The Smart2DC Microgrid Laboratory at Karlsruhe Institute of Technology

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***Abstract*—This paper presents the *Smart2DC Microgrid Laboratory* at the Karlsruhe Institute of Technology (KIT), a cutting-edge facility for DC microgrid research. The laboratory is equipped with modular power electronics, real-time simulation capabilities, and advanced control systems, enabling investigations into decentralized energy supply, demand-side management, and energy efficiency. Distinctive experimental setups—including a DC-powered residential test building, electric vehicle charging infrastructure, and integrated hydrogen systems—facilitate studies on renewable energy integration, energy storage optimization, and next-generation DC technologies. Designed as an open-science platform, the *Smart2DC Microgrid Laboratory* fosters innovation through research, education, and collaboration with industry.**

***Index Terms*—DC Microgrid, Energy Management Systems, Renewable Energy Integration, Grid Stability and Control.**

I. Introduction

The global energy landscape is evolving rapidly, driven by the need for more sustainable, efficient, and decentralized power systems [1]. Direct-current (DC) microgrids address these challenges by avoiding unnecessary AC/DC conversions, enabling seamless integration of renewable energy sources, and aligning with the native characteristics of modern electronic loads [2], [3]. Despite these benefits, significant technical challenges persist, such as the development of efficient power electronics, robust control strategies, and scalable architectures to support diverse applications [4]. Addressing these challenges requires advanced research infrastructures that bridge the gap between theoretical studies and real-world applications. To accelerate innovation and support the practical deployment of DC-based energy solutions, dedicated experimental environments are essential—enabling new concepts to be tested, validated, and refined under realistic conditions. The *Smart2DC Microgrid Laboratory*, established within the Smart Energy System Simulation and Control Center (SEnSSiCC) [5] at the Karlsruhe Institute of Technology (KIT), provides such a platform for cutting-edge research on DC power systems. As part of KIT's Energy Lab—a leading research hub for sustainable energy technologies—the open-science laboratory is designed to test, optimize, and validate advanced DC microgrid solutions. It supports research in renewable energy integration, energy storage management, and emerging applications such as e-mobility and hydrogen-based systems. The Energy Lab comprises various research units, including the *Carbon Cycle Lab*, the *Power-to-X (PtX) Lab*, the *High Power Grid Lab (HPGL)*, the *Hydrogen Integration Platform (HIP)*, and the *SEnSSiCC* [5], which houses the *Smart2DC Microgrid Laboratory*. Figure 1 provides an overview of the Energy Lab and its different research divisions.

The present paper introduces the *Smart2DC Microgrid Laboratory* and outlines its innovative infrastructure and capabilities. The laboratory is equipped with advanced tools, including a modular power electronics platform, real-time simulation systems, and high-fidelity power emulation. Experimental setups comprise a DC-powered residential test building, a DC electric vehicle charger, and an integrated fuel cell system connected to the microgrid. Leveraging its integration with the fully automated busbar matrix of the *Smart Energy Systems Control Laboratory* (SESCL), the *Smart2DC Microgrid Laboratory* serves as an open-science environment for in-depth studies of DC microgrids—facilitating the exploration of diverse participants and network topologies [5]. An overview of the laboratory's modular structure and main components is depicted in Figure 2. Collectively, these research resources support a wide range of investigations, from improving energy efficiency in decentralized systems to validating next-generation technologies under realistic conditions. The goal

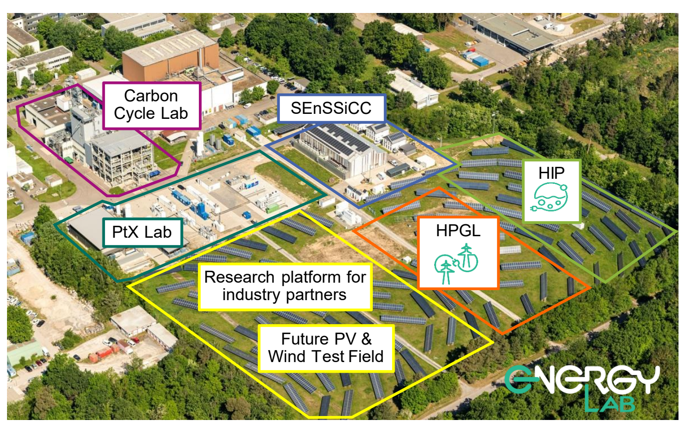

Fig. 1. Aerial view of the Energy Lab at the KIT, highlighting various infrastructure units including SEnSSiCC, where Smart2DC is hosted. Photo: Markus Breig (KIT).

of this paper is to provide a comprehensive overview of the laboratory's design, capabilities, and research potential.

The remainder of this paper is structured as follows. Section II provides an overview about some state-of-the-art DC microgrid laboratories. Section III provides an in-depth overview of the *Smart2DC Microgrid Laboratory*'s design and key hardware components. Section IV elaborates on the core capabilities of the laboratory, including experimental use cases and potential research applications and explores the broader implications of the lab for education, industrial collaboration, and technology development. Finally, Section V concludes the paper with a discussion of the impact of the lab and future directions.

II. Other DC microgrid laboratories

Research on DC power systems is supported by a growing network of dedicated laboratories worldwide. This section presents an overview of selected prominent DC laboratories.

Aalborg University in Denmark hosts the *Microgrids and Energy Internet Laboratory*, which is recognized for its real-time simulation and control strategies for hybrid energy systems under realistic conditions [6]. In China, the North China Electric Power University (NCEPU) operates the *Intelligent DC microgrid Living Laboratory* in collaboration with Aalborg University. This facility focuses on advanced control strategies, distributed generation, and seamless integration of renewable energy sources, providing a testing ground for future smart grid applications [7]. Similarly, Xiamen University established a DC microgrid for commercial building applications. This system integrates a 150 kWp rooftop solar array, 380 V DC bus, DC lighting, air conditioning, and EV charging, enabling studies on energy efficiency and hybrid AC/DC operations under realistic urban scenarios [8]. In Germany, the Fraunhofer IAO *Living Lab Micro Smart Grid* integrates photovoltaic systems, battery storage, and EV charging infrastructure to study decentralized DC systems and e-mobility solutions [9]. The National Renewable Energy Laboratory (NREL) in the United States operates the *Energy Systems Integration Facility* (ESIF), focusing on resilience and renewable energy integration in DC microgrids [10]. Similarly, the Power Integration Center by Cummins Inc. in Minnesota offers a scalable platform for validating DC systems, with an emphasis on grid reliability and system integration [11]. South Korea's *KAIST Smart microgrid Laboratory* is advancing next-generation DC technologies, with research in IoT-based control strategies and urban energy systems [12]. Across Europe, the *European Distributed Energy Resources Laboratory* (DERlab) provides a collaborative platform for addressing DC microgrid challenges at multiple scales [13]. In Tallinn, Estonia, the *DC Innovation Hub* under the I³DC Initiative at the Tallinn University of Technology (TalTech) focuses on modular DC grids, energy efficiency, and decentralized power systems, making significant contributions to the development of scalable DC energy solutions [14]. These laboratories form a global network of expertise that collectively drives innovation in DC microgrids. The *Smart2DC Microgrid Laboratory* at KIT complements these international efforts by offering a unique, modular, and open-science research environment for exploring next-generation DC microgrid technologies.

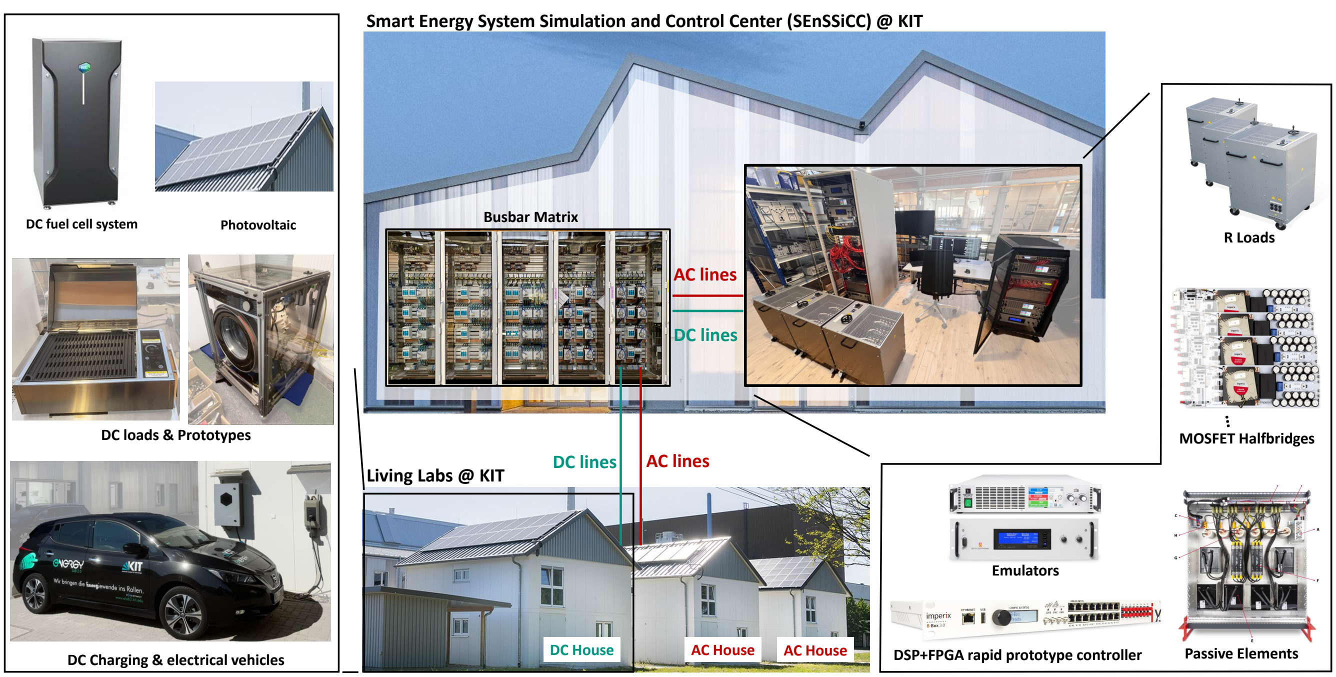

Fig. 2. Key components and interconnections within the *Smart2DC Microgrid Laboratory*, including converters, experimental buildings, EV charging, fuel cells, and power electronics testbeds.

III. Laboratory Design and Infrastructure

The *Smart2DC Microgrid Laboratory* at KIT is a cutting-edge research facility designed as an open platform for investigating advanced DC grid concepts. As an integral part of SESCL [5], the lab is directly connected to the DC section of the fully automated busbar matrix and inherits all of its core capabilities. These include: (i) flexible provisioning and reconfiguration of microgrid topologies, (ii) dynamic load shedding or integration of new grid participants, and (iii) runtime control and adjustment of setpoints and operating parameters for all connected components.
In combination with the DC experimental building of the Living Lab Energy Campus[1], integrated hydrogen-based energy systems[2], and Power Hardware in the Loop (PHIL) capabilities[3], the laboratory offers optimal conditions for developing and testing novel concepts in the field of DC grids. These include, among others, advanced vehicle-to-grid integration, hybrid energy systems, and sector coupling strategies. While many research institutions focus on specific aspects of DC microgrids, the *Smart2DC Microgrid Laboratory* integrates them into a unified and highly configurable experimental environment (see Figure 2). It thus acts as a bridge between theoretical research and real-world deployment, providing complementary resources that advance the development of sustainable and efficient energy technologies.

A. The busbar matrix with integrated DC buses

A central feature of the *Smart2DC Microgrid Laboratory* is its connection to the highly flexible busbar matrix, introduced in [5], which ensures flexible interconnection among microgrid components while enabling automated adjustments to overall grid topology. The busbar matrix is the principal interface for all components, such as chargers, the experimental building, dedicated loads, and specialized systems like fuel cells, it provides the foundation for the lab's modular, safe, and adaptive architecture. The DC section of the busbar matrix consists of two two-pole DC busbars, each rated for voltages up to $750\,\mathrm{V}$ and currents up to $220\,\mathrm{A}$ per output connection. In total, up to twelve DC nodes (e.g., sources, loads, energy storage units) can be tied into the matrix concurrently, subject to an aggregate maximum busbar current limit of approximately $579\,\mathrm{A}$ for safe continuous operation. A built-in safety factor of around 1.5 ensures reliable performance under dynamically changing loads or transient events. Notably, all switching elements are pole-disconnectable, allowing each port to be fully isolated for maintenance, fault handling, or other control operations. Unlike many conventional DC testbeds, the busbar matrix supports topology changes on-the-fly through software-driven contactors. Researchers can interconnect DC converters, battery systems, renewable sources, or even entire DC buildings with minimal manual intervention. This arrangement enables dynamic testing of diverse DC topologies—such as multi-terminal ring, radial, or star configurations—while the system is energized, significantly accelerating research cycles and prototyping efforts.

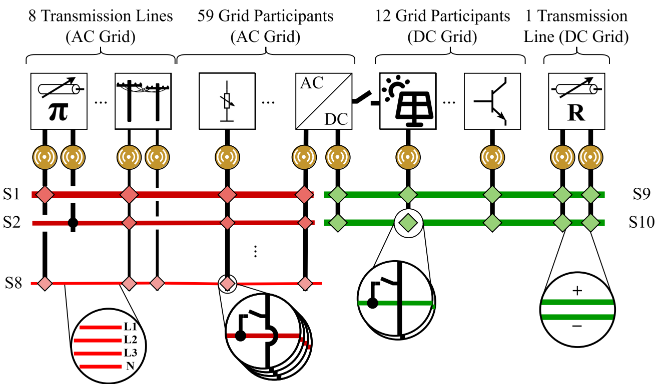

Fig. 3. Detailed layout of the Smart2DC busbar matrix highlighting flexible DC interconnection options.

Measurement Equipment

To ensure precise monitoring and operational safety, a high-fidelity measurement and data acquisition system has been integrated into every output of the matrix. Each terminal is equipped with a Q.bloxx-XL-A127 I/O module from Gantner Instruments, managed via a Station-XT Edge Controller. Voltage is measured directly at each terminal, while current sensing is performed by high-precision fluxgate current transducers (DS200UB-1V, Danisense). During the system's design phase, a comparative analysis of available current-sensing technologies—including shunt resistors, Hall-effect sensors, and fluxgate transducers—led to the selection of fluxgate devices. These sensors were chosen for their superior accuracy at low currents and galvanic isolation, which is essential for protecting measurement electronics from high potential differences. The measurement setup supports 24 analog channels (12 voltage and 12 current), with a bandwidth of up to $50\,\mathrm{kHz}$ (extendable to $100\,\mathrm{kHz}$) and a DC isolation voltage of $1200\,\mathrm{V}$. It is fully synchronized using Precision Time Protocol (PTP), which ensures consistent time alignment across all nodes—a crucial feature for correlating switching events with transient voltage or current behavior. The Station-XT controller communicates via two interfaces: a real-time EtherCAT link transmits safety-relevant but lower-resolution data to the control system, while a high-resolution Ethernet stream logs all measurements to a time-series database (InfluxDB) for offline analysis.

Safety and Monitoring Strategies

In addition to measurement accuracy, the laboratory places significant emphasis on operational safety and fault tolerance. To protect equipment and personnel, advanced safety features are integrated across both hardware and software layers:

- High-Fidelity Sensing: Voltage and current at each busbar node are continuously measured via galvanically isolated transducers (e.g., fluxgate sensors). This ensures accurate

[1]https://www.elab.kit.edu/english/llec.php
[2]https://www.elab.kit.edu/english/hip.php
[3]https://www.elab.kit.edu/english/phil.php

real-time monitoring and rapid detection of unsafe conditions, such as short circuits or over-current scenarios.
- Multi-Layer Protection: Besides software-based interlocks and threshold-based tripping, each DC node is equipped with additional thermal-magnetic breakers or high-rupture fuses, rated up to 75–120 kA. In the event of a severe fault, the system can reliably isolate affected nodes within milliseconds.
- Automated Conformity Check: Before making any electrical reconfiguration (e.g., switching a contactor), the lab's supervisory system verifies compatibility with user privileges, busbar current levels, and each component's voltage setpoint. This approach significantly reduces the risk of inadvertent overloads or undesired feedback loops.

B. Modular DC Microgrid Topology

The *Smart2DC Microgrid Laboratory* includes a fully modular and reconfigurable DC microgrid architecture built using multiple PEB8038 half-bridge power modules from *Imperix*. Each of these modules features high-performance Silicon Carbide (SiC) MOSFETs rated for 800 V / 38 A, enabling efficient and robust operation at high switching frequencies up to 50 kHz. The system supports the emulation of a wide variety of converter topologies, ranging from single-phase inverters to multi-terminal DC/DC or AC/DC architectures, making it suitable for cutting-edge research on advanced control and stability of DC grids. The power modules are directly interfaced to a central controller platform, the *Imperix* B-Box RCP, which manages real-time execution of control algorithms and communication with external systems.

The controller executes real-time code at 100 µs worst-case latency on a dual-core Cortex-A9 + Kintex-7 FPGA architecture and exposes 16 ADC channels at $2\,\mathrm{MS\,s^{-1}}$. Control firmware is generated automatically from MATLAB/SIMULINK® or PLECS models using the ACG-SDK workflow, allowing cycle-accurate offline–online transitions, parameter sweep testing and FPGA co-processing without manual code edits. PWM signals for the SiC MOSFETs are transmitted via optical fiber links which ensure noise immunity and galvanic isolation, while analog sensor data (including DC bus voltage and output currents) are routed back to the B-Box via shielded RJ45-based Ethernet cabling. On-board protections for over-voltage, over-current, and over-temperature ensure the system's resilience. Besides the on-board ±50 A fluxgate sensor and ±850 V divider provided by each PEB8038 cell, additional DIN-rail ModuLink sensors extend the measurable range to ±50 A with 200 kHz bandwidth and to ±800 V with 100 kHz bandwidth for remote nodes, while preserving 1 kV isolation. Bus voltages and fault injections are emulated by bidirectional laboratory supplies (EA PSI 1000 and Delta SM15K-CP series, 15 kW per unit) that offer auto-ranging up to 1500 V.

C. DC Experimental Building

The *Living Lab Energy Campus* experimental buildings at KIT are part of the Energy Lab infrastructure and are connected to the test microgrid of the SESCL laboratory. The buildings offer a living area of approximately 100 m² and are architecturally identical. They are equipped with a wide range of components that are operated via a SCADA system. Both AC and DC components are available for experimental purposes.

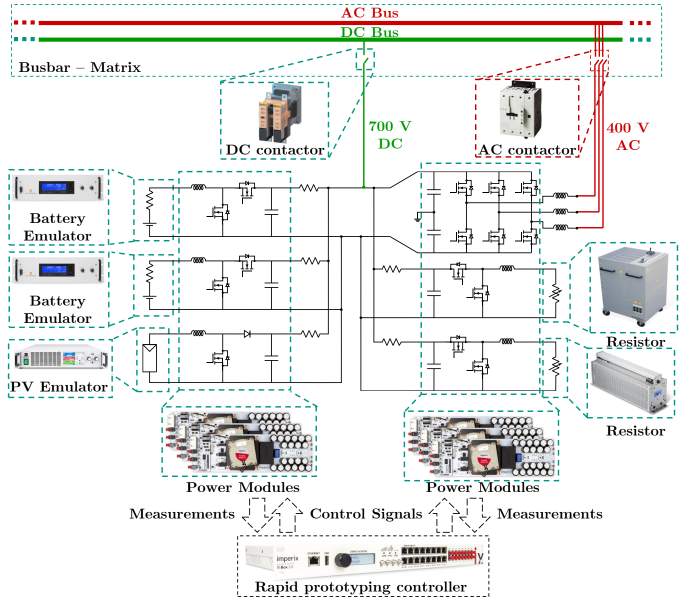

Fig. 4. Example of a modular DC microgrid configuration implemented in the Smart2DC testbed, illustrating key components such as converters, measurement equipment, and control infrastructure.

One building features a modular, flexible DC microgrid that allows for testing of various scenarios. The DC building can also be operated in hybrid mode with the AC grid via an AC/DC converter. Depending on the connected components (e-mobility, induction stove, fuel cell, etc.), the DC microgrid can be configured for voltages ranging from 0 VDC to 700 VDC, with a maximum power of up to 45 kW.

In summary, the buildings enable experiments such as:

- Investigating energy consumption patterns and load profiles.
- Testing demand-side management strategies and energy efficiency measures.
- Evaluating the benefits of direct DC supply in residential applications.
- Direct comparison between a DC and an AC building.

D. Effective DC Fault Interruption Realization

Effective DC fault interruption and protection have long been critical challenges limiting the widespread adoption of DC systems. Among its various research endeavors, this laboratory is dedicated to advancing innovative concepts and methodologies to achieve highly efficient DC fault interruption mechanisms. The main concepts followed can be outlined as follows:

- Development of breaker-less or converter-based fault interruption methodologies through the integration of DC circuit breakers into power converters.
- Developing decentralized fault interruption topologies as alternatives to centralized circuit breaker-based structures.
- Developing bidirectional wide-band gap solid-state DC circuit breakers for improved fault extinguishing speed and capabilities.

IV. Case Studies and Experimental Results

This section presents the experimental validations conducted in the *Smart2DC Microgrid Laboratory*. The studies are selected to demonstrate the breadth of ongoing research – from basic converter-level investigations to whole-microgrid Hardware trials – and to highlight how the lab's modular infrastructure accelerates the transition from simulation to reproducible, real-world validation.

A. Nonlinear Control of DC Microgrids

Isolated Operation in Multi-Terminal DC microgrids: A first series of real-time PHIL experiments evaluated a non-linear, distributed voltage–current controller for a four-node microgrid comprising a 5 kW battery port, a 3 kW PV emulator and two 2 kW programmable loads. In contrast to conventional PI-based cascaded control, the method enables improved transient performance, robust stabilization under model uncertainties, and effective decoupling of local control objectives. The control design considers different functional roles for each subsystem, including battery storage, photovoltaic generation, and DC loads. Experimental validation is conducted using a Power Hardware-in-the-Loop (PHIL) testbed developed in the laboratory. The setup emulates a realistic multi-terminal DC microgrid, including real-time control deployment, physical power converters, and grid-relevant operating scenarios. Results show that the nonlinear controller ensures superior voltage stability, faster convergence after disturbances, and significantly reduced reliance on passive components. These findings are particularly relevant for systems with highly dynamic behavior, such as electric vehicle charging or residential prosumer networks [15].

Extension to Grid-Connected Operation with AC Coupling: Building on the isolated DC microgrid implementation, the nonlinear control framework is extended to support AC grid interaction. A three-phase voltage source converter (VSC) is integrated to enable bidirectional power flow between the DC microgrid and the AC grid. Additionally, the control algorithm is adapted to coordinate two battery systems connected to the same DC bus. PHIL-based experiments in the lab confirm the controller's ability to regulate DC voltage during active and reactive power exchanges with the AC grid. While the extended strategy achieves superior voltage stability under dynamic conditions, a reduced load-sharing accuracy between the batteries is observed, highlighting a practical trade-off in the controller design. The laboratory setup proves essential for assessing such multi-domain interactions and validating control behavior under realistic disturbances and grid-connected scenarios [16].

B. Integration with the Energy Management System (EMS)

Rule-based energy management strategies are implemented and tested in a sector-coupled microgrid within the SESCL [5]. The setup includes PV, wind, battery storage, EV charging, heat pump systems, and the DC microgrid. Using real-time control and the ELLE middleware, scenarios with high and low renewable generation are evaluated.

Results show that central coordination with fast update rates (3 min) reduces grid exchange by over 75 % compared to uncoordinated operation. The experiments also uncover real-world challenges such as EV-induced voltage imbalance and communication failures. The laboratory proves essential for validating EMS strategies under realistic conditions and for identifying implementation-critical behavior [17].

C. Grid-Supportive Loads

A grid-supportive control method for power electronics-interfaced ZIP loads is experimentally validated on a real DC microgrid testbed. The method enables loads to adjust their consumption based on local DC voltage measurements, thereby stabilizing the DC bus without requiring communication or coordination with other components.

Figure 5 illustrates the hardware configuration and control scheme. Experimental results (Figure 6) show that, compared to conventional PI control, the proposed method significantly improves voltage stability and prevents system failure under high load steps. A load recovery mechanism ensures full functionality is restored after support action. The hardware setup plays a key role in testing practical feasibility and validating control performance under real-world conditions [18], [19].

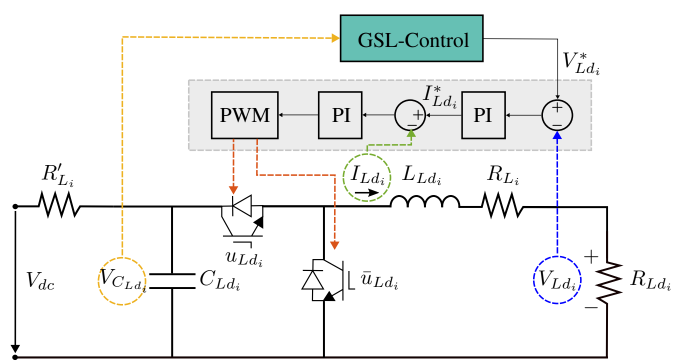

Fig. 5. Control architecture of the Grid Supportive Load (GSL) method, featuring a cascaded PI voltage and current controller. The GSL mechanism modulates load behavior based on local DC voltage to support system stability without external communication [18].

D. L-ADRC-Based Voltage Control for DC/DC Converters

A Linear Active Disturbance Rejection Control (L-ADRC) voltage controller is developed and validated for buck and boost DC/DC converters in low-voltage DC distribution grids.

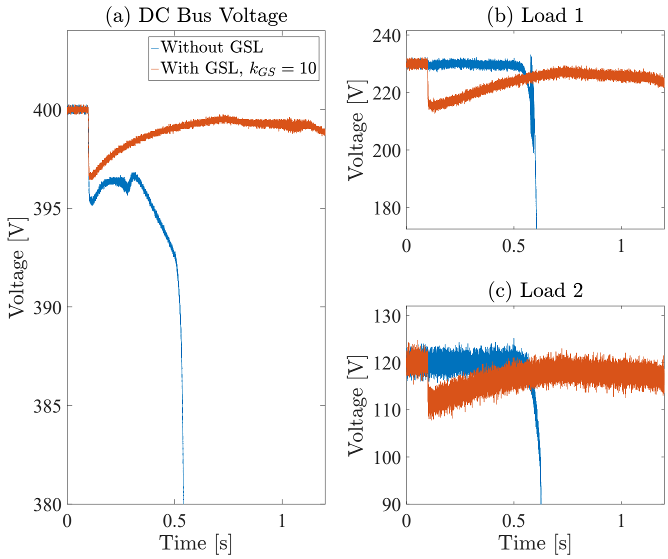

Fig. 6. Experimental comparison of DC microgrid behavior with and without Grid Supportive Load (GSL) activation: (a) DC bus voltage response, (b) voltage profile of Load 1, and (c) voltage profile of Load 2 during a critical load step. GSL operation clearly enhances voltage stability and prevents collapse.

The controller includes an augmented Kalman filter, a linear quadratic regulator, and an adaptive state trajectory generator, enabling robust performance against matched and mismatched disturbances. The approach is experimentally validated using a real-time hardware-in-the-loop (HiL) setup with multiple DC/DC converters operating under grid-forming conditions. The results demonstrate high disturbance rejection capability, stable voltage regulation in both small- and large-signal regimes, and negligible deviation between simulation and HiL tests. The formulation further enables the integration of protection features such as a virtual impedance-based current limiter [20].

V. Conclusion

The *Smart2DC Microgrid Laboratory* at KIT provides a versatile and advanced open platform for research, bridging theoretical concepts and real-world implementations in DC microgrid systems. Its unique features - including a reconfigurable DC busbar matrix, a full-scale DC test building, and integrated real-time simulation capabilities - enable innovative studies on renewable energy integration, energy storage, and next-generation technologies. By complementing global efforts in DC microgrid research, the laboratory stands out with its scalability, adaptability, and focus on interdisciplinary collaboration. It plays a pivotal role in driving sustainable and efficient energy solutions, addressing current challenges, and shaping the future of decentralized power systems.

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