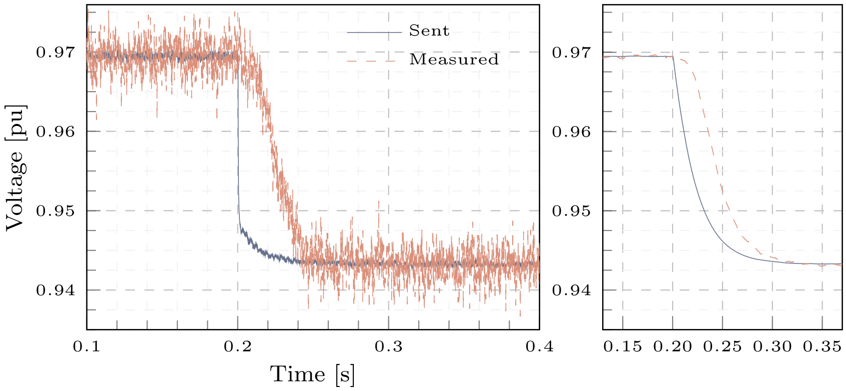

Figure 11. Comparison of RMS voltage at coupling point with no load (0 kW) on the experiment side. a) Actual RMS signals; b) RMS signals through a first-order lag function.

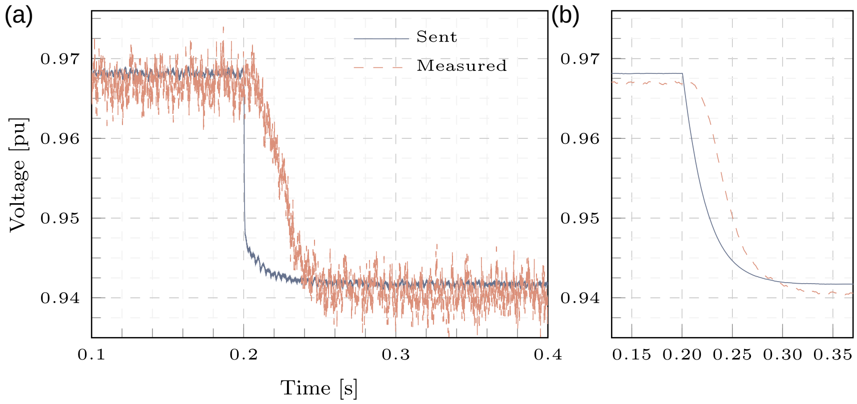

Figure 12. Comparison of RMS voltage at coupling point with 60 kW load on experimental hardware. a) Actual RMS signals; b) RMS signals through a first-order lag function.

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300 m per microsecond communication delay. Direct coupling of the simulators via fiber and the ITM method shows good accuracy but it is observed to be very sensitive to communication delays and phase shifts when considering fast varying time-domain instantaneous signals. The ITM-DP method shows improvements in the steady-state stability and is robust to communication delays, but fails to capture abrupt instantaneous changes in the interfacing signals. Regarding the interface of simulators to external hardware, the communication delay via the physical interface is shown to depend only on the simulation sampling time and does not significantly affect the interaction between the real-time simulation and the hardware. However, additional communication delays are experienced when interacting with real hardware in the form of hardware-in-the-loop setups.

5. Conclusion and Outlook

The current article presents the Energy Grids Simulation and Analysis Laboratory as part of a state-of-the-art Energy Lab 2.0 research platform for evaluating new solutions for future energy systems. The key features of the laboratory are described, showing potential for interconnection of geographically distant simulation hardware to expand the simulator cluster for real-time simulation of larger power networks. A preliminary use case is described showing the interface between the real-time simulations and the experimental hardware, thus providing a link between the simulation laboratory and the other laboratories in the Energy Lab 2.0 infrastructure. This also provides a possibility for a virtual interface of the Energy Lab 2.0 infrastructure to experimental hardware of geographically distant energy research infrastructures.

Part of the ongoing work is to include measured data from the installed phasor measurement units (PMU) on the KIT north campus electrical network into the real-time simulation in order to develop a digital twin of the campus network. In addition, the simulator cluster will be extended by interconnecting the different research infrastructures within the scope of ongoing research projects. This will result in a connection between KIT, a research center in Jülich (FZJ), and the German Aerospace Center (DLR) in Oldenburg, thus forming a geographically distributed real-time simulation infrastructure. The simulator cluster will also be extended beyond research institutes by including simulation and experimental hardware from industrial partners.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Keywords

distributed simulations, power grids, power-hardware-in-the-loop, real-time simulations

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