HackuLoop - An open-science project to create open-source real-time Hardware-In-The-Loop micro-grid systems

Luiz VILLA, Amalie ALCHAMI, Arnaud Gaillard, Pierre Haessig, Mathieu Rossi, Jean Alinei, Clement Foucher
Université de Toulouse, LAAS-CNRS, Université de Technologie de Compiègne, Université de Technologie de Belfort-Montbéliard
FEMTO-ST,CentraleSupélec, IETR, Université d'Artois, LSEE, OwnTech Technologies

RÉSUMÉ

This article documents the results of a hackathon focused on developing grid-forming and grid-following inverters. The event highlighted innovation and collaboration in the field of power electronics. This document provides an overview of the objectives, methodologies, and outcomes of the hackathon, along with lessons learned and future directions.

Mots-clés – Power converters, Hackathons, reproducible science.

1. INTRODUCTION

Real-time systems are crucial for testing and operating micro-grids effectively, as they enable accurate simulation and control of complex power dynamics. However, many available systems function as black boxes, presenting significant challenges when fine-tuning them for specific experimental setups. This limitation often hinders research progress and adaptability to new scenarios.

In response to this challenge, the HackuLoop project was initiated during a hackathon held at the JCGE conference in 2024. The project's primary aim is to provide modular building blocks for creating customizable and open-source simulation environments tailored to micro-grid applications. These blocks aim to bridge the gap between rigid proprietary solutions and the dynamic needs of research and experimentation.

This paper is organized as follows :

In Section 2, we introduce the HackuLoop project in detail, its building blocks, and development objectives. Section 3 presents the kick-off hackathon that took place during jthe JCGE conference hackathon. Section 4 covers the first hackathon of the project, focused on the inverter control block. In Section 5, we present the open-science contributions of this work, including links to the Git repository and licensing information. Finally, Section 6 concludes the paper and outlines directions for future developments of the HackuLoop platform.

2. PROJECT OVERVIEW AND DEVELOPMENT OBJECTIVES

The HackuLoop project is a nation-wide open-science initiative aiming to develop and disseminate open-source building blocks for real-time Hardware-In-the-Loop (HIL) simulation of micro-grids. Initiated at the JCGE 2024 hackathon, the project has since evolved into a coordinated effort among five French laboratories, each contributing to a specific domain of energy systems.

The key objectives of the HackuLoop project are to :

— Promote open-science practices through reproducible and interoperable experimental models ;
— Develop digital twins for power systems, focusing on micro-grids, storage systems, and converter durability ;
— Facilitate community-driven tool development through thematic hackathons and shared repositories ;
— Foster collaboration and knowledge exchange across the French power electronics research community.

Each partner laboratory leads the development of a specific simulation or control model, as listed in Table 1.

TABLEAU 1. HackuLoop Thematic Sessions and Hosting Institutions

No.	Theme	Laboratory - City
1	Object-Oriented Inverter	LAAS-CNRS
2	Grid-Connected Inverter	IETR - CentraleSupélec
3	Hydrogen Converter	FEMTO-ST - Belfort
4	Motor Control	LSEE - Artois
5	Micro-grid Management	AVENUES - Compiègne

Each Hackathon results in the publication of models, source code, and documentation in its open repository [1] under the GPLv3 license. The long-term vision of HackuLoop is to assemble these modular components into robust, reference-grade HIL demonstrators that can be used across academia and industry.

The remainder of this paper focuses on the JCGE 2024 kickoff hackathon and presents the first functional module developed under this initiative : the control of a single-phase inverter capable of both grid-forming and grid-following operation.

3. KICK-OFF : JCGE 2024 HACKATHON

During the JCGE 2024 hackathon session, participants successfully implemented an example that integrates a PLECS simulation with a real power converter board for a PV system [2]. The setup is shown in figure 1, where the data goes from the PLECS model through the USB down to the micro-controller of the power converter.

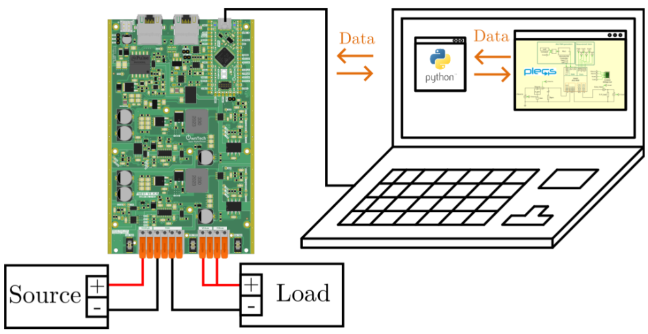

FIG. 1. Objective of the first Hackathon : connect a model to a power converter.

Figure 2 shows the model used in the first hackathon. The power board circuit, shown in the green dashed line, will behave as a voltage source in parallel with a current source, both connected to a resistor. The PLECS model shown on the right will behave as a PV model driven by a certain irradiance.

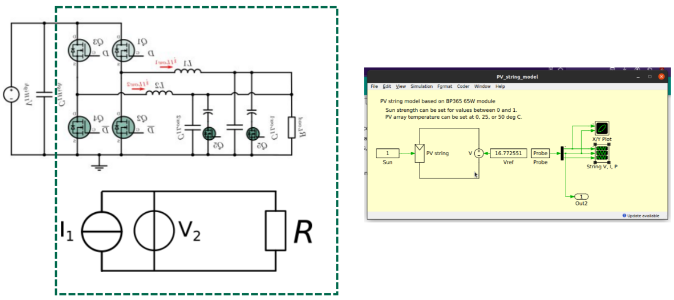

FIG. 2. Detail of the model used on the first hackathon.

The emulator was implemented in a sequence of steps, shown from top to bottom in Figure 4.

- **Step 1** : LEG1 sends I1 to the resistor.
- **Step 2** :LEG2 sets V2 and by consequences VR to a certain value.
- **Step 3** :LEG1 measures V1.
- **Step 4** :V1 is sent to the plecs model to trigger a simulation.
- **Step 5** :I1 is sent to LEG1
- **Step 6** :The loop starts again.

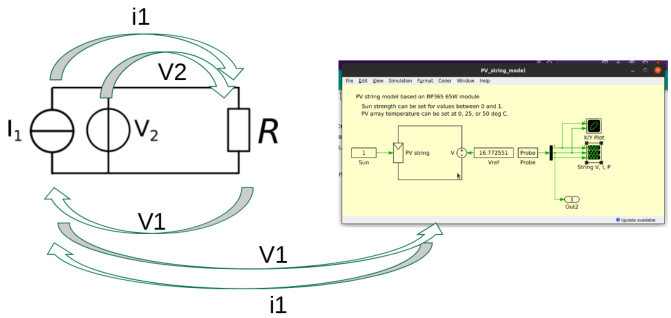

FIG. 3. Steps in the resolution of the system from top to bottom.

The emulator was validated experimentally using the setup below. While not real-time it showed the possibility of coupling the hardware with the model on a loop.

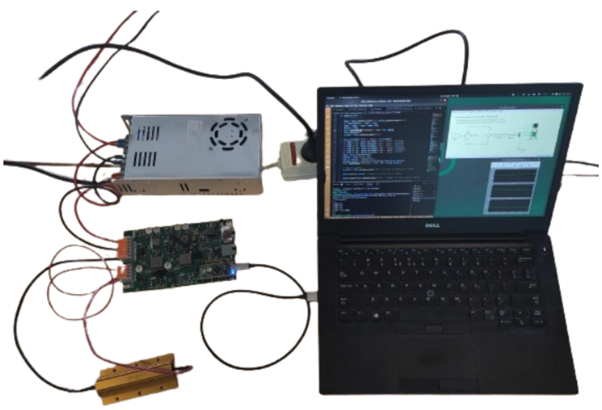
FIG. 4. The hardware setup that validated the emulator.

4. HACKATHON 1 : OBJECT ORIENTED INVERTER

In the first hackathon, we developed the C++ class that allowed deploying an inverter. This block is key to creating a full micro-grid on the long term, and its sub-blocks can be used in all other hackathons of the project.

There are two types of grid connected inverters : grid-forming and grid-following. The grid forming inverter will handle the frequecy of the grid as a voltage source inverter, while the grid following will operate as a current source that is synchronized to the grid voltage. Their control structures are very similar, meaning that the same base blocks can be used in both algorithms. Figures 5 and 6 show the blocks in detail.

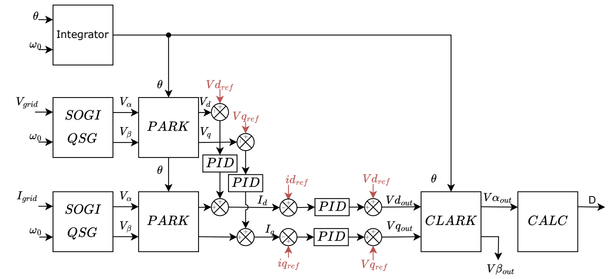

FIG. 5. Control structure for grid-forming inverter (based on [4]).

Grid-following inverter incorporates a PID-based PLL (Phase Locked Loop) that locks onto the V_q component of the SOGI and Park-transformed signal. This allows the system to synchronize seamlessly with the external grid.

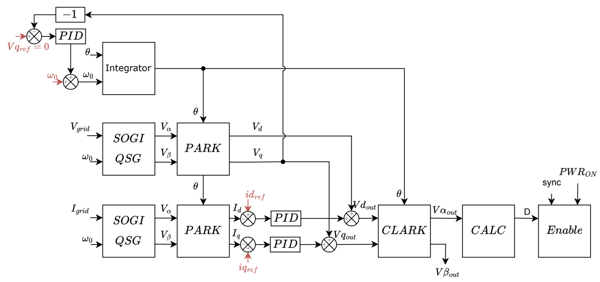

FIG. 6. Control structure for grid-following inverter (based on [5]).

The sub-blocks of both inverters are :

- SOGI[3] (Second Order Generalized Integrator) blocks : These processes the single-phase sine wave input to generate an $\alpha - \beta$ representation.
- PARK block : transforms the $\alpha - \beta$ into a d-q frame using a classic Park transformation, allowing control in the d-q domain.
- CLARK block : transforms the system back to $\alpha - \beta$, where the α signal is utilized to generate the duty cycle for the inverter.
- PID block : a generic PID controller that can be spawned and calibrated to the specific part of the control loop.

The grid-forming inverter control structure employs a straightforward d-q control loop without additional synchronization components. The grid-following inverter control structure uses the Vq resulting from the SOGI + PARK transform to trigger a PLL via the PID to synchronize with the grid forming inverter.

The team used two TWIST boards [6] from the OwnTech Foundation to fast prototype a micro-grid.

The wiring diagram of the two boards is shown in figure 7 and the equivalent circuit is shown in figure 8.

The callibration of the PIDs was done using the method in [7]. The current loop was first implemented, followed by the voltage loop. The parameters were first defined based on the size of the resistor (10Ω) for the grid forming inverter. It was then updated to the grid following inverter.

The grid forming converter is able to create a sinusoidal voltage on the output as shown in figure 9. However, this voltage

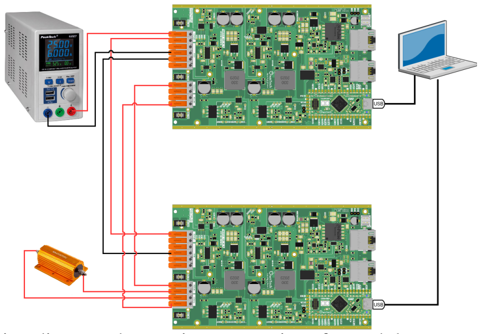

FIG. 7. Wiring diagram showcasing connections for each leg.

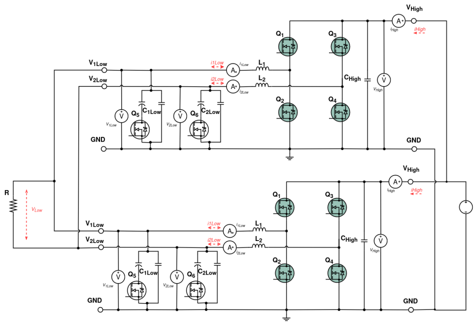

FIG. 8. Circuit diagram with both inverters connected to the same load.

has an important third and fifth harmonic content, which can be improved in future implementations.

FIG. 9. View of the current measurement of the grid forming board.

The grid following converter is able to synchronize and connect with the grid forming converter. However, it introduces a great amount of circulating currents, as seen by the harmonic content of the current measurements in both boards. The sum of the currents viewed by the output load is sinusoidal with a smaller harmonic content as seen in figure 9.

There was a point of operation that minimized this circulating currents, as seen in figure 11.

5. OPEN SCIENCE CONTRIBUTIONS AND REPOSITORIES

A core objective of the HackuLoop initiative is to ensure full transparency, reproducibility, and accessibility of its research outputs. To this end, all developed models, source code, schematics, and experimental results are shared under open-source licenses.

The complete implementation of the emulator developed during the JCGE 2024 hackathon is available at `https://github.com/owntech-foundation/examples/tree/main/TWIST/Hardware-in-the-loop/PV_emulator`

This repository includes :

FIG. 10. View of the current measurement of the grid forming (red) and following boards (green).

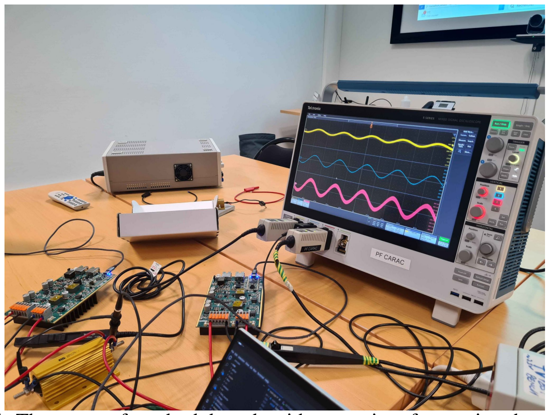

FIG. 11. The current from both boards with one point of operation that minimizes circulating currents

- Real-time control firmware for the TWIST board ;
- PLECS simulation model for PV emulator operation ;
- Wiring schematics and configuration files ;
- Documentation to reproduce the demonstration setup.

The central repository for the HackuLoop project aggregates documentation, and results from each hackathon : `https://github.com/owntech-foundation/HackuLoop`

It serves as the coordination hub for :

- Ongoing and past hackathon sessions ;
- Shared tools and libraries used across teams ;
- Datasets and benchmarks collected during experiments ;
- Roadmap and future planning of the HackuLoop initiative.

6. DISCUSSION AND PERSPECTIVES

The initial results obtained during the JCGE 2024 hackathon validate the relevance and feasibility of the HackuLoop approach through a simple emulator. The control blocks needed to create a grid-forming and grid-following inverter illustrates the potential for creating modular, reproducible code that can be adapted and reused across different hackathon sessions.

Several challenges remain to be addressed in the next stages of the project :

- **Real-time Co-Simulation :** Ensuring deterministic execution when combining software-based simulations (e.g., PLECS) with physical hardware in real-time. This will require synchronization mechanisms and low-latency communication.
- **Hardware Abstraction and Portability :** As more teams contribute to HackuLoop, achieving interoperability across various platforms will require robust abstraction layers. Future efforts may involve integrating support for fast-prototyping platforms such as Raspberry Pi 5 or NVIDIA Jetson Nano, with attention to real-time Linux

extensions or $PREEMPT_RT$ kernels.

- **Timing and Latency Constraints :** While TWIST demonstrated sufficient performance at 10 kHz, introducing more complex plant models or distributed nodes will increase computational demands. Profiling and optimizing scheduling will be necessary to maintain responsiveness.
- **Collaborative Development at Scale :** As the number of hackathons and partners grows, managing and maintaining repositories, documentation, and issue tracking will become critical. Establishing contributor guidelines and automated testing pipelines (e.g., via GitHub Actions) will support sustainable development.

Finally, as more building blocks (e.g., for hydrogen systems, storage, machine control) are implemented, the challenge will shift towards the integration and validation of full micro-grid systems. These composite setups will demand coherent interface specifications and multi-rate coordination mechanisms, reinforcing the need for open standards and cross-institutional benchmarking.

7. CONCLUSION

This paper shows how Hackathons can be a tool for creating reproducible hardware implementations that can drive collaboration and research among scientific peers. In this work, the grid-forming and grid-following building block of a series of Hackathons on micro-grids was presented, with its main structure and results. The final paper will include a more thorough discussion on the impact of the points of operation on the circulating currents and share the online repository with all the source code of this implementation.

8. REFERENCES

[1] https ://github.com/owntech-foundation/HackuLoop - accessed 11/06/2025

[2] https ://github.com/owntech-foundation/examples/tree/main/TWIST/Hardware-in-the-loop/PV$_emulator-accessed 11/06/2025 Yepes, Alejandro. (2011). Digital Resonant Current Controllers for Voltage Source Converters.$

[3][4] H. Zhang, W. Xiang, W. Lin and J. Wen, “Grid Forming Converters in Renewable Energy Sources Dominated Power Grid : Control Strategy, Stability, Application, and Challenges,” in Journal of Modern Power Systems and Clean Energy, Nov. 2021.

[5] https ://imperix.com/doc/implementation/grid-following-inverter - accessed 11/02/2025

[6] https ://github.com/owntech-foundation/TWIST - accessed 11/02/2025

[7] Skogestad, S., 2001, November. Probably the best simple PID tuning rules in the world. In AIChE Annual Meeting, Reno, Nevada (Vol. 77, p. 276h). Citeseer.