Smart Grid Laboratory as Testing Environment for innovative Technologies and Key Component for Knowledge Transfer

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Abstract

This contribution presents recent advancements of the Smart Grid Laboratory at the University of Wuppertal, which significantly broaden its scope for research, development, and education in the field of smart grids. Key enhancements include remotely controllable circuit breakers and a grid-forming inverter for microgrid operation. The laboratory also serves as a platform for peer-to-peer electricity market simulations and is integrated into academic teaching. These developments establish the laboratory as a key infrastructure for exploring decentralized energy systems and supporting the education of future energy professionals.

Keywords

Smart Grid, Laboratory, Automation, Microgrid, Flexibility, Energy Efficiency

1 Introduction

Germany's 2025 coalition agreement places strong emphasis on accelerating the energy transition through digitalization, decentralized markets, and innovation-friendly regulation [1]. However, real-world implementation of smart grid concepts still faces hesitation due to infrastructure risks and limited testing environments. This gap between political ambition and technical readiness underscores the need for safe, practice-oriented validation spaces. The Smart Grid Laboratory (SGL) of the University of Wuppertal addresses this gap by aligning its research and educational activities with the strategic objectives of national energy policy. It enables the development of future-proof solutions and supports the training of skilled professionals—both essential to realizing a secure, intelligent, and citizen-oriented energy system.

This scientific contribution is structured as follows: First the technical configuration and capabilities of the SGL prior to 2023 are summarized. Subsequently, the technological enhancements implemented during 2023 and 2024 are described in detail. These include the integration of remotely controllable circuit breakers and a grid-forming inverter (GFI), enabling microgrid operation within the scope of the SiSKIN research project [2–4]. Following this, recent applications of the SGL in research at the University of Wuppertal are presented. Notably, the laboratory has been employed as a field test environment for a platform simulating peer-to-peer (P2P) electricity trading, offering insights into future decentralized market models and contributing to local energy efficiency [5]. Finally, the paper outlines the integration of the SGL into academic teaching at the University of Wuppertal, highlighting its role in practical smart grid education [6].

2 Smart Grid Laboratory architecture

The SGL architecture and its core functions prior to 2023 are described in [7]. The SGL at the University of Wuppertal is a low-voltage laboratory grid in which each node is continuously measured and monitored in real time from a central control station. The grid hardware consists of 16 interconnected nodes and 21 branches, with a total cable length of 750 meters. The grid's reconfigurability supports a broad spectrum of topological arrangements, ranging from radial to meshed configurations, with several hundred switchable combinations available for testing and analysis.

To support realistic operational scenarios, the SGL was equipped with a range of hardware components:

– a 250 kVA line voltage regulator (LVR) for dynamic voltage adjustment,
– three adjustable load banks, each rated at 15 kW (adjustable in 0.25 kW increments),
– ten bidirectional frequency inverters (BFI), each rated at 9.7 kVA (enabling distributed active power control),
– eight 22 kW electric vehicle (EV) charging points, and
– a 115 kWp photovoltaic (PV) system.

All these components can be flexibly assigned to different nodes in the grid as shown in Figure 1, depending on the experimental configuration.

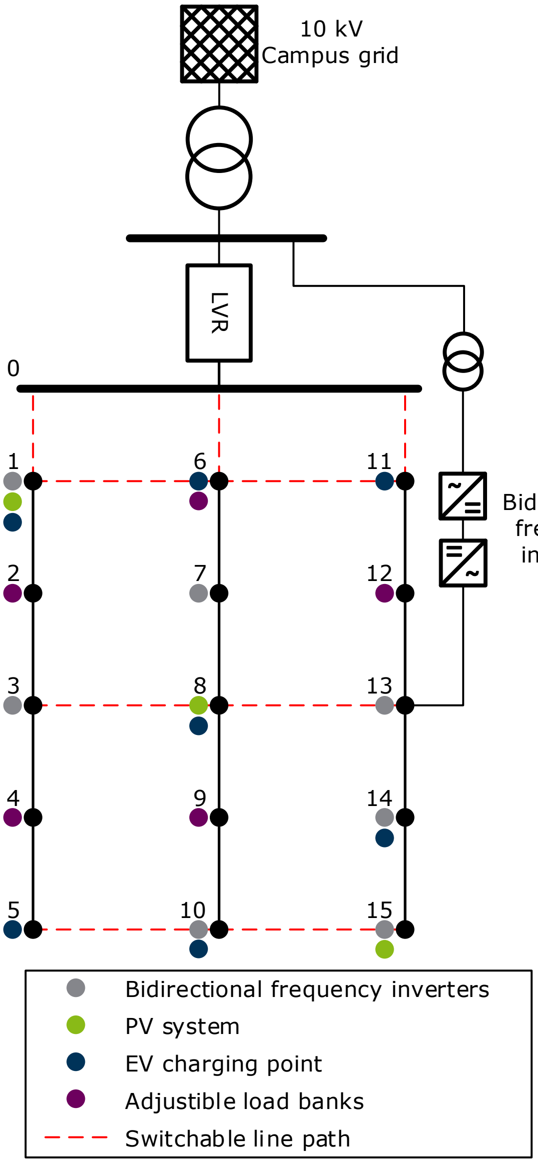

Figure 1 Technical setup of the Smart Grid Laboratory

Figure 1 also illustrates the configuration of a typical BFI pair within the SGL. One inverter is directly connected to the laboratory grid, while the other is coupled to the campus grid via an isolation transformer. Both inverters share a common DC intermediate circuit, which enables bidirectional power flows and full four-quadrant operation.

This configuration allows the BFI pair to either inject power into or absorb power from the laboratory grid, depending on the control parameters. The power exchange across the DC link creates a circulating current, which can emulate either a generator or a consumer from the laboratory grid's perspective. This emulation is achieved by programmable control of the inverter parameters—such as active power, reactive power, and power factor—allowing the devices to mimic a wide range of load and generation profiles dynamically.

A comprehensive measurement infrastructure complements the hardware setup. Voltage, current, and phase information is collected at every node and branch, supported by environmental data such as ambient temperature and global solar irradiance. Measurement and communication are implemented through a mix of remote terminal units, charge controllers and device-specific protocols. This allows selective data provision to test systems, while redundant measurements serve as references for validation and analysis.

3 Recent Technological Enhancements

While the initial configuration of the SGL already provided a versatile platform for distribution grid research, further enhancements were necessary to meet evolving technological and scientific challenges. The following section outlines the key upgrades introduced in 2023 and 2024, including components that enable advanced grid control and microgrid operation.

3.1 Remotely Controllable Circuit Breakers

To expand the automation capabilities of the SGL, load-capable circuit breakers from Siemens were installed in 2023, replacing the previously used manually operated switch disconnectors which were located in between the switchable line paths shown in Figure 1. In contrast to their predecessors—which could only be operated locally and under no-load conditions—the new circuit breakers are specifically designed to perform switching operations safely under load. This capability is essential for conducting topology changes without interrupting grid operation.

Each circuit breaker is equipped with a motorized actuator that enables remote operation via the control system. In addition to manual remote switching, this setup also allows programmatic control, making it possible to execute complex topology changes as part of automated test routines or scripted experiments. The combination of load-switching capability and full remote control marks a significant step toward realistic simulation of grid automation, fault response, and reconfiguration strategies within a controlled laboratory environment. This enables dynamic and repeatable testing scenarios without manual intervention, greatly enhancing both operational safety and experimental flexibility.

3.2 Grid-Forming Inverter for Microgrid Operation

Following the example of the already integrated BFI, a GFI in conjunction with a rectifier (Figure 2 in green) and a switching device (Figure 2 in blue) were added to the SGL in 2023. The GFI is capable of generating an AC voltage with configurable frequency and amplitude, and provides essential grid services such as frequency and voltage regulation for the laboratory grid through integrated control loops.

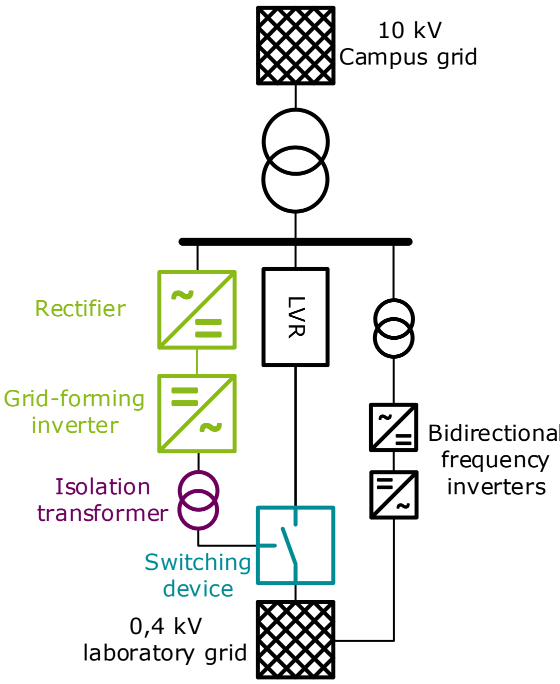

Figure 2: Technical setup of the Smart Grid Laboratory after integrating the GFI

As shown in Figure 2, the GFI is galvanically isolated from the laboratory grid via an isolation transformer (Figure 2 purple), enabling unbalanced load operation in microgrid mode. With the new switching device, the SGL can be operated as a microgrid, where it is electrically decoupled from the campus grid through the DC intermediate circuit between the GFI and the rectifier. In this mode, the system effectively emulates a microgrid environment, allowing for controlled studies on autonomous grid operation, grid stability, and reconstruction strategies.

4 Application for research purposes

The technological enhancements of the SGL described in section 3 enable laboratory tests to be carried out in various research projects with different research purposes. The following section provides a brief insight of the laboratory tests carried out in the SGL and the findings obtained in various research areas.

4.1 Integrating Peer-to-Peer Energy Trading and Flexibility Market

The first use case is a platform for local P2P energy and flexibility trading, which was developed as part of the research project PEAK[1] and validated in a laboratory test in the SGL [5]. The aim of the platform is to enable secure, automated P2P trading of green and local energy, while supporting market-based use of flexibilities with intelligent strategies for prosumers. With the combination of curative and preventive grid congestion management through grid state identification and grid state forecasts, it contributes to secure and automated grid operation in distribution grids. The platform is based on a multi-agent-system and includes a dual local market approach, comprising a P2P energy market and a flexibility market.

The field test of the platform in the SGL was carried out in several test scenarios that pursued different testing objectives in various grid and market scenarios and by applying the standard ISO 29119, a standard defining a framework for testing software systems [8]. This approach ensures that both the individual components of the platform as well as their interaction is validated. The testing objectives are local P2P energy trading between individual prosumers and grid congestion management due to the thermal overload of a cable and the violation of the permissible voltage band. In the case of the testing objective grid congestion management, each grid scenario is carried out with deactivated and activated grid state control in order to evaluate its influence on the grid state. Figure 3 shows the results of the grid scenario of the thermal overload of cable 0-1 from Figure 1 with deactivated grid state control in purple and with activated grid state control in green.

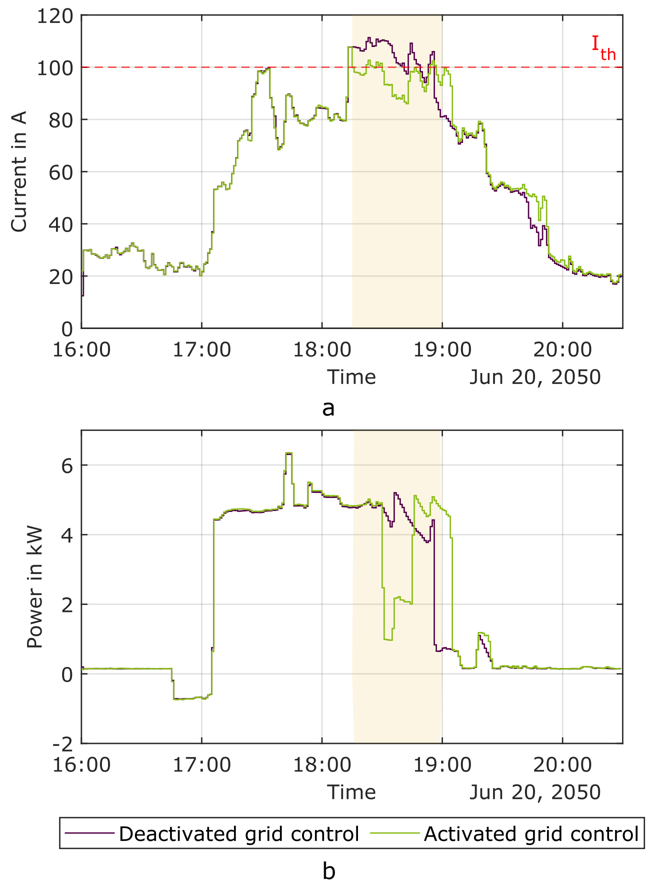

Figure 3 Measured current at cable 0-1 (a) and measured power of prosumer at node 10 (b) for a deactivated and activated grid state control scenario and with highlighted active flexibility market periods

In Figure 3a the measured current at cable 0-1 and in Figure 3b the measured power of the prosumer at node 10 over the test period of 4 hours and 30 minutes is shown. The value I_{th} in Figure 3a displayed in red corresponds to the thermal limit current of cable 0-1, the exceedance of which represents a grid congestion and should be prevented through grid state control. The flexibility market is activated between 18:15 to 19:00 and leads to a significant reduction of the cable overload compared to the test

[1] https://www.peak-plattform.de/

with deactivated grid state control. This is achieved by simulating individual prosumers with the actuators of the SGL in form of the load banks and BFI. In this case the flexibility of reducing the charging power of an EV is offered by the prosumer at node 10 to the flexibility market and realized at times when the offer has been rewarded on the flexibility market.

The multi-agent system implements automated decision-making, ensuring both financial benefits for prosumers and congestion management for grid operators. The findings suggest that future market designs should integrate decentralized, privacy-preserving identity solutions and market-based grid coordination, supported by appropriate regulatory frameworks.

4.2 Controlled Microgrid Build-Up and Operation

As part of the SiSKIN research project, microgrid concepts were tested in the SGL to enable the emergency supply of critical infrastructure during a blackout. For this purpose, the GFI and the remotely controllable circuit breakers were used to build and operate microgrid segments under realistic conditions.

The GFI controls frequency and voltage using predefined droop characteristics, which can be set by the system configuration. For frequency control, a f(P)-droop can be set, which describes the grid frequency in relation to the active power fed into the grid by the GFI. The following equation describes the droop s_f for the frequency and active power relationship, where Δf describes the deviation from the nominal frequency, f_n is the nominal frequency, ΔP is the generated active power, and P_n is the nominal active power.

$$s_f = \frac{\frac{\Delta f}{f_n}}{\frac{\Delta P}{P_n}} \quad (1)$$

In parallel, the GFI also controls voltage by using a u(Q)-droop, which also uses a droop function. The voltage is controlled based on the generated reactive power. The following equation describes the droop s_u for the voltage and reactive power relationship, where Δu represents the deviation from the voltage, $\mathrm{u_n}$ describes the nominal voltage, ΔQ signifies the generated reactive power, and Q_n represents the nominal reactive power.

$$s_u = \frac{\frac{\Delta u}{u_n}}{\frac{\Delta Q}{Q_n}} \quad (2)$$

Based on the described droop control, three concepts were implemented to build up a microgrid [4]. These concepts were tested in the laboratory grid, where the load banks were used as loads and the BFI served as additional generation units for power injection. Furthermore, the switching devices were used to interconnect the microgrid step by step.

In the first concept, the microgrid is build up solely by the GFI, which regulates voltage and frequency. Once the microgrid reaches a stable state, additional load banks are gradually added and supplied by the GFI. When the GFI reaches its power limit, a BFI is connected to supply additional active power and reduces the load of the GFI.

In the second concept, a droop control is configured on the GFI. This enables the BFI to detect the load within the microgrid. Based on the resulting variations in frequency and voltage, the BFI adjust their power output. As in the previous approach, load banks are connected gradually.

The third concept is based on a central controller that manages all generation units within the microgrid. Both GFI and BFI are controlled by this central controller and receive setpoints of the power that they should generate.

The following Figure 4 shows the active power and frequency of the GFI in the second concept.

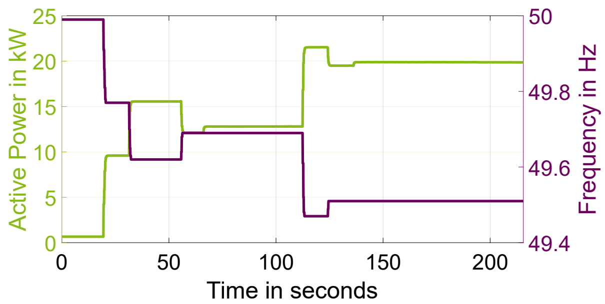

Figure 4 Measured active power and frequency of the GFI in the second concept.

The microgrid has a base load of 0.7 kW. The following connections are possible due to the remotely controllable circuit breakers described in section 3.1. First, the microgrid is gradually expanded by connecting a load bank of 9 kW, followed by an additional load bank of 6 kW. Afterwards, a BFI is connected, which produces 3.4 kW. This BFI uses a proportional controller that adapts its active power depending on the measured frequency. This reduces the active power supplied by the GFI to 12.798 kW. Finally, the last load of 9 kW is added. The power supply is now shared between the GFI and the BFI. The frequency is adapted by the GFI.

5 Integration into Teaching and Education

In addition to its use for research purposes, the SGL is also used to demonstrate practical examples in the field of smart grids in teaching. As part of the teaching module "Smart Grids - Intelligent Distribution Grids" [6], students can test the theoretical basis for the appropriate use of modern intelligent grid operating equipment and grid automation systems of the lecture in five practical lab-trainings including following modules:

- Module 1: MATLAB introduction
- Module 2: Database communication
- Module 3: Power flow calculation
- Module 4: Grid state identification
- Module 5: Grid state control

Figure Figure 5 shows an exemplary result of a grid state control in the event of a lower voltage band violation, which is to be developed in module 5 by the targeted control of individual actuators in the SGL. The basis for this is the grid state identification, which is used to determine the operating variables in the grid in the form of the vector of the complex voltages of all grid nodes and the complex power flows across all operating resources for a point in time and represents the content of module 4.

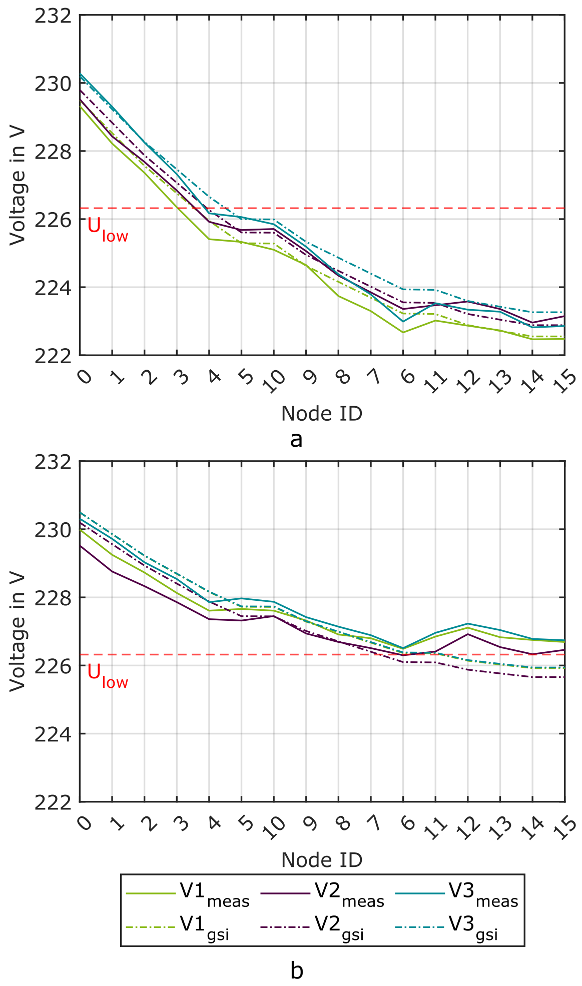

Figure 5 Measured and estimated voltage values through grid state identification for each node before grid state control (a) and after grid state control (b)

Figure 5a shows the measured and estimated grid state, whereby the grid topology is switched to a long strand and only loads are connected to the grid nodes. This results in a voltage drop that falls below the specified lower voltage limit U_{low} and thus leads to a lower voltage band violation. The estimated grid state can be used to calculate and subsequently implement the required control measures, resulting in a changed grid state, which is illustrated in Figure 5b. It can be seen that the voltage band violation is eliminated by the targeted control measures. By working on a real grid with real measured values, there are fluctuations, e.g. in the voltage measurements at the feed-in point, which is also the case in real low-voltage grids and thus provides an insight into the challenges of implementation of smart grid systems in practice.

The didactic concept of the teaching module “Smart Grids - Intelligent Distribution Grids” aims to deepen the content of the lecture with the help of practical lab-trainings. Feedback from the students' learning experiences is continuously taken into account and the scope of the lab-training is expanded with new modules relating to current topics in the energy industry. By practicing on a real low voltage grid with real measured values, the students are prepared in the best possible way for the upcoming challenges of practical implementation.

6 Conclusion and Outlook

The SGL at the University of Wuppertal has proven to be a versatile and practical platform for advancing smart grid research and education. Key achievements include the integration of remotely controllable circuit breakers for safe, load-capable switching, and the implementation of a GFI enabling stable microgrid operation with autonomous voltage and frequency regulation. The SGL has successfully validated P2P energy trading concepts and various microgrid control strategies, demonstrating its value for future decentralized energy systems. Furthermore, its incorporation into academic teaching effectively links theoretical knowledge with practical application.

Looking forward, the integration of a grid-forming energy storage system will enhance microgrid stability and operational flexibility. Alongside this, the development of advanced control algorithms for the GFI will optimize dynamic grid response and ancillary services. Additionally, future work will focus on incorporating artificial intelligence-based component control and integrating weather forecasting data to enable predictive grid management and improved operation under variable renewable generation. These advancements will strengthen the SGL’s position as a state-of-the-art testbed for resilient, autonomous, and intelligent smart grids

7 References

[1] CDU, CSU, SPD, *Verantwortung für Deutschland: Koalitionsvertrag zwischen CDU, CSU und SPD*. 21. Legislaturperiode. Berlin.

[2] Bergische Universität Wuppertal, *SiSKIN - Großflächiger Stromausfall – Möglichkeiten zur Teilversorgung von kritischen Infrastrukturen.* [Online]. Available: https://www.evt.uni-wuppertal.de/de/forschung/forschungsgruppe-energiemaerkte-und-flexibilitaetsmanagement/siskin/ (accessed: Jun. 18 2025).

[3] G. Puleo, M. Mütherig, M. Zdrallek, and D. Aschenbrenner, "Extension of a low-voltage laboratory grid by a grid-forming unit to perform microgrid studies," *IET Conf. Proc.*, vol. 2024, no. 27, pp. 186–190, 2025, doi: 10.1049/icp.2024.2593.

[4] M. Mütherig, G. Puleo, W. Krause, and M. Zdrallek, "Laboratory test to validate concepts to build up and operate a microgrid at distribution grid level after a blackout," *IET Conf. Proc.*, vol. 2024, no. 27, pp. 147–151, 2025, doi: 10.1049/icp.2024.2584.

[5] M. Kilthau *et al.,* "Integrating Peer-to-Peer Energy Trading and Flexibility Market With Self-Sovereign Identity for Decentralized Energy Dispatch and Congestion Management," *IEEE Access*, vol. 11, pp. 145395–145420, 2023, doi: 10.1109/ACCESS.2023.3344855.

[6] Bergische Universität Wuppertal, *Lehrveranstaltung Smart Grids - Intelligente Verteilnetze.* [Online]. Available: https://www.evt.uni-wuppertal.de/de/

lehre-studium/lehrveranstaltungen/regenerative-energiequellen-1/ (accessed: Jun. 18 2025).
[7] M. Koch, M. Tafuro, D. Cano-Tirado, M. Forchheim, M. Wazifehdust, and M. Zdrallek, "Low Voltage Laboratory Grid for Smart Grid Systems with Bidirectional Power Flows," in *ETG Congress 2023*, 2023, pp. 1–5.
[8] *Software and systems engineering — Software testing: Part 4: Test Techniques*, 29119-4, ISO/IEC/IEEE 29119-4, 2015.