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The Kopernikus ENSURE Co-Demonstration Platform

GERT MEHLMANN [1], UWE KÜHNAPFEL [2], FELIX WEGE [3], ALEXANDER WINKENS [4,9], CHRISTIAN SCHEIBE [5] (Member, IEEE), STEFFEN VOGEL [6], PETER NOGLIK [7], MICHAEL GRATZA [8], JULIAN RICHTER [1] (Student Member, IEEE), MORITZ WEBER [2] (Student Member, IEEE), ILYA BURLAKIN [1] (Member, IEEE), ANANYA KURI [5] (Member, IEEE), TIMO WAGNER [1], SEBASTIAN HUBSCHNEIDER [6], RAFAEL POPPENBORG [2], TOBIAS HEINS [3], KEVIN FÖRDERER [2], ANDREAS ULBIG [4,9] (Member, IEEE), ANTONELLO MONTI [3,9] (Senior Member, IEEE), VEIT HAGENMEYER [2] (Member, IEEE), and MATTHIAS LUTHER [1] (Member, IEEE)

[1]Institute of Electrical Energy Systems, Friedrich-Alexander-Universität Erlangen-Nürnberg, 91058 Erlangen, Germany
[2]Institute for Automation and Applied Informatics, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany
[3]E.ON Energy Research Center, Institute for Automation of Complex Power Systems, RWTH Aachen University, 52074 Aachen, Germany
[4]Institute of High Voltage Equipment and Grids, Digitalization and Energy Economics, RWTH Aachen University, 52062 Aachen, Germany
[5]Siemens AG, 91058 Erlangen, Germany
[6]OPAL-RT Germany GmbH, 90408 Nürnberg, Germany
[7]Hitachi Energy Germany AG, 68309 Mannheim, Germany
[8]TenneT TSO GmbH, 95448 Bayreuth, Germany
[9]Fraunhofer Institute for Applied Information Technology FIT, Aachen Germany

CORRESPONDING AUTHOR: Gert Mehlmann (e-mail: gert.mehlmann@fau.de).

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ABSTRACT The Kopernikus ENSURE Co-Demonstration Platform enables the investigation of components and processes for the changing power system with grid models adapted to the respective problem. The platform is developed from the power system's perspective. A central aspect of the platform is to analyze several technical solutions of different stakeholders in shared power system models. Furthermore the platform enables the investigation of interactions between different technologies, the system stability or protection scenarios that cannot be simulated in the real power system or only to a very limited extent. The comparison of solution approaches on a common model basis enables reliable overall systemic statements. To realize this, a multi-domain and multi-vendor approach is pursued, covering electromagnetic transients, electromechanical transients, continuous power flow simulations, and real-time simulators from different manufacturers. The core components of the platform are distributed real-time simulations, including the coupling of different laboratories in Germany and the developed power system models. Investigations with the real-time capable platform can be carried out purely simulatively or, depending on the connected laboratory, as Control/Power-Hardware-in-the-Loop simulations.

INDEX TERMS Distributed Co-Simulation, Electromagnetic Transients, Electromechanical Transients, Hardware-in-the-Loop, Power System Stability

I. Introduction

THE idea of setting up a large distributed co-simulation platform emerged in the project Kopernikus ENSURE in 2018 to analyze various solutions for the energy transition systematically. Furthermore, many power system studies cannot be performed in the field for reasons of supply security. Since its inception, the platform has been undergoing continuous development and refinement.

The platform itself has functionalities comparable to digital twins. The energy industry is one of the last areas in

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which topics such as "digital twin" or "digital image" are becoming established [1]. This is especially true in the area of grids because of the size of the system, the small-scale ownership structures, and regulatory framework conditions. Many approaches of digital twins like [2]–[6] are based on real-time systems. These approaches pursue the goal of developing a digital twin for a specific application, or the digital twin itself is a component of the application in question. The Co-Demonstration Platform clearly goes beyond these common approaches: A platform is developed on which the most diverse technologies can be investigated, such as primary technology, secondary technology, and new processes. Additionally, real components can be integrated via Hardware-in-the-Loop (HiL) simulations. In [7] a real-time platform was developed by the Massachusetts Institute of Technology (MIT) specifically for microgrid controllers. According to the MIT technical report, HiL simulation has the same degrees of freedom as classical offline simulations, with significantly more valid statements regarding controller behavior. Power Hardware-in-the-Loop (PHiL) simulations offer an advanced possibility to integrate and test real plants with power exchange - e.g., a complete microgrid - into a simulated grid [8]–[10]. A reconfigurable real-time power grid emulator is introduced in [11]. The emulator takes advantage of the fact that a wide variety of plants and devices can be emulated very precisely using scaled-down converters. Using PHiL, the testbed can also be connected to digital real-time simulators. In [12], a HiL platform developed explicitly for HVDC grid integration studies is presented. For this purpose, RMS-EMT co-simulation is implemented within the platform. Such HiL simulations thus allow to validate and demonstrate developed solutions. The difference between the presented platform and established platforms like [7], [10], [11], and [12] are the possibilities of geographically distributed real-time simulations and the severe focus on systemic investigations in various real-time power system models developed for this purpose.

In the area of real-time co-simulation, a key focus is on the development of the interface with the aim of coupling (distributed) simulators from different manufacturers and also to enable multi-domain simulations [13]–[17]. Particularly noteworthy is [18], where a worldwide coupling of real-time simulators and associated laboratories was achieved via the co-simulation gateway VILLASnode. This was purely a demonstration of feasibility. The ENSURE Co-demonstration platform builds on this idea but clearly goes further. The publication [18] can be seen as an important preliminary study to the platform implemented here. In contrast to the above publications, the Co-Demonstration Platform has a strong focus on power systems models to develop a platform that is suitable for technologies in all voltage levels and time domains. Therefore, the platform is designed modular. The co-simulation is a pure tool for coupling the laboratories and their integration into the systemic simulations.

For the Co-Demonstration Platform, different approaches from the field of digital twins, as well as technologies from the field of co-simulation and real-time simulation, are linked via detailed power system models in such a way that a unique platform is created for the benefit of different users, like manufacturers, Transmission System Operators (TSOs), Distribution System Operators (DSOs) and universities.

The publication is structured as follows. Section II explains the overall concept of the platform. Section III presents the status of the platform's power system models. Section IV describes three important labs for the platform. In Section V, the interfaces between the models and laboratories are presented before Section VI gives exemplary results for a distributed co-simulation between two labs. Furthermore, Section VII presents the planned applications of the platform. Finally, Section VIII concludes and gives an outlook for the further use of the platform.

II. Concept

The platform is described briefly below. Fig. 1 shows the basic structure of the platform. It is designed to be as modular as possible to meet the different requirements for time domains and voltage levels.

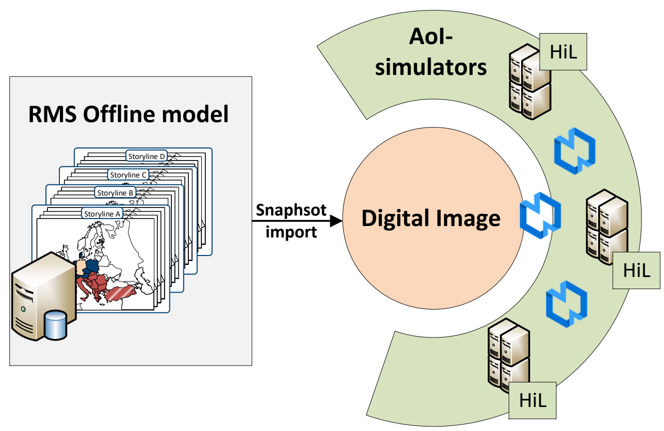

FIGURE 1. Concept of the Co-Demonstration Platform

The base of the platform is the transmission grid model of Germany, which is implemented as a non-real-time (offline) model in PowerFactory (see Section *III-A*). It is a phasor-based model for investigations in the time domain of electromechanical transients (RMS) and includes controllers for conventional power plants, renewable sources and HVDC systems [19]. The grid model is developed for the target year 2030 with four expansion scenarios, each with 8,760 load flow situations [20]. Steady-state and dynamic security assessment can filter load flow situations (snapshots) suitable for planned simulations (e.g. low inertia). In the same way, it should be possible to import a sequence of load flow cases to run continuous test cases. To use the offline model - respectively the snapshots - for real-time simulations, automation of the import from the offline model to the

Digital Image will be a key function of the platform (see Section *V-B*).

The Digital Image represents the real-time model of the transmission system. The simulation environment is ePHASORSIM on an OPAL-RT real-time simulator. The simulator includes appropriate interfaces and protocols, for example, for the future connection of control rooms. The Digital Image uses load flow snapshots as a data source. In the current approach, these come from modeled grid expansion scenarios and build practically an offline database. In the future, it would also be possible to take Day Ahead Congestion Forecast (DACF) and Real-Time Snapshot (RTSN) files from the power system control. The tools for processing and dynamization of these files to RMS models in PowerFactory are available (see Section *III-A*). These RMS models can then be exported to OPAL-RT (see Section *V-B*). The process could be fully automated to establish a coupling to the field level. DACF datasets also replicate the whole ENTSO-E European transmission grid. This would give the Digital Image the functionality of a digital twin. Fields of application would be in the area of Dynamic Security Assessment.

The Area of Interest (AoI) simulators belong to the laboratories of the respective partners. Depending on the requirements of the technology to be investigated, the time domain and application domain of the simulators may differ. On the AoI-simulators, a section of the transmission system, a distribution system, or just a coupling point to the laboratory can be implemented. The coupling between the AoI-simulators is realized via VILLASnode. In addition to joint HiL simulations, the approach offers further advantages, such as increased computing power, multi-vendor capabilities, and no exchange of confidential models is necessary. The coupling between the AoI-simulators themselves and the Digital Image varies depending on the application. Simulations that do not require a transmission network model, for example, can also be studied separately from the Digital Image. Besides HiL simulations (including PHiL), Software-in-the-Loop (SiL) use cases are possible.

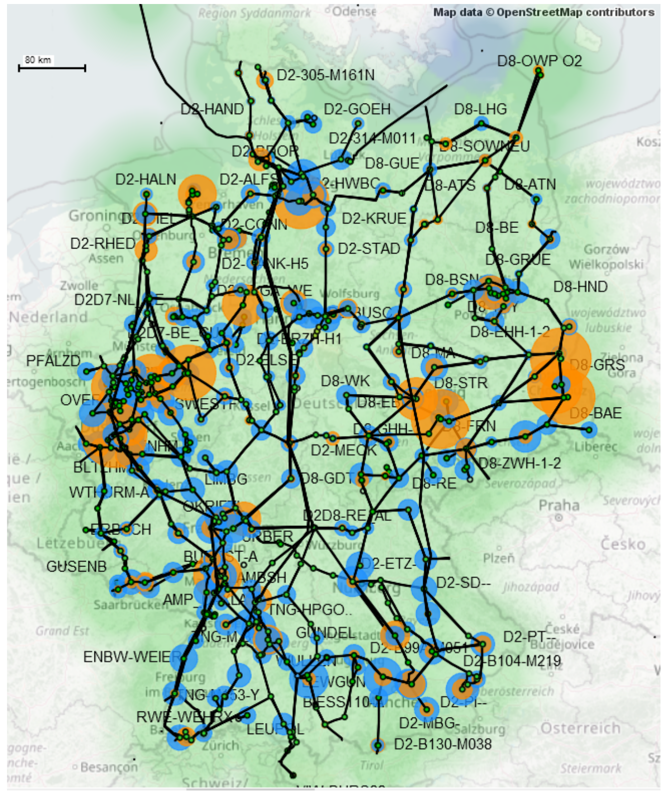

FIGURE 2. Transmission network model of Germany with generation/load and voltage heatmap.

III. Power System Models

A. Transmission System Model of Germany

Based on the ENTSO-E CE transmission grid model of Central Europe, the static transmission grid model of Germany (DE model) is developed for the target year 2030 using the PowerFactory software as a development platform. The transmission grid includes the AC voltage layers above 150 kV (220, 380 kV) and several HVDC links for offshore wind generation and wide-distance energy transmission, mainly in the north-south direction. In the ENTSO-E dataset, the network model of each area is provided in Common Interface Model (CIM) standard format by each TSO. For Germany, the regional submodels of the four TSOs were combined in a common project, together with the connecting border nodes to neighboring countries. Since the original dataset did not include any geographical data, geographic coordinates, and detailed station models (busbars, switches, voltage compensation) of the 711 stations and 1291 switching fields were added to the dataset. The final model includes 2,894 busbars, 1,492 transmission lines and underground cables, and 219 transformers. In summary, 1,250 loads are transposed to VHV-voltage. Generation is provided through 1,577 synchronous machines and 2,561 current sources for renewable energy (wind, solar, bio, etc.). Local static controllers (PV or PQ control) are defined for each generator, together with tap-controllers for the transformers and controllers of the 128 FACTS devices used for voltage control (MSCDNs, STATCOMs, capacitive and inductive shunts, synchronous condensers). For local and cross-border power flow control, several controlled phase-shift-transformers are modelled. Grids are interconnected through Extended Ward elements in the border crossing power lines. Last but not least, a frequency-power controller for load-balancing is introduced for the DE grid. The static DE grid model allows for load-flow calculations, short-circuit and frequency analysis, and quasi-dynamics simulation of time-series datasets. Fig. 2 shows the transmission grid model Germany with load-flow simulation results (load/generation dislocation and voltage heatmap).

Based on the steady-state grid model, a functional RMS power grid model of the German transmission grid is developed for dynamic stability investigations. To this end, adjustments are made to the topology. These include convert-ing synchronous generators into controlled current sources to emulate converter-based generation plants from renewable energy sources and inserting block and machine transformers. The implementation of dynamic controller models for synchronous generators is based on resilient standard controllers according to [21], [22]. A distinction is made here between primary energy sources. For converter-based generation plants, a simplified WECC model is developed based on the WECC Type 4B model [23]. Here, the focus is on voltage control during normal operation and fault ride-through capability during fault conditions. Converter stations of offshore wind farms and HVDC links are also equipped with dynamic controllers. Compared to the converter-based controllers, the focus is on voltage and active power control. The converter-internal current control is represented in a simplified way by a first-order delay element. Further information regarding the modeling can be found in [19].

B. Real-Time Model of North Germany

Based on a dynamic network reduction of the transmission grid model from Section *III-A*, a real-time grid model of a region in northern Germany was developed. The geographic extent of the most distant substations in the model is about $120\,\mathrm{km}$. The model includes numerous devices, for example, several HVDC converter stations (onshore and offshore). Among other things, a WECC control with Fault Ride Through (FRT) capabilities had to be developed in RSCAD to simulate the dynamic behavior of onshore wind plants. The resulting real-time grid model covers the frequency range of electromagnetic transients (EMT), such as investigating the interactions between AC and DC systems, studies on harmonic interactions, or integrating real components in HiL experiments. Fig. 3 shows the developed network model. For further information, please refer to [24].

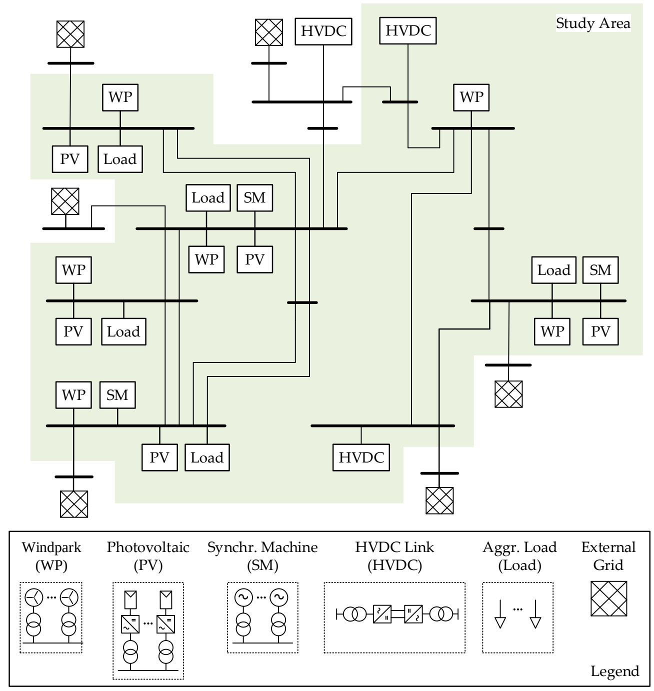

FIGURE 3. Schematic single line diagram of real-time model

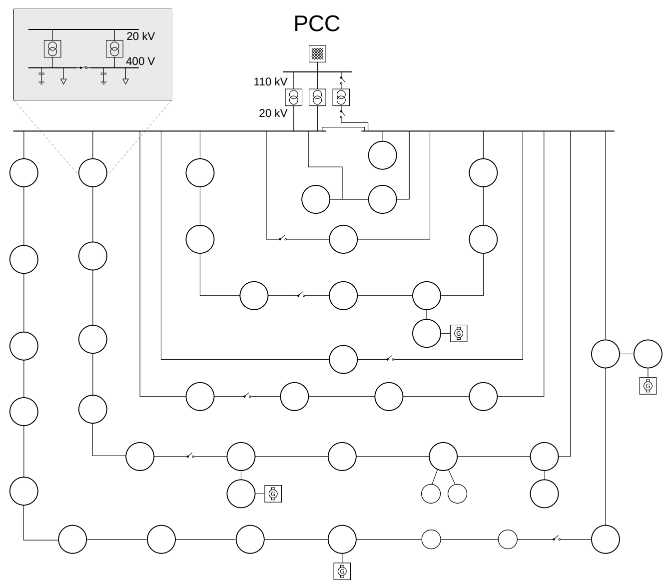

FIGURE 4. Single line diagram of the RSCAD model of the Campus North 20 kV grid.

C. Real-Time-Model of the IEEE Nordic Testsystem

The IEEE Nordic test system is recommended by CIGRE Task Force 38-02-08 as a benchmark network for long-term voltage stability analysis. For the platform, the grid model was remodeled on OPAL-RT in ePasorsim (RMS) and on RTDS in RSCAD, adapted for higher frequency EMT simulations. More information about the version in ePHASORSIM can be found in [14].

D. Campus North Testsystem

KIT Campus North is a former nuclear research facility and is now the research campus of KIT. It contains office buildings, laboratories, and energy-intensive test facilities. The power grid of the campus is connected to the 110 kV distribution grid via three transformers with a combined rating of 87 MVA. Those three transformers are connected to two 20 kV buses that supply the rest of the campus grid in a topology that consists of seven open rings containing 42 MV/LV stations.

A PowerFactory model was created, modeling this grid on the 20 kV and lower levels in detail. The model contains around 1,800 buses and almost 1,000 switches and breakers, realistically representing the switching capabilities of the real grid. Connecting those buses are almost 500 line elements with a length between 10 and 1500 m, most of them underground cables modeled as pi sections. 122 transformers connect the 20 kV grid to the lower levels, mostly 400 V but also 10 kV and 6 kV. On these lower voltage levels, the model contains 15 synchronous machines and 10 smaller

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asynchronous machines, most of which are operated in an experimental setting or are reserved for emergencies. Furthermore, the model contains a photovoltaics array with 1 MVA peak power. Around 430 loads represent the various consumers in the grid, most of which are located on the 400 V level.

The Campus North System can be used for individual load-flow calculations and time-series calculations with thousands of time steps, short-circuit analysis, RMS simulations, and to some extent, even EMT simulations.

For real-time EMT simulations, a reduced model of the KIT Campus North grid was created in RSCAD occupying roughly nine cores of the NovaCor real-time simulators. This model, shown in Fig. 4, contains all MV/LV stations but reduces the total number of buses to 120 and the number of switches to 20. While this limits the overall complexity of the model, detailed switching capabilities can easily be implemented on demand. The number of transformers was slightly reduced to 113, and the loads were aggregated at each bus, leading to a total of 47 loads. The model omits the smaller synchronous machines and asynchronous machines and only contains the four largest synchronous machines with a combined rating of 13.5 MVA. While the PV array is not included in the grid model directly due to complexity restrictions, it can be coupled with the grid model as described in [25].

In combination, these two models allow a wide variety of simulations, from quasi-dynamic time-series simulations over the timespan of years to highly detailed hardware-in-the-loop simulations in real-time. The synergies between the two different models are further enhanced by the Python-API for RSCAD modeling that was developed for this project [26]. This API allows the programmatic manipulation of RSCAD models, e.g. to apply changes or reintroduce details from the PowerFactory model.

As part of the demonstration platform, the Energy Hub represents a sector-integrating flexibility option for the electric grid. Here, the simultaneous provision of multi-modal energy sources makes an important contribution to industrial decarbonization. As an exemplary use case for the test system described above, the energy hub can be integrated into the model. Thus, an instance of the energy hub model is investigated with the Campus North test system. Within the simulation period, as shown in Fig. 5, the power fluctuation at the electrical connection point of the Energy Hub could be reduced by 11.6 %.

E. MVDC/HVDC Testsystem

As generation shifts to lower voltage levels, system services must also be provided from lower-level grids. Grid-forming controls are essential for the provision of instantaneous reserve and for stabilizing the power system. For the evaluation of grid-forming control concepts and their interactions, both in medium-voltage (MV) and high-voltage (HV) grids, an MVDC/HVDC test system is developed. In this model, the

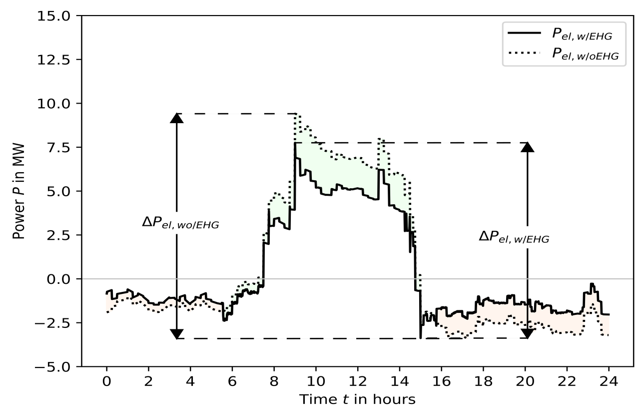

FIGURE 5. Resulting power with and without energy hub integrated into the grid model for an exemplary day [27]

virtual synchronous machine (VSM) control is integrated, as well as the grid-forming phase restoring principle (PRP) [28], [29]. In addition, the test system includes an interface to a low-voltage PHiL converter setup to investigate the control concepts with active power hardware connected [30]. The combined system is simulated in real-time in the EMT domain to investigate various dynamic interactions, including islanding scenarios. The test system is a modular test bed of a future hybrid power grid to investigate various grid-forming controls, novel power hardware, and secondary technology. Via the co-simulation gateway VILLASnode, it is possible to couple the test system with real-time simulations and thus use cases of other partners.

Fig. 6 shows the structure of the test system. The MVDC head-end stations feed into the transmission network. Due to the VSM control implemented, the head-end station on the left side (terminal 1, T1) can provide inertia and primary control power in combination with other equipment. The MVDC network is implemented as a symmetrical monopole configuration with a DC voltage of ±55 kV. Each converter station has a rated power of ±100 MW (Q: ±30 Mvar). With the HVDC, the MVDC forms a multiterminal system with two voltage levels, where a DC/DC converter increases the voltage from 110 kV to 640 kV. Integrated on the DC side of the MVDC are a simulative scaled dynamic wind-infeed and a highly scaled battery storage system. The storage system is implemented using the State-Space-Averaging (SSA) method as a cascaded Dual-Active Bridge 3 (DAB3) [31]. The time step for the power electronic elements is $\Delta t = 5\,\mu$s, for the other network elements $\Delta t = 50\,\mu$s. The MVDC and HVDC converters are implemented as MMC average models, with the controls developed in Simulink and partially tested using simulators built by OPAL-RT and Speedgoat. The controls were finally transferred to RTDS via a C-code export/import. The model itself is implemented in RSCAD®FX on RTDS. The converter on the right side (terminal 2, T2) of the MVDC is modeled at the switching level to implement blocking

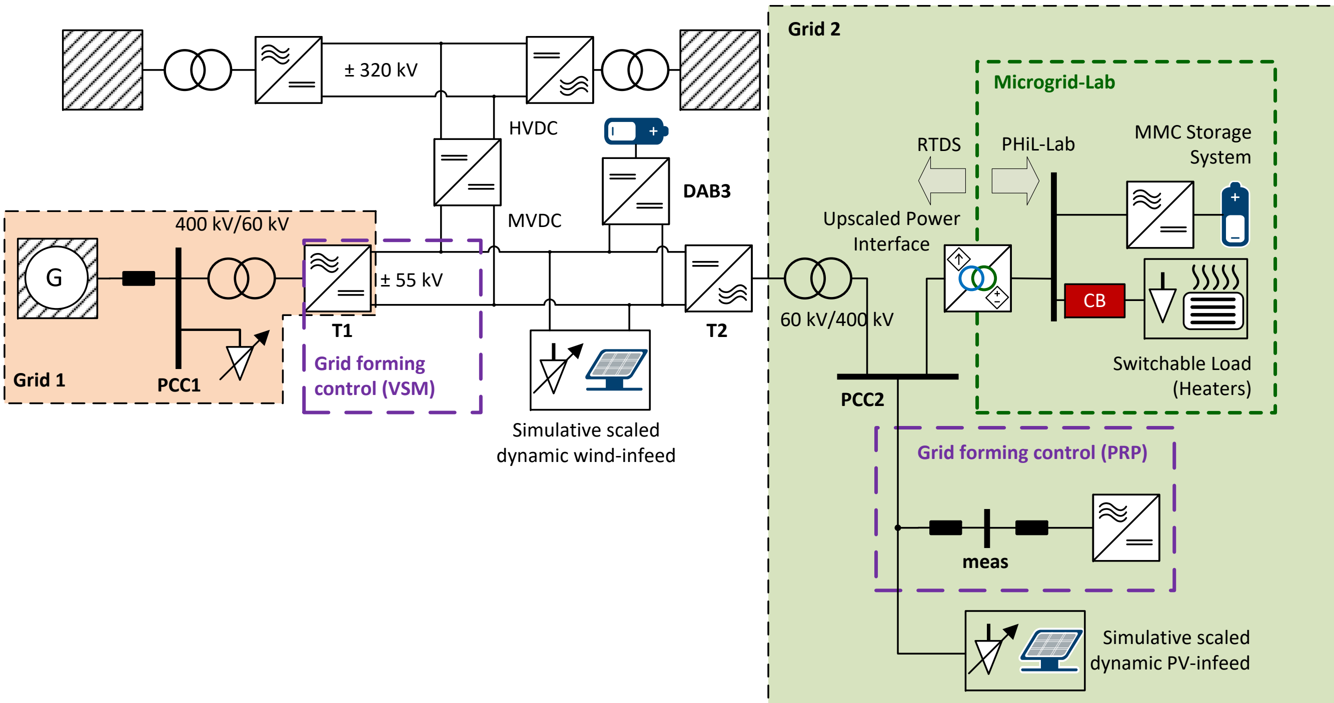

FIGURE 6. **Basic structure of the MVDC/HVDC testsystem**

capability. This enables the study of the islanding operation of the right-side AC network. The multiterminal DC-side control bases on a droop control. The test system is modular and can be integrated in its entirety into transmission network models. It is also possible to use only sections of the test system in studies. In [24], a part of the test network was integrated into the network model from Section *III-B*.

In Fig. 7 an example case is given. In the scenario, the converter station T2 blocks, meaning AC network 2 is in island operation. The grid-forming control PRP builds the network and can keep the AC network 2 stable even during this highly dynamic event, particularly evident from the voltage curves. The MMC converter in the PHiL laboratory, which was in grid-following operation, was not affected by the event. Likewise, in the multi-terminal DC network, the power loss from station T2 can be completely compensated by redistributing power. The power is now being provided by the HVDC via the DC/DC converter and by the battery. The wind-infeed is not in operation in the example.

Employing various investigations, the PRP-concept is thoroughly tested and shall be transferred to actual industrial application. This shows the added value of a test platform developed and run by industry and academic partners. Furthermore, the concept of providing inertia from DC collector networks could be demonstrated.

IV. Distributed Laboratories

A. Energy Lab 2.0

As outlined in Section *III-D* and visualized in Fig. 8, there are infrastructures and laboratories used for research in many different energy-related fields at KIT Campus North. In the following, an overview of the infrastructures and laboratories involved in the Co-Demonstration Platform is given. A particular evaluation or demonstration scenario does not necessarily require utilizing all the named facilities. Instead, individual facilities are connected as needed.

a: Energy Grids Simulation and Analysis Laboratory (EGSAL)

The EGSAL is the main grid simulation facility at the Energy Lab. Its hardware equipment ranges from several workstations and servers for individual offline simulations of large power grid models and extensive co-simulation scenarios to a capable real-time simulation infrastructure. This real-time infrastructure is centered around three RTDS NovaCor racks with 30 licensed cores that can be interconnected with other local simulators from RTDS and OPAL-RT and power hardware in the Energy Lab, as described in [32]. The methods for the integration of these capable simulators include the RTDS Global Bus Hub (GBH), fiber connection via the Aurora Protocol and VILLASnode for distributed co-simulation. For this purpose, a Meinberg microSync RX401HQ provides the system with a GPS-based time signal for the means of synchronization.

b: Smart Energy System Control Laboratory (SESCL)

The core of the SESCL is a matrix with ten busbars and 424 contactors that comprises an AC segment and a DC segment [33]. This busbar matrix is controlled by a central automation system that allows the interconnection of various components in a flexible topology. These grid components

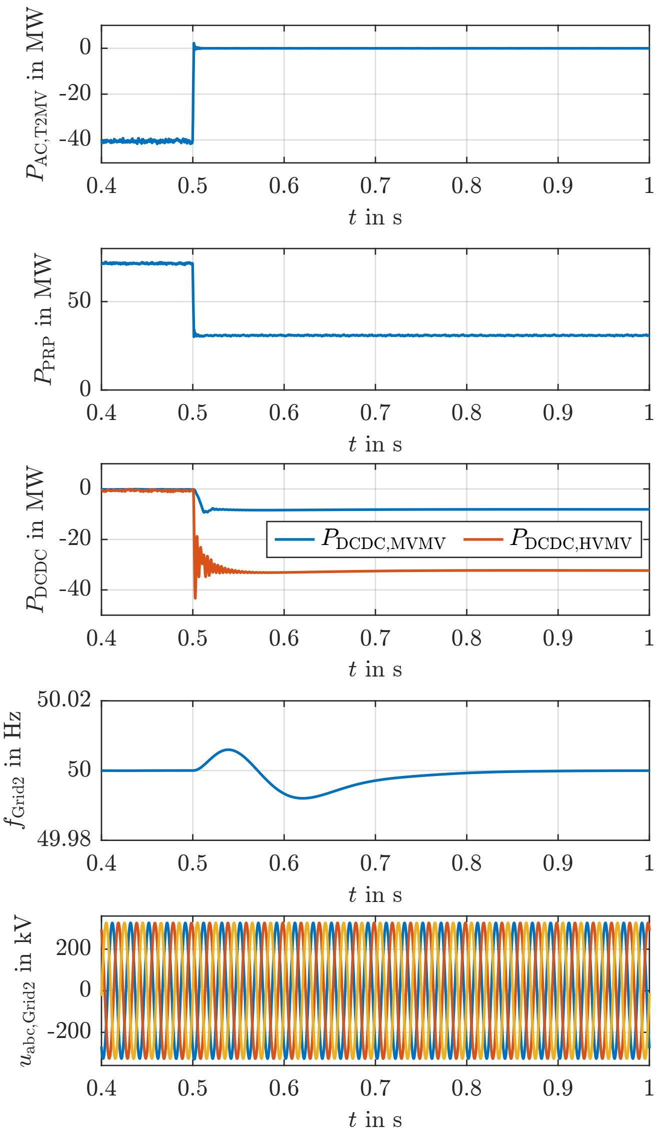

FIGURE 7. Example simulation for blocking station 2 and islanding

include generators, converters, inverters, a PV system, several battery energy storage systems (BESS), real transmission lines, transmission line replicas (pi section models), and three smart houses. Moreover, new components can easily be added or removed. Multiple OPAL-RT real-time simulation systems, in combination with two Egston Power-hardware-in-the-Loop (PHiL) amplifiers with a total power of 200 kVA enable the integration of the aforementioned hardware components into simulated systems. Furthermore, these OPAL-RT systems form the link to the EGSAL, described in the previous paragraph, enabling the integration of the SESCL hardware infrastructure into large-scale grid-simulations.

c: Security Lab Energy (SecLabE)

Cyber-security in energy systems is the research focus of the SecLabE. It will provide a replica of an industry-scale machine park with renewable energy sources, enabling the

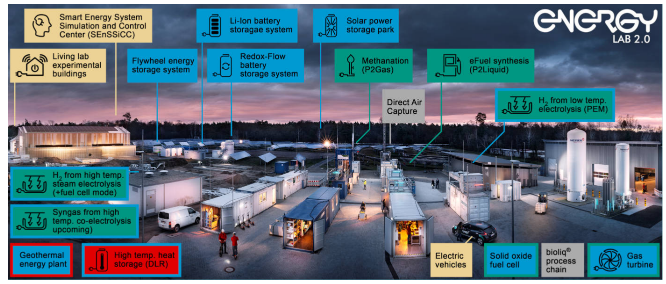

FIGURE 8. Overview of the EnergyLab at KIT Campus North (Source: KIT)

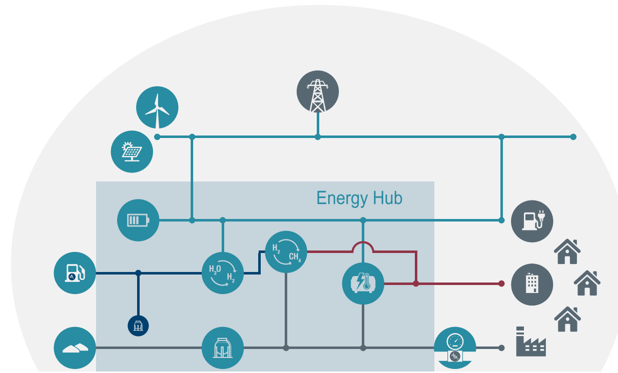

FIGURE 9. Overview of the Energy Hub Gas instance implemented as co-simulation model adapted from [34]

evaluation of the cyber-resilience of telecontrol systems. One goal in ENSURE is the development and demonstration of concepts for vendor-independent firmware management for telecontrol systems.

d: KIT Campus North Energy Grid(s)

While being a place for researchers from many different fields to work on their projects, the campus and its environment are viewed as an opportunity for energy research. The KIT Campus North comprises electricity, heat, and gas grids. Several models of these grids, with different levels of detail, have been developed in the past and are used for evaluations and demonstrations, especially the electrical grid models (see Section *III-D*). Given its structure and dimension, the grid is especially suitable for evaluating technologies from a smart district perspective. The grids are equipped with measurement devices and sensors. The electrical grid of the campus, for instance, is (partially) equipped with phasor measurement units (PMUs) for monitoring and persisting the state of the grid and further analysis. These data streams, for instance, are relevant for dynamic grid topology decisions and dynamic protection, which is investigated as a building block of future energy systems in ENSURE.

e: Energy Hub (Gas)

The Energy Hub (EH) concept, first introduced by [35], is instrumented by a co-simulation model and developed for the use on the Co-Demonstration Platform within the ENSURE project. This highly configurable and adaptable

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system model consists of several component models representing already existing technologies as distributed energy resources (DERs). As an instance of the EH concept, the Energy Hub Gas is implemented and provided on the Co-Demonstration Platform. This instance includes electrolysis, methanation, combined heat and power plant, and battery and gas storage as depicted in Fig. 9. Furthermore, the modular co-simulation system of the EH itself, described in [34], can be adapted to different scenarios, which in turn can be analyzed together with the grid model, as described in Section *III-D*. The underlying real-world components, for instance Power2X facilities (e.g., [36]), are available research infrastructures within the Energy Lab at KIT. Various EH compositions are possible using real and simulated DERs. For instance, an EH demonstration may use the large-scale lithium-ion storage [37] or the available electric vehicle charging infrastructure. This enables the possibility of combining the co-simulation with real DERs. Overall, the goal is the optimized operation of EH to provide flexibility to the electrical grid infrastructure through the opportunities arising from sector-integration.

B. Center of Applied System Simulations

The Center of Applied System Simulations has operated since 2019 at FAU University. Fig. 10 illustrates the comprehensive concept of the laboratory. The real-time simulators from RTDS, OPAL-RT, and Speedgoat are the basis of the laboratory. Interoperability and modularity serve as the core of the laboratory setup. To achieve these objectives, a co-simulation interface between the NovaCor chassis from RTDS and the Speedgoat real-time target, as well as the communication between the NovaCor chassis and the OP5707 from OPAL-RT, has been successfully established. Fiber optic or Ethernet cables handle the communication via Aurora or Internet Protocol [14]. A Meinberg Lantime M1000 real-time clock provides a GPS reference time for the internal synchronization as well as for the external synchronization for the distributed co-simulation via VILLASnode.

The three distinct real-time simulators allow to address a range of investigation scenarios. The RTDS simulator, equipped with 24 licensed cores, is utilized for electromagnetic transient (EMT) simulations, focusing on converter-driven stability. The OP5707 from OPAL-RT is primarily employed for phasor-based (RMS) simulations in the time domain of electromechanical transients. Additionally, control development investigations are conducted using the Speedgoat real-time target. Referring to Fig. 1, the OPAL-RT simulator is used in the Co-Demonstration platform as the Digital Image to run the transmission grid model of Germany and, if required, additional distribution systems. The RTDS simulators are used as AoI-simulators, e.g. for the MVDC/HVDC test system described in Section *III-E*.

The Control Hardware-in-the-Loop setup (Fig. 11) incorporates several CMS 365 measurement amplifiers manufactured by Omicron electronics GmbH, as well as different control hardware components such as protection devices, phasor measurement units, power plant, and microgrid controllers. The focus of the laboratory is CHiL including protection systems. The setup's modularity enables easy expansion with a wide range of hardware components. The hardware components can be interconnected with the real-time machines through analog and digital signals or via common power system protocols such as IEC 60870-5-104, Modbus UDP/TCP, C37.118 and IEC 61850. Programming interfaces of the real-time machines e.g. with Matlab or Python enable users to automate several processes like data exchange, enhancing efficiency and control within the system.

The Power Hardware-in-the-Loop setup (Fig. 12) comprises two power amplifiers, including a switch-mode power amplifier and a linear amplifier manufactured by Triphase and Spitzenberger and Spies, respectively. The power amplifiers establish connections between the real-time machines and power hardware components through optical fibers and the Aurora protocol. Within the laboratory setup, several technologies are under investigation. These include battery storages such as a single-phase lead-acid storage and a 50 kWh lithium-ion storage connected to the laboratory via a 25 kVA MMC and a 70 kVA 2-level VSC, a microgrid controller, and a 17.4 kWp PV-plant and its associated converters. The setup's modularity is achieved through a switching station, which enables the flexible interconnection of devices. More information about the laboratory including achievements in the implementation of the interoperability of the components are given in [38].

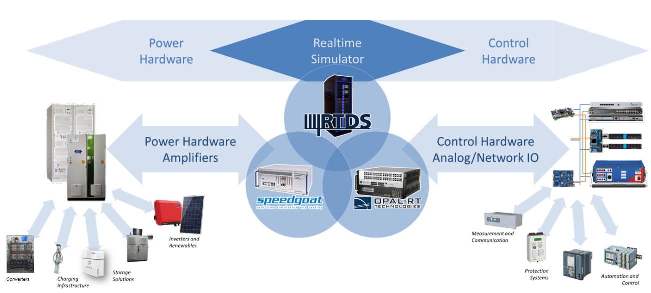

FIGURE 10. Concept of the Center for Applied System Simulations

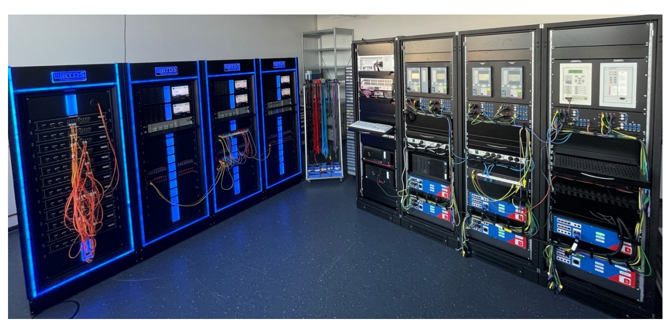

FIGURE 11. Control Hardware-in-the-Loop Laboratory at FAU

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FIGURE 12. Power Hardware-in-the-Loop Laboratory at FAU

FIGURE 13. Testing hall of the Distribution Grid Laboratory at RWTH Aachen University

C. Distribution Grid Laboratory

The chair of Active Energy Distribution Grids of the IAEW at RWTH Aachen University contributes to the ENSURE Co-Demonstration Platform with the Distribution Grid Laboratory which is shown in Fig. 13.

The laboratory consists of a real distribution grid at the low and medium voltage levels, which can be flexibly switched into variable grid topologies. This test grid can either be fed by the public medium voltage grid or can be operated in an islanded configuration. A variety of generation units and loads with nominal powers in the range of up to 100 kW can be connected to the grid. These units comprise different power-electronic converters, such as PV-inverters or programmable converters, charging infrastructure, passive loads, as well as a synchronous generator testbench [39]. This infrastructure allows, among others, the development, testing, and demonstration of innovative controllers or operational concepts for electric distribution grids. In order to implement operational concepts or controllers in the laboratory infrastructure, a real-time co-simulation framework is used as laboratory control, which is able to collect and exchange setpoints and measurement values with the distributed units using the Modbus protocol [40], [41].

Furthermore, the laboratory is equipped with real-time simulators allowing the dynamic simulation of electrical grids in phasor or in the electromagnetic transient domain. In the context of the Co-Demonstration Platform, these simulators are used as an interface to the partners' laboratories and the real-time model of the German transmission grid, as shown in Fig. 14. The coupling of the distributed simulators is realized using the VILLAS framework. In order to couple the low voltage test grid to the real-time simulation, a power amplifier acting as a grid-forming unit provides the grid voltage. The reference value for the grid voltage as well as current measurements are exchanged between the power amplifier and the simulator in real-time, establishing a PHiL setup. On the one hand, this setup allows testing centralized controllers by integrating them into the co-simulation framework used for laboratory control. On the other hand, distributed controllers can be tested by the implementation of programmable converters.

In previous projects, the laboratory infrastructure has e.g. been used for investigating the impact of distributed generation unit controls on the stability and dynamics of islanded microgrids [42]. As an example, [43] shows the use case of testing a grid-forming converter control operated in parallel with a synchronous generator in an islanded configuration of the low voltage grid. Furthermore, the coordinated flexibility provision by several generation units has been demonstrated [44]. By connecting the infrastructures of several partners, the concept of the Co-Demonstration Platform offers the advantage of additionally testing the systemic impact of these and comparable centralized and distributed control schemes using real hardware and coupled real-time simulators.

V. Interfaces of the Platform

A. VILLASnode Co-Simulation Gateway

Within the context of Kopernikus ENSURE, the VILLASnode gateway is a central component used to provide coupling between the laboratories of partners that are participating in the Co-Demonstration Platform.

VILLASnode is part of the VILLASframework, which is a collection of tools designed for interconnecting test beds

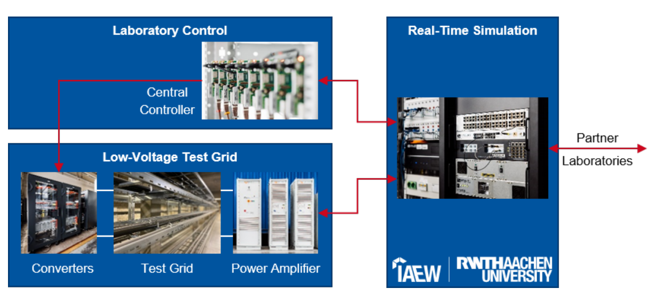

FIGURE 14. Concept of Co-Demonstration Platform at the Distribution Grid Laboratory at RWTH Aachen University

and real-time simulators across geographically distributed laboratories [18]. As shown in Fig. 15, it is composed of multiple independent components that can be assembled to fulfill the specific needs and functionalities of the targeted experiment. Its modular design facilitates the extension of existing components with new interfaces, protocols, and data formats. This flexibility enables the framework to adapt to changing requirements of the co-simulation and the involved simulators.

At the core, VILLASnode is used as a real-time capable data exchange between the laboratories and their connected simulators. It implements various common communication protocols (e.g. MQTT, Kafka, FIWARE NGSI, WebRTC, RTP or plain UDP/TCP sockets) and data formats (e.g. raw binary, CSV, JSON) to directly interface various open-source and commercial real-time simulators like OPAL-RT and RTDS. To translate between the protocols and formats of the various endpoints in the Co-demonstration Platform, VILLASnode converts received data samples to a common intermediate representation. In this representation, signal routing is performed before sample data is translated again to the protocol and format of their respective destinations [45].

This eases data exchanges between laboratories and simulators of different types, allowing a heterogeneous co-simulation across different AoI-simulators and entire laboratories. Additionally, the VILLASweb component provides a customizable, web-based user interface that allows the visualization and collaborative management of scenarios, user groups, laboratory infrastructure, and simulation results [45]. This allows to monitor and control of executed simulations by means of a virtual control room. This is achieved by transferring real-time data of the experiment under study to a VILLASweb instance, using the VILLASnode gateway. The VILLASframework is open-source software released under the Apache 2.0 license, enabling external users to collaborate and extend the existing code base.

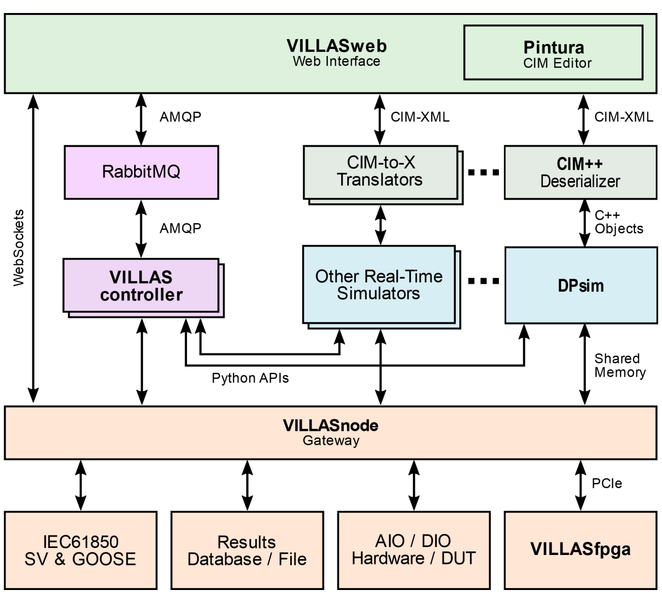

FIGURE 15. **Architecture of the VILLASframework. Reprinted from [45]**

B. Converter between PowerFactory and OPAL-RT

Running distributed real-time simulations can be challenging as a model of the entire power system is usually not available. Without a monolithic model, proper load flow initialization or basic stability studies cannot be performed. To overcome this limitation, a complete monolithic representation of the network is desirable for the purpose of running offline (non real-time) simulations. In Kopernikus ENSURE, DIgSILENT PowerFactory has been established as the main tool for model input and exchange. Large parts of the power system models are managed and provided in a proprietary PowerFactory format.

This requires an automated method for translating the PowerFactory models into the respective real-time simulation tools, such as OPAL-RT's ARTEMiS / ePHASORSIM or HYPERSIM. In recent years, OPAL-RT has developed a Unified Database (UDB) to convert model data between different internal and third-party simulation tools. Fig 16 shows the processing workflow of the UDB, which parses model data from various external formats such as PowerFactory DGS files, CYME or PSS/e models and uses a mapping engine to translate components and their attributes into a user-defined intermediate representation that is persisted in a PostgreSQL database. For use with OPAL-RT's tools, the intermediate model representation is exported by tool-specific callbacks. For example, in the case of the ePHASORSIM solver, `.opal` files are generated by the UDB and consumed by the solver.

In the future, the Unified Database will be extended with the support of additional import formats like CIM-CGMES or built-in dynamization to allow utilizing RMS-component parameters for electromagnetic transient (EMT) simulations. While this is already partially supported for PSS/e models, with a heuristic estimation of line lengths for example, it needs to be extended to cover the PowerFactory input format to be employed in the Kopernikus ENSURE Co-Demonstration platform.

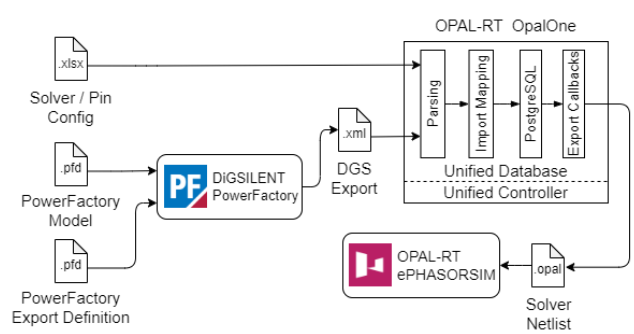

FIGURE 16. **Model conversion from PowerFactory to ePHASORSIM using the Unified Database.**

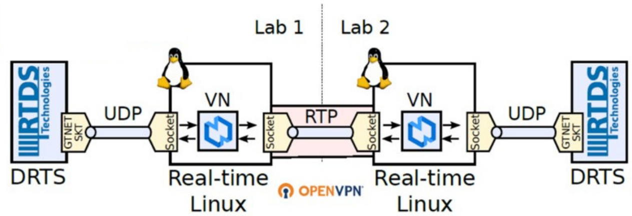

FIGURE 17. Set up of the distributed co-simulation

VI. Distributed Co-Simulation

In the following, an example of the distributed Co-Simulation is given. Fig. 17 gives an overview of the setting. The RTDS simulators of KIT and FAU are coupled via VILLASNode, which runs on RTLinux Servers. The time is synchronized with GPS clocks. The distance between Erlangen and Karlsruhe is about 200 km. At FAU, the Nordic Test System in RSCAD is used as a transmission system, and at KIT, the Campus Nord System as a distribution system (see Section *III*). The co-simulation is implemented via a controlled current source on the FAU side and a controlled voltage source on the KIT side.

Fig. 18 shows a load change from 1 MW to 6 MW on the KIT side. The FAU side follows the load change. The latency is in the two-digit ms range due to the transmission of the signals via the network layer, signal processing in switches and routers. On the time-axis, the real time is applied.

As a second example, a three-phase short-circuit directly at the coupling point on KIT side is evaluated. By means of Fig. 19 and Fig. 20, the curves will be explained. At (1), a short circuit is applied on the KIT side, and a short circuit current flows. The voltage source on the KIT side remains unaffected. At the next simulation time step, the measured current is entered into the current source on the FAU side (2). This leads to a voltage drop on the FAU side at (3). This voltage is measured and entered into the voltage source on the KIT side (4).

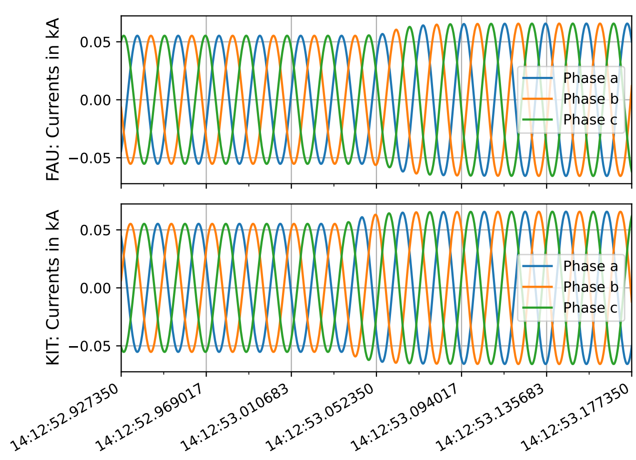

FIGURE 18. Load change at KIT side

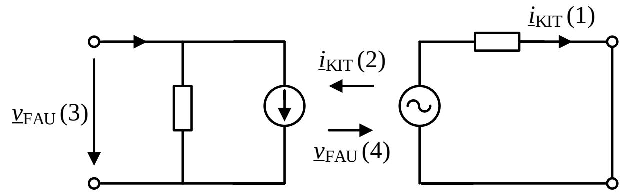

FIGURE 19. Schematic representation of the coupling point

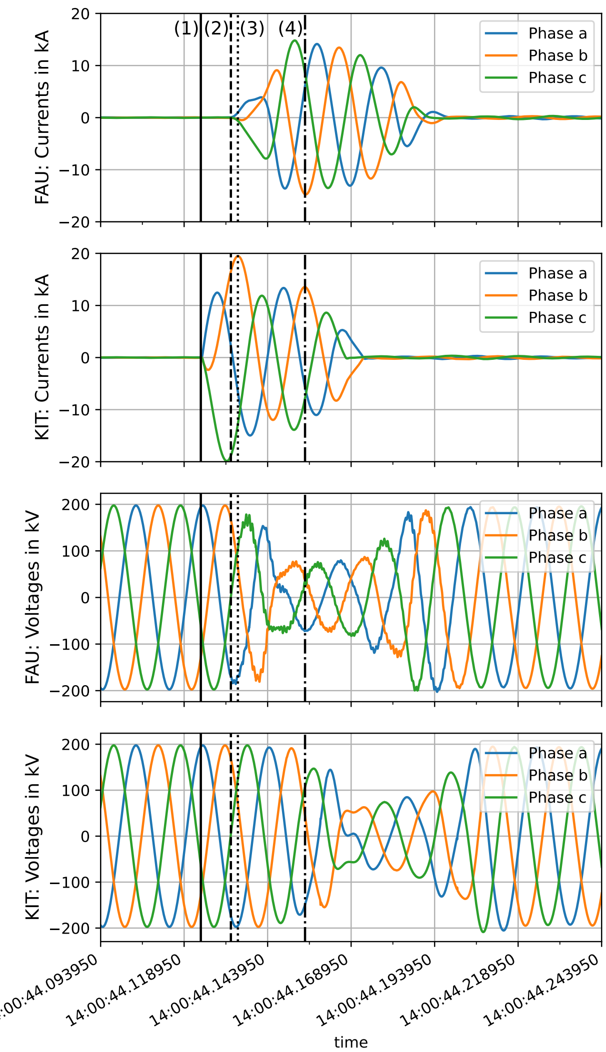

FIGURE 20. Short-circuit simulation directly at the coupling point

Within the distributed co-simulation, latencies occur due to the transfer of values between the simulators, which is only possible after each simulation step, and the distance between Karlsruhe and Erlangen. But even for the extreme case of a short circuit directly at the coupling point (no damping), the simulation performance is stable. Therefore, such a co-simulation is well-suited for most applications. An exception would be high-frequency traveling waves, e.g. switching surges studies. This is because a co-simulation of higher-frequency traveling waves via the coupling point leads to deviations in the signals on both sides. Therefore, it is necessary to pay attention to the definition of the area of interest for the respective application on each simulator. For example, the transition from EMT to RMS should only take place at a distance where higher-frequency signal components are sufficiently attenuated.

VII. Future application of the Co-Demonstration Platform

The platform is transitioning from initial use with some partners to widespread use in the Kopernikus ENSURE project. At the same time, a concept is to be developed to enable the platform to be operable beyond the project.

In the final phase of the joint project, a wide range of applications are to be demonstrated on the platform until 2026. Each of these use cases in ENSURE represents a separate research project in terms of scope, with several partners from industry and research involved. Where technically feasible, the demonstration will combine use cases to show systemic interaction and interoperability. The demonstration results and, thus, the validation of the technologies will be incorporated into the systemic assessment of the use cases. Based on these assessments, recommendations for action will be developed for various stakeholders.

The use cases planned on the platform primarily address grid management, grid protection, ancillary services, and grid integration of power electronic equipment. Some modules have already been demonstrated on the platform but will be further developed. Especially for HVDC systems, the approach followed here is well suited because the grid area around the terminals and the terminals themselves can be modeled in EMT, or the HVDC stations can be implemented in detail on individual HVDC emulators if required. These models can then be incorporated into a more extensive RMS system using co-simulation. Both in offline simulation [46], [47] and in real-time simulation [12], the approach has already been shown to be promising.

VIII. Conclusion

With the presented Co-Demonstration Platform, laboratories across Germany are coupled via suitable power grid models using VILLASnode. This enables joint simulations in a systemic context.

The increase in power electronic generation, as well as the increasing coupling of different sectors of the energy supply with the electrical grid require simulations across several time domains. The co-simulation approach allows to link multiple domains. This makes it possible to simulate the German transmission grid 2030 in the RMS domain on the platform and the use cases to be investigated in their respective domains with associated grid sections on AoI-simulators.

During ongoing grid operation, grid studies are only possible to a limited extent or cannot be realized for safety reasons. This is due to the size of the system under consideration, the inadmissible direct intervention in the critical infrastructure, and the probabilistic nature that cannot be mapped. Real-time simulation is the link between the real world and simulation and is thus the only way to perform experimental studies on a large scale in the field of power grids. The integration of real-time simulators into the platform thus makes it possible to connect entire laboratories via HiL interfaces and to analyze applications in a practical manner. This allows the demonstration and validation of new technologies. It enables different partners to access the platform to investigate applications individually or as a team and thus optimizes the use of existing and possibly protected resources such as laboratory infrastructure and power system models. The main advantages of the platform are that the laboratory infrastructure of different partners can be used, the increased computing power by coupling of simulators, and that no exchange of confidential models is necessary. The technical and financial efforts for the pure coupling between simulators are low and limited to a few days of engineering work and additional required hardware besides the simulators (GPS clock and a RTLinux server). The disadvantages are the complex coordination between the partners and the effort to develop and maintain the power system models. In addition, a monolithic simulation is more suitable for transient studies in the high-frequency range.

Finally, it should not be neglected that considerable investments are necessary in the future, in Germany and worldwide, both in power system expansion and in the digitalization of the power system. In contrast, there is a high shortage of skilled engineers. Against this background, the platform should not only serve as a tool for demonstrating and validating use cases but rather bundle and provide competencies. Thus, the platform can represent a competence center that can be used for the success of the energy transition and meet the requirements induced by the increasing shortage of skilled engineers. Therefore, the platform should be open to users worldwide.

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REFERENCES

[1] P. Palensky, M. Cvetkovic, D. Gusain, and A. Joseph, "Digital twins and their use in future power systems," *Digital Twin*, vol. 1, p. 4, 2021.

[2] A. Mingotti, F. Costa, D. Cavaliere, L. Peretto, and R. Tinarelli, "On the Importance of Characterizing Virtual PMUs for Hardware-in-the-Loop and Digital Twin Applications," *Sensors (Basel, Switzerland)*, vol. 21, no. 18, 2021.

[3] C. Brosinsky, D. Westermann, and R. Krebs, "Recent and prospective developments in power system control centers: Adapting the digital twin technology for application in power system control centers," in *2018 IEEE International Energy Conference (ENERGYCON)*. IEEE, 2018, pp. 1–6.

[4] Z. M., Y. J., and F. D., "Digital twin and its application to power grid online analysis," *CSEE Journal of Power and Energy Systems*, 2019.

[5] A. Ebrahimi, "Challenges of developing a digital twin model of renewable energy generators," in *2019 IEEE 28th International Symposium on Industrial Electronics (ISIE)*. IEEE, 2019, pp. 1059–1066.

[6] R. Darbali-Zamora, J. Johnson, A. Summers, C. B. Jones, C. Hansen, and C. Showalter, "State Estimation-Based Distributed Energy Resource Optimization for Distribution Voltage Regulation in Telemetry-Sparse Environments Using a Real-Time Digital Twin," *Energies*, vol. 14, no. 3, p. 774, 2021.

[7] Reynaldo O. Salcedo Ulerio, John K. Nowocin, Christopher L. Smith, Raajiv P. Rekha, Edward G. Corbett, Erik R. Limpaecher, Jason M. LaPenta, "Development of a real-time hardware-in-the-loop power systems simulation platform to evaluate commercial microgrid controllers."

[8] G. Lauss, M. O. Faruque, K. Schoder, C. Dufour, A. Viehweider, and J. Langston, "Characteristics and Design of Power Hardware-in-the-Loop Simulations for Electrical Power Systems," *IEEE Transactions on Industrial Electronics*, vol. 63, no. 1, pp. 406–417, 2016.

[9] C. S. Edrington, M. Steurer, J. Langston, T. El-Mezyani, and K. Schoder, "Role of power hardware in the loop in modeling and simulation for experimentation in power and energy systems," *Proceedings of the IEEE*, vol. 103, no. 12, pp. 2401–2409, 2015.

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

[11] L. M. Tolbert, F. Wang, K. Tomsovic, K. Sun, J. Wang, Y. Ma, and Y. Liu, "Reconfigurable real-time power grid emulator for systems with high penetration of renewables," *IEEE Open Access Journal of Power and Energy*, vol. 7, pp. 489–500, 2020.

[12] Y. Feng, X. Xiong, C. Scheibe, H. Wang, P. La Seta, and H. Müller, "Co-simulation of real-time and offline power system models: An application example," in *2023 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*. IEEE, 2023.

[13] M. Stevic, A. Estebsari, S. Vogel, E. Pons, E. Bompard, M. Masera, and A. Monti, "Multi–site European framework for real–time co–simulation of power systems," *IET Generation, Transmission & Distribution*, vol. 11, no. 17, pp. 4126–4135, 2017.

[14] C. Scheibe, A. Kuri, L. Graf, R. Venugopal, and G. Mehlmann, "Real Time Co-Simulation of Electromechanical and Electromagnetic Power System Models," in *2022 International Conference on Smart Energy Systems and Technologies (SEST)*. IEEE, 2022, pp. 1–6.

[15] João José R. Oliveira, "Real-Time Cooperative Simulation Between RTDS and HYPERSIM, Test Results for the IEEE 39 Bus System," in *OPAL-RT's 10th International Conference*.

[16] Henildo M. de Barros, "Heterogeneous Real-Time Simulation Platform - the ONS Experience," in *OPAL-RT's 10th International Conference on Real-Time Simulation (RT18), 2018*.

[17] L. Barbierato, E. Pons, A. Mazza, E. F. Bompard, V. S. Rajkumar, P. Palensky, E. Macii, L. Bottaccioli, and E. Patti, "Stability and Accuracy Analysis of a Distributed Digital Real-Time Cosimulation Infrastructure," *IEEE Transactions on Industry Applications*, vol. 58, no. 3, pp. 3193–3204, 2022.

[18] A. Monti, M. Stevic, S. Vogel, R. W. de Doncker, E. Bompard, A. Estebsari, F. Profumo, R. Hovsapian, M. Mohanpurkar, J. D. Flicker, V. Gevorgian, S. Suryanarayanan, A. K. Srivastava, and A. Benigni, "A Global Real-Time Superlab: Enabling High Penetration of Power Electronics in the Electric Grid," *IEEE Power Electronics Magazine*, vol. 5, no. 3, pp. 35–44, 2018.

[19] I. Burlakin, J. Porst, E. Scheiner, A. Kuri, G. Mehlmann, U. Kuehnapfel, and M. Luther, "Dynamic modelling of transmission systems based on primary energy sources," in *NEIS 2022; Conference on Sustainable Energy Supply and Energy Storage Systems*, 2022, pp. 1–6.

[20] C. Perau, V. Slednev, M. Ruppert, and W. Fichtner, "Regionalization of four storylines for the decarbonization of the european power system including flexibilities," in *12. Internationale Energiewirtschaftstagung, IEWT: Das Energiesystem nach Corona: Irreversible Strukturänderungen - Wie?. 8. - 10. September 2021, Karlsplatz & Online, TU Wien*, 2021.

[21] Task Force on Turbine-Governor Modelling, "Dynamic Models for Turbine-Governors in Power System Studies: Technical Report PES-TR1," 2013.

[22] IEEE Power and Energy Society, "IEEE Recommended Practice for Excitation System Models for Power System Stability Studies. IEEE Std 421.5-2016 (Revision of IEEE Std 421.5-2005)." IEEE, 2016.

[23] Western Electricity Coordinating Council, "WECC Wind Power Plant Dynamic Modeling Guide: Prepared by WECC Renewable Energy Modeling Task Force," 2014.

[24] J. Richter et al., "Integration of a Grid-Forming MVDC-System into a Transmission Grid Section for Real-Time Applications," in *8th IEEE Workshop on the Electronic Grid*, 2023.

[25] M. Weber, M. Kyesswa, U. Kühnapfel, V. Hagenmeyer, and H. K. Çakmak, "Case study of designing a locally distributed real-time simulation infrastructure," in *2021 IEEE Electrical Power and Energy Conference (EPEC)*, Oct. 2021, pp. 310–315.

[26] M. Weber, J. Enzinger, H. K. Çakmak, U. Kühnapfel, and V. Hagenmeyer, "Pyapi-rts: A python-api for rscad modeling," in *2023 Open Source Modelling and Simulation of Energy Systems (OSMSES)*, Mar. 2023, pp. 1–7.

[27] R. Poppenborg, M. Chlosta, J. Ruf, C. Hotz, C. Düpmeier, T. Kolb, and V. Hagenmeyer, "Energy hub gas: A modular setup for the evaluation of local flexibility and renewable energy carriers provision," in *2022 IEEE 10th International Conference on Smart Energy Grid Engineering (SEGE)*, 2022, pp. 33–41.

[28] A. Kuri, R. Zurowski, G. Mehlmann, D. Audring, and M. Luther, "A Novel Grid Forming Control Scheme Revealing a True Inertia Principle," *IEEE Transactions on Power Systems*, vol. 36, no. 6, pp. 5369–5384, 2021.

[29] A. Kuri, R. Zurowski, G. Mehlmann, and M. Luther, "Power Dispatch Capacity of a Grid-Forming Control Based on Phase Restoring Principle," *IEEE Systems Journal*, vol. 17, no. 3, pp. 3389–3400, 2023.

[30] J. Richter, S. Resch, G. Mehlmann, and M. Luther, "An Enhanced Ideal Transformer Method to Integrate Low-Voltage Power Hardware in Arbitrary Voltage Levels," in *2023 IEEE PES General Meeting*. IEEE, 2023.

[31] S. P. Engel, N. Soltau, H. Stagge, and R. W. de Doncker, "Dynamic and Balanced Control of Three-Phase High-Power Dual-Active Bridge DC–DC Converters in DC-Grid Applications," *IEEE Transactions on Power Electronics*, vol. 28, no. 4, pp. 1880–1889, 2013.

[32] M. Kyesswa, M. Weber, F. Wiegel, J. Wachter, S. Waczowicz, U. Kühnapfel, and V. Hagenmeyer, "A digital framework for locally and geographically distributed simulation of power grids," *Energy Technology*, vol. n/a, no. n/a, p. 2201186, 2023.

[33] F. Wiegel, J. Wachter, M. Kyesswa, R. Mikut, S. Waczowicz, and V. Hagenmeyer, "Smart energy system control laboratory : a fully-automated and user-oriented research infrastructure for controlling and operating smart energy systems = smart energy system control laboratory : hochgradig automatisierte und nutzerorientierte forschungsinfrastruktur zur steuerung und zum betrieb intelligenter energiesysteme," *at - Automatisierungstechnik*, vol. 70, no. 12, p. 1116–1133, 2022, 37.12.03; LK 01.

[34] R. Poppenborg, J. Ruf, M. Chlosta, J. Liu, C. Hotz, C. Düpmeier, T. Kolb, and V. Hagenmeyer, "Energy hub gas: A multi-domain system modelling and co-simulation approach," in *2021 9th Workshop on Modelling and Simulation of Cyber-Physical Energy Systems (MSCPES)*, 2021, pp. 67–72.

[35] M. Geidl, G. Koeppel, P. Favre-Perrod, B. Klockl, G. Andersson, and K. Frohlich, "Energy hubs for the future," *IEEE Power and Energy Magazine*, vol. 5, no. 1, pp. 24–30, 2007.

[36] B. Emonts, M. Müller, M. Hehemann, H. Janßen, R. Keller, M. Stähler, A. Stähler, V. Hagenmeyer, R. Dittmeyer, P. Pfeifer, S. Waczowicz, M. Rubin, N. Munzke, and S. Kasselmann, "A holistic consideration of megawatt electrolysis as a key component of sector coupling," *Energies*, vol. 15, no. 10, 2022. [Online]. Available: https://www.mdpi.com/1996-1073/15/10/3656

[37] T. Grün, M. Mast, and B. Schwarz, "Großspeicherwahl," *Nachrichten aus der Chemie*, vol. 68, no. 10, p. 37–39, 2020, 37.01.03; LK 01.

[38] G. Mehlmann et al., "Concept and operation of a distributed multi-domain power system laboratory with hil-capabilities," in *ETG Congress 2023*, 2023.

[39] P. Erlinghagen, M. Knaak, T. Wippenbeck, and A. Schnettler, "Development of a modular CHP test stand for the analysis of the dynamic behaviour of small synchronous generators," in *24th International Conference on Electricity Distribution (CIRED)*, 2017.

[40] Ö. Sen, F. Schmidtke, F. Carere, F. Santori, A. Ulbig, and A. Monti, "Investigating the Cybersecurity of Smart Grids Based on Cyber-

Physical Twin Approach," in *2022 IEEE International Conference on Communications, Control, and Computing Technologies for Smart Grids (SmartGridComm)*, 2022.

[41] I. Hacker, F. Schmidtke, S. Bahn, D. van der Velde, and A. Ulbig, "Full-Stack Development Process for Demand Side Flexibility Solutions from Cyber-Physical Testbeds to Field Operation," in *ETG Congress 2023*, 2023.

[42] D. Willenberg, S. Simon, R. Bertram, and T. Sowa, "Impact of Synchronous and Distributed Generation Unit Characteristics onto the Stable Operation of Low Voltage Islanded Microgrid," in *25th International Conference on Electricity Distribution (CIRED)*, 2019.

[43] A. Winkens, I. Contu, P. Linnartz, and A. Ulbig, "Experimental Validation of the Parallel Operation of Grid-Forming Converters and Synchronous Generators in Temporary Islanded Microgrids," in *2022 International Conference on Smart Energy Systems and Technologies (SEST)*, 2022.

[44] F. Klein-Helmkamp, F. Böhm, L. Ortmann, A. Winkens, F. Schmidtke, S. Bolognani, F. Dörfler, and A. Ulbig, "Providing Curative Distribution Grid Flexibility Using Online Feedback Optimization," 2023.

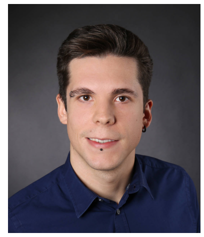
[45] S. Vogel, M. Mirz, L. Razik, and A. Monti, "An open solution for next-generation real-time power system simulation," in *2017 IEEE Conference on Energy Internet and Energy System Integration (EI2)*. IEEE, 2017, pp. 1–6.

[46] C. Scheibe, M. Richter, A. Raab, B. Stopfer, and G. Mehlmann, "Integration of an emt hvdc model into a transient stability study using co-simulation," in *2022 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, pp. 1–5.

[47] A. Raab, D. Frauenknecht, G. Mehlmann, M. Luther, and A. Wellhoefer, "Hybrid phasor- and emt-based multi-terminal mmc-hvdc model with grid-forming control," in *2023 IEEE Power & Energy Society General Meeting (PESGM)*. IEEE, 2023, pp. 1–5.

Gert Mehlmann received the diploma degree in electrical engineering in 2008 and the Ph.D. degree in electrical engineering in 2013 from Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany. From 2013 to 2016, he was a Power System Consultant with Siemens PTI before moving to university. Since 2016, he has been a Senior Lecturer with the Institute of Electrical Energy Systems, Friedrich-Alexander-Universität Erlangen-Nürnberg. He is responsible for the power system stability group, the affiliated Center for Applied System Simulations and a member of the extended scientific board of the Energie Campus Nürnberg. His research focus is particulary on the borderline area of electromechanic and electromagnetic transients as well as LCC and VSC grid integration.

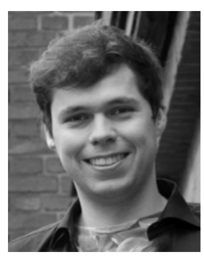
Uwe Kühnapfel (Member, IEEE) is a senior scientist and research division head for Energy System Integration (ESI) at the Institute for Automation and Applied Informatics (IAI) at Karlsruhe Institute of Technology (KIT) in Germany. He graduated 1985 (Diploma) in Electrical Engineering and Control Systems at University Stuttgart and received a Dr.-Ing. degree at University Karlsruhe (1991). He worked for 3 years as a KIT-delegate at the European Fusion Energy project JET at Culham Labs in England. Since 1988 he holds a permanent position at KIT within various national research programmes of the Helmholtz-Society in Germany. He is also responsible for a number of 3rd party projects with industry participation (Siemens, Hitachi Energy, a number of electricity TSOs and DSOs). His personal interests focus on electricity grid modelling and simulation, PHIL, energy system integration and grid control.



Felix Wege received his B.Sc. (2017) and M.Sc. (2020) in electrical engineering with a focus on computer engineering from RWTH Aachen University, Aachen, Germany. In 2020, he joined the E.ON Energy Research Center, Institute for Automation of Complex Power Systems, RWTH Aachen, as a Research Associate and Ph.D. student. His research interests include the development and application of highly performant simulation approaches for large scale electrical grids.

Alexander Winkens received the B.Sc. and M.Sc. degrees in electrical engineering, information technology and computer engineering from RWTH Aachen University, Aachen, Germany, in 2016 and 2019. From 2019, he is research assistant at IAEW at RWTH Aachen University, Germany, pursuing the Ph.D. degree in electrical engineering. From 2023, he additionally is with Fraunhofer FIT, Aachen, Germany.

Christian Scheibe (Member, IEEE) finished his Master's degree in 2015 and started with Siemens PTI working on Power System Transients right after that. The work included switching and lightning overvoltage analysis as well as HVDC and converter integration in the grid and their interaction based on electromagnetic transient anaysis. In 2019, he joined the Chair of Electrical Energy Systems at the Friedrich-Alexander-Universität Erlangen-Nürnberg in parallel to his work in Siemens. The topics involved power system co-simulation, especially in the RMS-EMT domain. He took lead of the chair's real-time simulation laboratory in 2020. After finishing his PhD Thesis in early 2023, he is now with Siemens Technology working in the field of power electronics integration and co-simulation of power systems.



Steffen Vogel received the B.Sc. and M.Sc. degrees in electrical engineering, information technology, and computer engineering from RWTH Aachen University, Aachen, Germany, in 2014 and 2017, respectively. From 2017 to 2023, he has been working as a Research Associate with the Institute for Automation of Complex Power Systems, Rheinisch-Westfälische Technische Hochschule Aachen University. In 2023, he started a new position as an R&D Software Engineer at OPAL-RT Germany in which he participates in several publicly funded German R&D projects. His current research topics are real-time simulation, Controller/Software-in-the-Loop testing and Power System Digital Twins.

Peter Noglik graduated from the Technical University of Kaiserslautern in 1994 with a degree in electrical engineering, specializing in digital technology. He worked for Wikon GmbH for 3 years in hardware and software development for IoT devices. In 1998 he joined ABB Netzleittechnik. There he was responsible for SCADA communication. Later he was the technical project manager for network control system projects. When he moved to the Business Development Smart Grids in 2010, he took over the project management of the research projects Grid4EU and Smart Area Aachen. In 2014 he joined ABB Research Center as Principal Scientist to work on energy research. Focus was the Kopernikus ENSURE project, started in 2016, which he led as project manager within Hitachi Energy. Since May 2023 he is responsible for the technical marketing of RTU applications for distribution automation.

Michael Gratza received his M.Sc. Degree in Electrical Engineering and Information Technology from the Technical University of Munich (TUM), Germany, in 2015. From 2015 to 2020, he worked as a research associate at the Chair of Electric Power Transmission and Distribution at TUM. Since 2021 he works in asset management at TenneT TSO GmbH and is project manager for the Kopernikus ENSURE project within TenneT.

Julian Richter (Student Member, IEEE) received the bachelor's and master's degree in energy engineering from the Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany, in 2018 and 2020. Since 2021, he is working toward the Ph.D. degree in electrical engineering with the Institute of Electrical Energy Systems, Friedrich-Alexander-Universität Erlangen-Nürnberg, Germany. He is responsible for the Institute's Microgrid Laboratory at the Center of Applied System Simulation in Nürnberg, Germany and the portfolio elements "Flexibilities and System Services" within the power system stability group of the Institute.

Moritz Weber (Student Member, IEEE) received the B.Sc. and M.Sc. degrees in computer science from Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, in 2016 and 2020, respectively. He is currently a research associate and Ph.D. student with the Institute of Automation and Applied Informatics (IAI) at KIT. His research intereset includes power grid model reduction, automation of grid model conversion and manipulation, and the automated generation of grid models from open data sources.

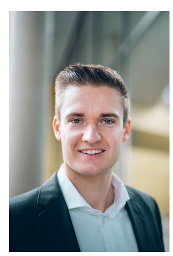
Ilya Burlakin (Member, IEEE) received the bachelor's degree in Power Engineering & Renewable Energies from the University of Applied Science Karlsruhe, Germany, in 2018 and the master's degree in Sustainable Electrical Power Supply from the University of Stuttgart, Germany, in 2020. He has been a research associate and Ph.D. candidate with the Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Germany, since 2021 and responsible for the power system dynamics and control portfolio elements within the Institute of Electrical Energy Systems (EES). His areas of research focus on modeling and simulation of power systems, as well as stability analysis in the context of renewable energy system integration.

Ananya Kuri (Member, IEEE) received the bachelor's degree in Electrical and Electronics Engineering from M.S. Ramaiah Institute of Technology, Bangalore India in 2011 and the master's degree in Electrical Engineering from RWTH Aachen, Aachen Germany in 2015. She was a senior power system consultant at Siemens PTI, Germany, from 2016-2023. Since 2023, she has been working at Siemens Technology as an R&D manager in the field of grid operations with a high focus on power electronics-dominated networks and grid-forming control concepts. In July 2023, she submitted her Ph.D. thesis at the Institute of Electrical Energy Systems from Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany.

Timo Wagner is a research associate and Ph.D. candidate at the Institute of Electrical Energy Systems from Friedrich-Alexander-Universität Erlangen-Nürnberg since 2020. His work at the Institute revolves around the field of Digital Twins and corresponding data interfaces within real-time simulators. In relation to his work, he is responsible for the real-time simulation laboratory of the Center of Applied System Simulation, including several real-time simulators and corresponding control hardware.

Sebastian Hubschneider received his B.Sc. and M.Sc. degrees in electrical engineering and information technology from Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, in 2012 and 2015, respectively. From 2015 to 2021, he worked as a research associate at the Institute of Electric Energy Systems and High Voltage Technologies (IEH) at KIT and received his Ph.D. in 2022. Since 2022 he works as an R&D Engineer at OPAL-RT Germany, where he focuses on research and projects in the areas of real-time simulation and digital twins of power grids, (power) hardware-in-the-loop systems and related topics.

Rafael Poppenborg received his M.Sc. degree in mechanical engineering from the Ruhr University Bochum (RUB), Germany in 2019. He is currently a research associate with the Institute of Automation and Applied Informatics at the Karlsruhe Institute of Technology (KIT). His research interest includes the optimization of distributed energy resources operation to provide flexibility to the electrical grid infrastructure.



Tobias Heins received the master's. degree in electrical engineering from RWTH Aachen University, Aachen, Germany, in 2020. He is currently a research associate with the Institute for Automation of Complex Power Systems, E.ON Energy Research Center, RWTH Aachen University. His research interests include control, stability, modelling and analysis of converter-driven power systems.

Kevin Förderer studied Industrial Engineering and Management (B.Sc.) and Economathematics (M.Sc.) at Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, before working at FZI Forschungszentrum Informatik as Research Associate. He received the Ph.D. degree from KIT in 2021. In 2021, he became Head of Group for the research group IT Methods and Components for Energy Systems (IT4ES) at the Institute of Automation and Applied Informatics at KIT.

Andreas Ulbig (Member, IEEE) received the M.Sc. degree from Supélec, Paris, France, in 2006, the Dipl.Ing. degree in engineering cybernetics from the University of Stuttgart, Stuttgart, Germany, in 2007, and the Ph.D. degree from ETH Zurich, Zurich, Switzerland, in 2014. He is full professor at the Chair for Active Energy Distribution Grids (IAEW) at RWTH Aachen University and Group Leader at Fraunhofer Center Digital Energy in Aachen, Germany since 2021. Prof. Ulbig was the co-founder and COO of ETH spinoff company Adaptricity. He was also a lecturer (part-time) for electric power systems at ETH Zurich and is vice president of the Swiss Energy Foundation (SES). Previous industry positions include the R&D Department of RTE, the French TSO, and the International Energy Agency (IEA), Paris, France. He was an academic visitor in 2007 at Caltech (Control and Dynamical Systems), Pasadena, CA, USA and in 2012 at PNNL (Advanced Power & Energy Systems), Richland, WA, USA as well as at the University of California, Berkeley (Energy and Resources Group), CA, USA. His research interests include power and energy system modeling, RES grid integration, ancillary services, energy storage, and operational flexibility of power systems.

Antonello Monti (Senior Member, IEEE) received the M.Sc. (summa cum laude) and Ph.D. degrees in electrical engineering from Politecnico di Milano, Italy, in 1989 and 1994, respectively. He started his career with Ansaldo Industria and then moved to Politecnico di Milano, as an Assistant Professor, in 1995. In 2000, he joined the Department of Electrical Engineering, University of South Carolina, USA, as an Associate Professor, and then a Full Professor. Since 2008, he has been the Director of the E.ON Energy Research Center, Institute for Automation of Complex Power System, RWTH Aachen University. He is the author or coauthor of more than 300 peer-reviewed papers published in international journals and in the proceedings of international conferences. He was a recipient of the 2017 IEEE Innovation in Societal Infrastructure Award. He is a member of the Editorial Board of Sustainable Energy, Grids and Networks journal (Elsevier) and a member of the Founding Board of the Energy Informatics journal (Springer). He is an Associate Editor of the IEEE Systems Journal and IEEE Electrification Magazine.

Veit Hagenmeyer (Member, IEEE) received the Ph.D. degree from the Laboratoire des Signaux et Systèmes (L2S), C.N.R.S.-Supélec,Université Paris-Sud, Bures-sur-Yvette, France, in 2002. From 2002 to 2003, he held a post-doctoral position at L2S, C.N.R.S.-Supélec, Université Paris-Sud. From 2003 to 2006, he was a Research Engineer with the Advanced Process Control Group, BASF SE, Ludwigshafen, Germany. From 2007 to 2008, he was the Head of the Advanced Process Control Group, BASF SE. From 2008 to 2009, he was a Senior Consultant for Verbund Simulation of BASF sites in Europe. From 2009 to 2010, he was the Personal Assistant to the European Site Manager Europe (Level 2 of BASF Group). From 2010 to 2014, he was the Power Plant Director of BASF (three power plants and energy grids). In 2014, he became the Director of the Institute of Automation and Applied Informatics, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany, where he became a Full Professor of energy informatics at the Faculty of Informatics.

Matthias Luther (Member, IEEE) received the Ph.D. degree in electrical engineering from the Technical University of Brunswig, Braunschweig, Germany, in 1992. From 1993 until 2010, he held different functions and management positions in the electricity industry at PreussenElektra, E.ON Netz, and TenneT TSO. Since 2011, he has been a Professor and the Director with the Institute of Electrical Energy Systems, Friedrich-Alexander-University of Erlangen-Nuremberg, Germany. He is a member of several national and international institutions and panels, i.e., VDE/ETG, CIGRE, and IEEE.