

Real-Time Testing of Microgrid Control Algorithms: Development of Experimental Setup

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Abstract— This paper provides an overview of microgrid control strategies, examining differences between centralized and decentralized approaches, and focusing on classical hierarchical control schemes as well as the structure of three-layer microgrid control systems. It also explores Hardware-in-the-Loop modeling, a crucial approach for microgrid simulation, with particular emphasis on devices supporting microgrid modeling. The paper primarily focuses on the design and implementation requirements of an experimental setup for real-time testing of microgrid control algorithms. The setup incorporates Hardware-in-the-Loop device, a power amplifier, a power converter, a battery energy storage system, and a digital controller. It is specifically designed to handle both power and information (control) signals, facilitating a comprehensive approach to evaluating and validating microgrid control strategies in real-world conditions. A detailed analysis of the setup elements and their interactions is also provided.

I. INTRODUCTION

A microgrid (MG) can be described as a cluster of loads, Distributed Generation (DG) units and Energy Storage Systems (ESSs) operated in coordination to reliably supply electricity, connected to the main grid at a single point of connection, the Point of Common Coupling (PCC) [1]. Control and operation are crucial for the success of MGs, especially due to challenges like managing operation in island mode and power exchange with the main grid [2]. Numerous reviews on MG control are available in the

*This research was supported by Western Balkans Mobility Scheme project ReCMARES – Real-Time Control of Microgrid Assets Incorporating Renewable Energy Sources funded through the grant of the Horizon project POLICY ANSWERS – R&I Policy Making, Implementation, and Support in the Western Balkans. Additionally, parts of the research were supported through the grant of the Horizon project SUNRISE – Setting Up Green Energy Research in Serbia.

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literature, highlighting key challenges and essential functionalities [3-5]. A MG should operate as a single controllable entity, capable of connecting to or disconnecting from the main grid [6]. Modern MG control strategies even facilitate the provision of ancillary services (ASs) to the main grid [7-8].

Real-time (RT) MG control is crucial for ensuring reliable and efficient operation by dynamically balancing supply and demand, maintaining stability during transitions between grid-connected and islanded modes, optimizing the integration of renewable energy sources, and providing ASs to the main grid. Testing MG RT control algorithms requires the development of an experimental setup capable of supporting real-time operations. Several notable papers [9-12] address experimental setups for RT operation and control of MGs. The core concept in all proposed setups is modeling MGs using hardware-in-the-loop (HIL) RT simulation devices. This paper focuses on developing an innovative experimental setup for HIL-based modeling of universal MG real-time operation and control. The setup features real devices, including a digital MG centralized controller (MGCC), a centralized ESS, and a centralized power converter for interfacing with the main grid. The setup is primarily designed to facilitate the implementation and testing of real-time MG control algorithms.

II. OVERVIEW OF MICROGRID CONTROL STRATEGIES

A. Centralized vs Decentralized Control Strategies

Centralized and decentralized strategies represent two opposite approaches to controlling MG. A centralized control strategy primarily relies on a MGCC that coordinates all local controllers (LCs), including those for DGs, ESSs, and loads. In contrast, a decentralized control strategy treats LCs as a Multi-Agent System (MAS). Centralized control strategies are most common in smaller MGs, whereas decentralized approaches are more advantageous for larger MGs. Different control strategies ranging from fully decentralized to fully centralized can be achieved by the classical hierarchical control schemes [2].

B. Classical Hierarchical Microgrid Control Schemes

The three levels of the hierarchical schemes which are

applied in AC microgrids can be classified as [13]: (1) primary control, (2) secondary control, and (3) tertiary control schemes.

The principal task of the primary control scheme is to manage the lower-level control functions, such as voltage/frequency control, active/reactive power control, and device specific functions. It maintains stable voltage and frequency within the acceptable limits [14]. The other major functions of this scheme include: (1) ensuring plug and play operation, and (2) active and reactive power sharing between parallel operating DGs [15].

The secondary control scheme manages core level control functions. Two main core control functions, which supervise the lower-level control functions are: (1) dispatch function, which dispatches individual devices in given operating modes and with specified setpoints, (2) transition function, which supervises the transitions between connected and disconnected states, and ensures the dispatch is appropriate for the given state [6].

The tertiary control scheme oversees higher-level functions, including optimal economic dispatch, participation in electricity markets, and the provision of ASs. It manages power exchange with the main grid by adjusting power references for distributed generators (DGs), energy storage systems (ESSs), and controllable loads [13].

C. Structure of Three-layer Microgrid Control

MG control schemes are typically implemented across the following three control layers within the MG structure [16]:

(1) The bottom layer, local control layer, executes coordination of DGs, charging and discharging control of ESSs, and load control within the MG.

(2) The middle layer is the centralized control layer. It forecasts DG output and load demand, develops operation plans, and adjusts the plans and controls start and stop of DGs, loads, and ESSs in real-time. During grid-connected operation, MGCC prioritizes optimal economic efficiency, while in islanded operation, it maintains stable and secure operation.

(3) The top layer is the distribution network dispatch layer, which coordinates and dispatches MG to maintain security and economy of the distribution network. MG is managed by the distribution system operator (DSO) through the distribution management system (DMS).

Fig. 1 illustrates the three-layer MG control concept applied to the MG model proposed by the EU. The considered MG model was proposed through the joint efforts of ABB, Fraunhofer IWES, and SMA (Germany); ZIV (Spain); The University of Manchester (UK); EMforce (Netherlands); and NTUA (Greece) [16].

The proposed MG model features an open-ring topology, enhancing supply reliability. Customers are connected to the low-voltage (LV) grid through corresponding switchboards (SWBs). Each MG customer can function as a consumer (load), DG, prosumer, or ESS. As a result, MG assets may vary depending on the specific case studies being considered. The MG is connected to the main distribution grid through an

MV/LV substation, with the LV busbars serving as PCC. The active and reactive power flows between the MG and the main distribution grid can be bidirectional.

For normal and reliable operation, the MG requires effective control and protection systems. The protection system is out of the scope of this paper. The control system follows a hierarchical scheme and is structured into three layers.

LCs manage DGs, loads, and other MG assets, forming the local control layer. They are connected to the MGCC through a bidirectional communication system, represented by blue lines in Fig. 1. The switches in the SWBs are controlled by SWB local controllers (SWB LCs), which also communicate with the MGCC. The MGCC coordinates LCs and SWB LCs, forming the centralized control layer. It is typically located in the MV/LV substation to facilitate easier connection and communication with the DMS. DMS coordinates the MGCC and constitutes the distribution network dispatch layer. The software implemented in the MGCC operates based on real-time control algorithms for managing the MG. All management functions together form the microgrid energy management system (MG EMS).

III. HARDWARE-IN-THE-LOOP MODELING FOR MICROGRIDS

Inverter-based DERs and their control systems require comprehensive testing methods that evaluate not only the hardware components and related controllers but also their integration into the grid to ensure optimal performance and development [18], [20]. HIL, a robust testing methodology that has been extensively employed in testing applications, enables the interface of external devices to a RT simulation running on a digital RT simulator (RTS) to enhance the consistency of the outcomes and facilitate secure, reliable, and economical testing of controller patterns and devices. HIL systems allow high fidelity experimental validation by modeling the electrical supply system on an RTS and then integrating that simulation with the real hardware. By connecting actual devices to modeling, users can describe the behavior of the device as well as its effect on the system, creating a closed loop [17].

There are two distinct HIL arrangements: controller hardware-in-the-loop (CHIL) and power hardware-in-the-loop (PHIL). Platforms for MG RT testing typically integrate both CHIL and PHIL. Advanced controls for wind, photovoltaics (PV), ESS, MGs, and cybersecurity are examples of CHIL testing and implementation for grid integration. While CHIL testing usually uses low voltage/current signal connections, PHIL has made it possible to connect hardware at full capacity with real-time electrical system simulation [18-19].

A. Overview of HIL Devices Supporting Microgrid Modeling

RT MG modeling requires HIL devices like OPAL-RT, RTDS, and Typhoon HIL, which allow system testing and validation in a secure setting.

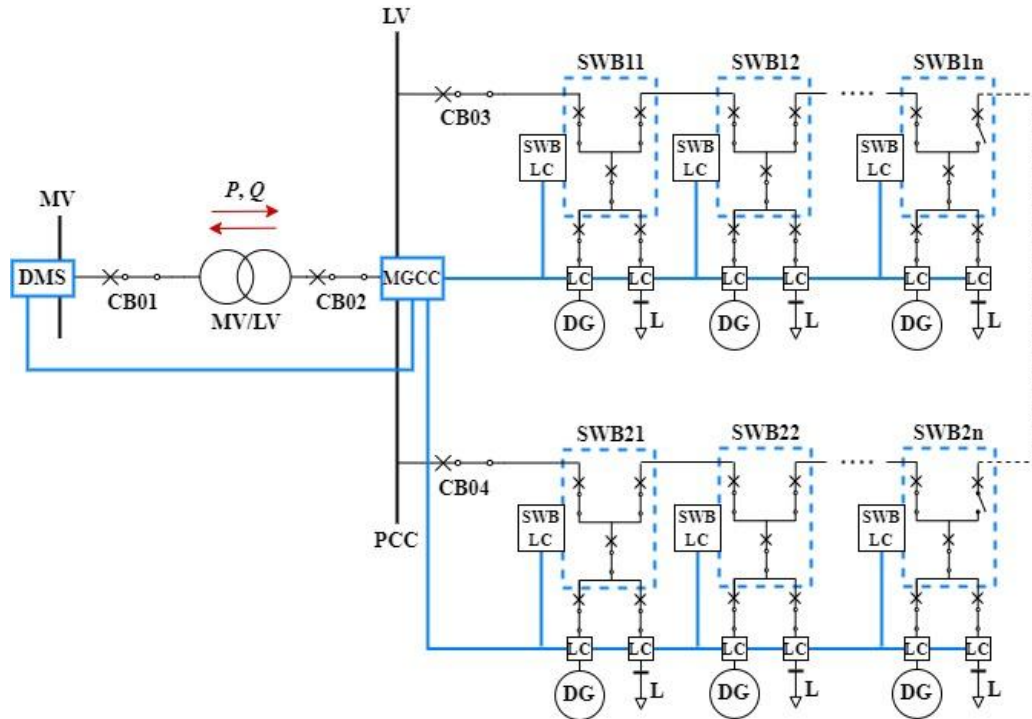


Figure 1. Three-layer MG control concept applied to the MG model proposed by the EU

OPAL-RT is excellent for power electronics and hybrid systems because of its great versatility and compatibility with programs like MATLAB. With its powerful RSCAD software, RTDS is excellent at grid-level protection and stability studies, but its third-party compatibility is restricted [21-22]. Typhoon HIL is a user-friendly, reasonably priced platform that specializes in power electronics and fast-switching devices; nevertheless, it is less scalable for intricate grids [23]. Project requirements, such as complexity, simulation accuracy, and money, will determine the decision as shown in Table I [18], [21-22], [23-24].

IV. EXPERIMENTAL SETUP FOR TESTING MICROGRID CONTROL ALGORITHMS

To validate the operation of RT MG control algorithms, it is essential to develop a specialized experimental setup that supports RT operation. The setup should be designed as a universal platform capable of modeling a variety of MG configurations and assets. HIL devices enable both RT simulation and versatility in modeling MG configurations and assets. As a result, they are a crucial enabler and an indispensable component of modern experimental setups for testing MG control algorithms.

TABLE I
FEATURES OF HIL DEVICES FOR MODELING OF MGS

<i>Features</i>	<i>OPAL-RT</i>	<i>RTDS</i>	<i>Typhoon HIL</i>
Focus Area	HIL (PHIL and CHIL), EMT, RCP	Stability, protection, grid integration	Power electronics (MGs, HIL)
Software	MATLAB	RSCAD	HIL SCADA
MG Scalability	High	Medium	Limited
Ease of use	Medium	Medium	High
Hardware support	FPGA+CPU	Proprietary DSPs	Proprietary DSPs
PHIL support	Good	Good	Limited
RE integration	High (detailed, flexible)	Moderate (grid- tied focus)	High (inverter-based focus)
Control algorithm testing	Extensive support for advanced controls (fast response)	Medium respond (basic control schemes)	Excellent (real-time, low latency (fast response))
Best for	Flexible research, EMT modeling	HVDC, Grid protection	MGs, Power electronics
Cost	Expensive	Very expensive	Not expensive

A. Experimental Setup Diagram

The diagram of the proposed experimental setup for testing MG RT control algorithms is presented in Fig. 2. The proposed experimental setup includes the following elements:

(1) OPAL-RT OP4610XG simulator implementing a universal MG model.

(2) REGATRON 20 kVA power amplifier generates power signals controlled by information signals from the OP4610XG simulator.

(3) General-purpose power converter prototype with back-to-back configuration composed of two voltage source converters (VSCs) sharing a common DC bus. The prototype was developed by researchers at the University of Seville, and it offers flexibility and efficiency in controlling power flow between two AC systems, in this case, between the experimental setup and the LV distribution grid.

(4) PYLONTECH Force-H2-V2 high voltage battery storage system functions as the ESS in the experimental setup, representing the centralized ESS for the MG.

(5) SIEMENS SICAM A8000 universal digital controller acts as the MGCC, coordinating the operation of all other experimental setup components. It also enables the software implementation of real-time MG control algorithms. OP4610XG was tested to validate its CPU performance, confirming that the model can run without overruns while maintaining functional inputs and outputs at a minimum step size of 8 μ s. The testing was performed with MATLAB R2021b and RT-LAB version 2024.1.1.38.

The experimental setup is designed to manage both information and power signals, enabling the implementation and testing of various MG power, automation, and communication systems. The RT operation of a MG with various assets and configurations can be modeled using the OP4610XG simulator. The output information signals from the OP4610XG, simulating power signals at the PCC, are

converted into corresponding real power signals by the REGATRON power amplifier. Acting as a four-quadrant AC power source, the amplifier enables the MG model to function either as an AC power source or a load. The general-purpose power converter prototype allows flexible and efficient control of power flow between the experimental setup and the LV distribution grid, enabling the MG model to exchange power with the real LV distribution grid. Force-H2-V2 EES enables efficient energy storage for the MG model, optimizing the use of intermittent renewable energy sources. Additionally, it provides rapid response for voltage and frequency regulation within the MG model. The SICAM A8000 universal digital controller can be used to implement a real MGCC. It is designed to manage the assets of the MG model, regulate the operation of the prototype power converter, and control the charging and discharging of the ESS. The controller must support bidirectional communication with LCs, such as those for the ESS and power converter, as well as with the DMS.

B. Experimental Setup Elements

(1) OPAL-RT OP4610XG simulator

OP4610XG is a complete simulation system operating with a Kintex7 Field-Programmable Gate Array (FPGA). It contains a powerful Target Computer and a flexible, high-speed Front-End Processor and a signal conditioning stage. Target Computer includes the features listed in Table II [26].

OP4610XG was tested to validate its CPU performance, confirming that the model can run without overruns while maintaining functional inputs and outputs at a minimum step size of 8 μ s. The testing was performed with MATLAB R2021b and RT-LAB version 2024.1.1.38.

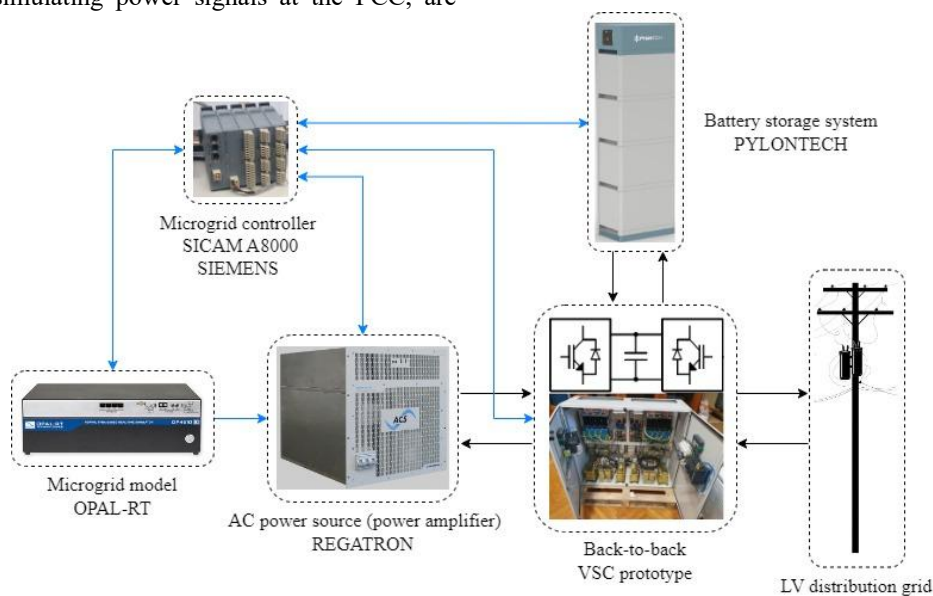


Figure 2. Experimental setup for testing MG RT control algorithm

TABLE II
LIST OF FEATURES OF TARGET COMPUTER

<i>Items</i>	<i>Description</i>
Operating system	OPAL-RTLinux 3.5.4
CPU	AMD Ryzen 5 3600XT, 6-Core, 3.8 GHz
Memory	8 GB
Motherboard	X570D4U-2L2T AsRock uATX Server Motherboard
AC input	100-240 V, 60-50 Hz
AC output	± 16 V

(2) REGATRON TC.ACS 20 kVA power amplifier

The TC.ACS Regenerative Grid Simulator allows for all relevant testing according to the grid-feed-in regulations (CENELEC, DIN, IEC). It supports Source Mode and Sink Mode. Here the sign of the power determines the direction of the energy flow, and thus which of the two modes is active. The main features of TC.ACS are listed in Table III [29].

TABLE III
LIST OF FEATURES OF TC.ACS 20 kVA POWER AMPLIFIER

<i>Items</i>	<i>Description</i>
Power	0-20 kVA
Power direction	programmable 4-quadrant
Voltage range	3 x 0-305 VACrms (L-N)
Current range	3 x 0-43 AACrms / 1 x 0-86 AACrms

The TC.ACS operates in conjunction with a fast-discharge AC filter (XCD) and a liquid-to-air heat exchanger (TC.LAE). It is controlled and programmed using the application software ACSControl 2.8. TC.ACS can communicate with an OPAL-RT device, typically through a communication interface that supports the transfer of control and simulation data between the systems.

(3) Power converter prototype – back-to-back VSCs

The power converter prototype is implemented as a three-phase AC/DC/AC converter in a back-to-back configuration. With an appropriate control strategy, it enables output voltage regulation (maintaining stable output voltage despite input variations), frequency control (precisely regulating output frequency independent of input frequency), and power factor improvement (allowing control of active and reactive power through bidirectional power flow) [25]. These functions are critical in microgrids, where diverse sources (particularly renewables) and loads are common [27]. For the experimental setup, this power converter topology satisfies all the requirements: grid connection, bidirectional power flow, and the implementation of various control algorithms for microgrid optimization. The main electrical parameters of power converter prototype are listed below:

- Rated power: 20 kVA; Rated frequency: 50 Hz

- Rate voltage: 400 V; Rated current: 40 A
- Rated switching frequency: 10 kHz
- Rated DC voltage: 730 V
- Rated DC bus capacity: 2200 μ F

(4) PYLONTECH Force-H2-V2 ESS

The battery ESS (BESS) planned to be used in the setup is the Force-H2-V2, a lithium iron phosphate battery developed and manufactured by PYLONTECH. This BESS supports parallel operation of multiple strings, offering significant flexibility in system design and configuration. The Force-H2-V2 is particularly well-suited for applications requiring high power output, compact installation, restricted load-bearing capacity, and a long cycle life. The system has a rated capacity of 37 Ah and can be expanded to include up to four modules. The experimental setup is designed to utilize all four modules of BESS. The main electrical parameters of Force-H2-V2 are listed below [28]:

- Battery module capacity: 37 Ah, 3.55 kWh
- Battery module voltage: 96 Vdc
- Battery System Charge Upper Voltage: 432 Vdc
- Battery System Discharge Lower Voltage: 730 V
- Efficiency: 96 %; Depth of Discharge: 95 %.

(5) SIEMENS SICAM A8000 digital controller

The SICAM A8000 CP-802x is a versatile platform capable of implementing a wide range of applications, including telecontrol and automation solutions, tailored to specific requirements. It is universally deployable and particularly well-suited for electrical distribution substations. Given its primary application in Local Network Control (LNC), it serves as an effective solution for implementing MGCC.

CP-802x supports both multi-point communications (via the RS-232 or RS-485 interface for joint traffic transmission) and LAN/WAN communications using Ethernet TCP/IP [30]. One of its notable features is the integrated web server, which enables engineering, diagnostics, and testing via a web browser using the SICAM WEB application. The basic system of CP-802x consists of the following components: Master Module and external Power Supply Module. The basic system can be expanded, as needed, with up to 4 optional protocol elements for communication with higher-level automation units or a control center, such as a DMS, and up to 8 external I/O modules for interfacing with field processes, such as LCs.

V. CONCLUSION

The main contributions of this paper include the proposal of a novel HIL-based experimental setup for testing MG RT control algorithms, a comparative analysis of three commercial HIL devices supporting MG modeling, and a theoretical overview of MG control strategies. Additionally, the fundamental features of all key elements of the experimental setup are analyzed. The proposed HIL-based

experimental setup allows for the simulation of various MG configurations and assets while facilitating direct connection to the LV grid, making it an effective platform for testing and validating MG control algorithms under real-world operating conditions. By bridging the gap between simulation and real-world applications, the setup offers flexibility and scalability for a wide range of MG scenarios. Upon completion, the proposed experimental setup will offer possibilities not only for advanced research studies but also for standard-based compliance testing of industry MG controllers.

ACKNOWLEDGMENT

This research was supported by Western Balkans Mobility Scheme project *ReCMARES – Real-Time Control of Microgrid Assets Incorporating Renewable Energy Sources* funded through the grant of the Horizon project *POLICY ANSWERS – R&I Policy Making, Implementation, and Support in the Western Balkans*. Additionally, parts of the research were supported through the grant of the Horizon project *SUNRISE – Setting Up Green Energy Research in Serbia*.

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