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AGISTIN
Advanced Grid Interfaces for innovative STorage INtegration

D4.2: Validation process, results and lessons learned

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Introduction

The increasing integration of renewable energy sources and the electrification of industrial processes are driving significant changes in power system operation and stability. As the share of inverter-based resources grows, maintaining grid reliability and flexibility becomes more challenging, especially in low-inertia environments. Advanced energy storage technologies and innovative grid interface solutions are essential to address these challenges and enable the rapid deployment of renewables in industrial settings.

This report presents the validation process, results, and lessons learned from the AGISTIN project, which aims to develop and demonstrate advanced storage integration concepts for industrial grid users. The project focuses on the development of novel energy storage technologies, such as aqueous batteries and the use of irrigation systems for energy storage, as well as the implementation of advanced grid interface designs. These solutions are tested in realistic laboratory environments, including the Fraunhofer Sandbox, to ensure their effectiveness in providing grid services, supporting grid stability, and reducing the cost and impact of new industrial loads.

The following sections detail the technical approaches, experimental setups, and validation activities carried out within the project. Key findings and insights are discussed to inform future developments and support the broader adoption of innovative storage and grid interface technologies in industrial applications.

1 Geyser Aqueous Battery

1.1 Introduction and operating principles

Within the AGISTIN project, the consortium relies on Geyser Batteries to develop and demonstrate its proprietary aqueous battery technology. This innovative solution is designed to address the stability gaps of modern, low-inertia power systems by providing impactful bursts of power and energy to the grid while maintaining a small operational footprint.

The Geyser battery utilizes a unique water-based electrochemistry and carbon-based electrodes built into a bipolar cell design. Unlike standard hybrid supercapacitors, the electrochemical reactions in the Geyser battery occur on both the cathode and the anode sides of the cell.

Fundamentally, the technology is uniquely capable of storing energy both electrostatically and electrochemically. Because the chemical reactions occur near the surfaces of the electrodes without causing mechanical stress, electrode degradation is exceptionally slow. By combining the rapid response of an Electric Double Layer Capacitor (EDLC) with a longer sustained energy delivery through Faradaic reactions the system is engineered to endure complex cycling patterns including hundreds of thousands of high-power charge-discharge events. [1]

1.2 Technology positioning and key advantages

While lithium-ion batteries possess higher overall energy density, Geyser's aqueous battery is engineered to bridge the gap between these high-energy storage systems and high-power supercapacitors. The technology is versatile, allowing its performance to be tailored to specific application needs. Depending on the system configuration and operational mode, it can be optimized to offer up to a five-fold increase in energy capacity compared to standard supercapacitors. It can also be geared to deliver cyclic peak specific power comparable to them. Furthermore, unlike conventional high-energy batteries, the Geyser system is capable of undergoing extremely rapid charge and discharge cycles, making it highly effective where high power bursts are needed.

The Geyser's battery technology also offers significant safety benefits. By replacing the organic solvents and toxic materials found in most competing systems with a water-based electrolyte, the technology is inherently fire-safe. This non-flammable chemistry completely removes the risk of thermal runaway. On top of that, the modules exhibit excellent thermal stability, meaning they do not require active cooling even when subjected to intense electrical stress.

From a sustainability perspective, the battery does not contain critical raw materials and is based largely on widely available, European Union-sourced materials. The technology requires no energy-intensive dry or clean rooms, which reduces both capital expenditure and carbon intensity. Geyser's Generation 1 cells have already achieved up to a 74% reduction in their carbon footprint compared to competing technologies. Furthermore, the bipolar design and safe electrolyte ensure a highly streamlined and exact recycling process for all cell components at the end of life.

1.3 Battery development

The progression of the Geyser battery technology within the AGISTIN project work package 4 (WP4) followed a scale-up process designed to ensure stability and performance at every integration level. The development journey began with the fundamental approval and validation of the baseline cell design. Once the core electrochemical architecture was validated, the focus shifted to production and strict batch testing to guarantee uniform quality and performance across all manufactured cells. Following batch approval, these individual cells were integrated for cellblock design validation, allowing the engineering team to confirm mechanical stability and electrical connectivity at a localized scale. Upon successful validation, these blocks were assembled into larger vertical subunits, where early in-house testing verified the baseline electrical and thermal behavior prior to full-scale module assembly shown in figure 1. It is noteworthy that the entire manufacturing and assembly process, from individual cells to the final module comprising hundreds of cells was largely manual. While manual assembly inherently introduces higher probability of variations between individual components compared to automated production lines, the successful construction of fully functional, high performance module demonstrates the robust tolerance of underlying design and the effectiveness of the team's quality control measures.

Figure 1.1 – (Left) Geyser Batteries Cells. (Middle) Vertical Sub-units for Modular Assembly. (Right) Assembled Module being Tested at Fraunhofer IEE.

For the AGISTIN grid-forming tests, Geyser Batteries developed a 400 V class battery system specifically to match the DC interface requirements of the Fraunhofer IEE grid-forming inverter test platform, while operating in a standard 400 V, 50 Hz AC environment. The delivered system was a high-voltage stack with a 440-volt nominal capability, chosen to sit comfortably inside the inverter's usable battery voltage window and to ensure stable operation during aggressive, fast transients. A key design decision was to prioritize power response and controllability over bulk energy, because the AGISTIN scenarios are built to validate fast dynamic behavior and grid events rather than long-duration cycling.

The architecture used 768 cells arranged as three parallel strings of 256 series cells, providing both the voltage level needed by the inverter and sufficient current capability for short, high-power activations. While a single string of 256 cells in series provided the 440-volt operating level required by the inverter, the decision to parallel three strings was a deliberate engineering choice to cut the system's Equivalent Series Resistance. By minimizing this resistance, the battery reduces internal voltage drops during severe high-current transients. Mechanically and electrically, the module was implemented as a compact, serviceable assembly using robust terminal structures and a modular layout that supports repeatable assembly, monitoring, and test handling.

The Geyser battery module utilized in this testing was originally designed and optimized specifically for grid-forming inverter applications, focusing strictly on delivering the instantaneous power bursts required for sub-cycle grid stabilization. However, once highly stable performance of the subunits was observed in these high-stress regimes, the testing scope was expanded to also subject the module to continuous Frequency Containment Reserve for Normal Operation (FCR-N) market profiles and an islanded energy management scenario. During these expanded validations, the battery demonstrated its ability to handle longer, continuous, and highly volatile activations that would typically accelerate heating and degradation in conventional battery systems.

The system maintained real-time tracking of the power load curve while operating within a controlled voltage envelope of approximately 220 to 440 volts. Despite the intense continuous cycling and peak current pulses of up to 200 amperes, the module exhibited exceptionally low heat generation. Operating at an ambient laboratory temperature of 16 degrees Celsius, the module maintained a comfortable thermal envelope between 15.8 and 25.8 degrees Celsius, averaging 20.3 degrees Celsius throughout the testing without active cooling. This thermal stability comes on top of the baseline safety profile of Geyser’s water-based electrolyte.

1.4 Validation and testing activities

The primary objective and core focus of the testing phase at the Fraunhofer IEE laboratory was to evaluate the Geyser battery in a high-voltage grid-forming environment. To verify performance under complex grid conditions, several test scenarios were executed. High-fidelity grid-forming load profiles developed by Fraunhofer IEE were utilized to test sub-cycle dynamic responses to step changes in phase, frequency, and voltage amplitude. These profiles emulate some of the most critical stressors of a low-inertia grid. During these events, the battery stabilizes the system through rapid active and reactive power injection or absorption, resulting in power spikes. Despite their short duration, these spikes involve high currents, demonstrating the battery’s ability to maintain synchronization and provide critical support under extreme grid conditions.

Three scenarios of AC grid events were considered according to the defined Use cases from Deliverable 4.1 and listed in Table 1.1. Scenario 1 covers different phase jumps. Scenario 2 addresses RoCof scenarions in addition to the phase steps. Scenario 3 covers jumps in the voltage amplitude.

The grid-forming control provides inertia according to its P(f) and Q(U) characteristic. For phase and frequency changes, mainly the active power is affected. Hence, there can be noticed significant changes in the battery voltage. For voltage amplitude changes, mainly reactive power is provided what does not need any power from the battery.

Table 1.1 – Grid event scenarios

Scenario 1		Scenario 2			Scenario 3	
Time [s]	$\Delta\varphi$ [deg]	Time [s]	$\Delta\varphi$ [deg]	Freq [Hz]	Time [s]	Voltage amplitude [p.u.]
0	0	0	0	50	0	1
2	-10	2	-30	50	2	0.95
4	-40	2.5	-30	51	4	1
6	-30	5	0	51	6	0.9
8	0	5.5	0	50	8	1
		8	30	50	10	1.05
		8.5	30	49	12	1
		12	0	49	14	1.1
		12.5	0	50	16	1

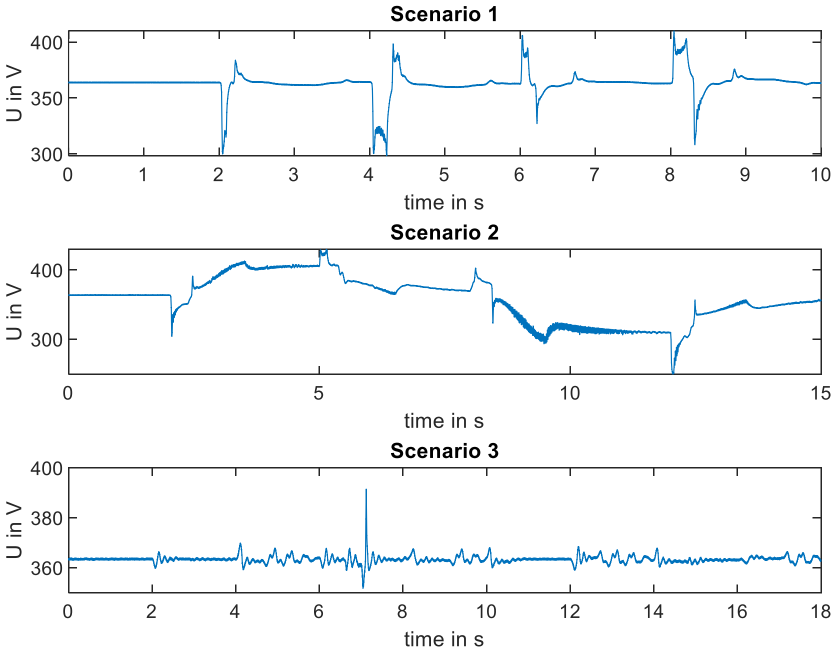

Figure 1.2: Battery voltages

Beyond individual grid disturbances, the testing scope was expanded to evaluate the battery's ability to orchestrate a complete microgrid during islanded grid operation. This test profile, also developed by Fraunhofer IEE, emulated a real-world grid section transitioning to an autonomous island mode. This use case is especially relevant for the growing number of AI data centers and energy communities. In these environments, a microgrid must be capable of operating based on local renewable energy generation, particularly solar photovoltaics supported by batteries for load balancing and the autonomous, off-grid prevention of blackouts.

In this test, the grid-forming inverter with the battery was connected to a P-HiL setup. As power amplifier we used an Egston CSU200GAMP6 and air coils for using the damping impedance method (DIM) for the interface method. The aim of the test is to control PV inverters in an islanded microgrid by adjusting the grid frequency to stabilize the system and balance PV generation and load. Initially, the microgrid is grid-connected; at $t = 10\,s$, a switch is opened and the microgrid transitions to islanded operation. The grid-forming inverter maintains uninterrupted supply and charges the battery with surplus PV power. As the SoC increases, the grid-forming controller raises the grid frequency; in accordance with VDE-AR-N 4105, the PV inverters reduce their output power. The SoC can be easily calculated from the battery voltage. Assuming a capacitor behaviour of the battery, the SoC is calculated by using the formular for capacitor energy $E_{\text{cap}} = \frac{1}{2}CU^2$. With a defined minimum and maximum operating voltage of the battery, the SoC can be calculated by:

$$SoC = \frac{{U_{Bat}}^2 - {U_{min}}^2}{{U_{max}}^2 - {U_{min}}^2}$$

The results in Figure 1.3 show that, at the instant the switch opens, the power step causes a jump in battery voltage. Consequently, the controller overestimates the SoC relative to the battery's actual energy content. This can be improved by augmenting the strategy to consider not only instantaneous voltage during such events but also power over time.

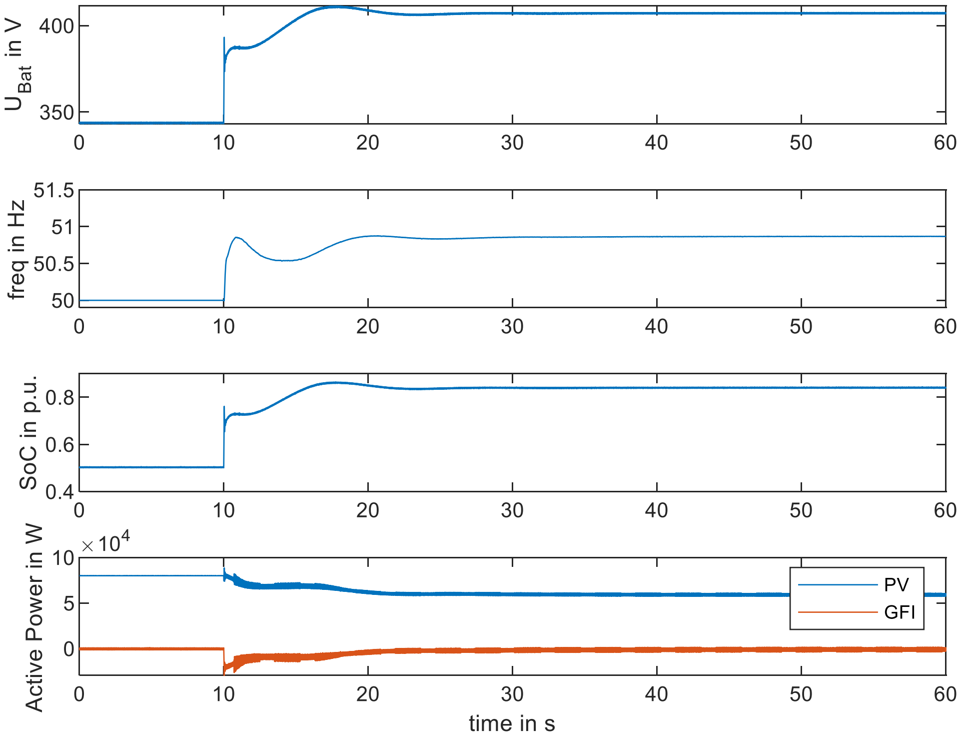

Figure 1.3: Energy management results

To demonstrate functional suitability for stability markets, another additional test included a FCR-N market scenario. This represents a market-driven service provided by an energy storage asset to a large grid to maintain its AC frequency during normal operation, continuously managing the fine balance between power supply and demand. A realistic, three-hour-long load profile was scaled from a physical hybrid supercapacitor and hydropower asset currently operating in a Nordic market. The test profile was validated and provided by a Finnish Energy Market Operator. The successful execution of this profile would validate the battery's suitability for high-cycling applications, proving its hybrid electrochemistry and bipolar battery design can handle the continuous, rapid power adjustments required for Nordic grid frequency containment.

Overall, the testing and validation campaign was highly successful, and the Geyser battery prototype passed all executed test scenarios. While the exact empirical data and specific testing results are reserved for Deliverable 4.3, which will be completed later in 2026, the current findings definitively confirm the technology's capability and readiness for demanding grid-forming applications.

1.5 Lessons learned and next steps

The testing within the AGISTIN WP4 project represents a highly successful development journey, advancing the Geyser aqueous battery from foundational cell-level development to successfully executed module-level testing at the Fraunhofer IEE laboratory. By progressing through batch testing, cellblock validation, and finally full-scale high-voltage module prototype integration, the technology has taken a step towards industrial readiness. A key high-level takeaway from this journey is the hardware's exceptional thermal stability and inherent safety. The system handled demanding testing profiles without requiring active cooling, which translates directly to a simpler balance of plant and lower operational expenditure for future industrial end-users.

Following the successful completion of these controlled stress tests, the next strategic step is the transition to live infrastructure. Later in 2026, this exact battery module is planned to be integrated into Fraunhofer IEE's microgrid sandbox test site. This deployment will serve as a critical pre-commercial pilot, exposing the system to the unpredictable physical dynamics of an actual microgrid rather than digitally simulated hardware. By interacting directly with real solar arrays, physical loads, and live grid hardware, this deployment will generate the operational track record necessary to support larger-scale industrial rollouts and future commercial pilots.

Looking ahead, Geyser Batteries is primarily focusing its commercialization efforts on stationary markets that demand robust, high-power solutions. Core target use cases include integrating with Power-to-X (P2X) applications, pairing with Long-Duration Energy Storage (LDES), hybridizing with existing hydropower assets to deliver rapid ancillary services, and providing foundational grid-forming capabilities. While these stationary energy sectors represent the immediate strategic focus due to the urgent need for low-inertia grid stabilization, the fundamental versatility of Geyser's battery technology allows for exploring and expanding into other high-power markets in the future.

2 Rapid Inverter Control Prototyping Solutions (RICOSO)

The RICOSO (Rapid Inverter Control Prototyping Solution) platform is a development and research system that enables fast design and practical testing of inverter controllers. Figure shows a recent photo of the RICOSO system; further information can be found online [2]. It consists of highly dynamic power amplifiers and a model-based development environment—typically MATLAB/Simulink—where users can create, simulate, and deploy control algorithms directly onto the target hardware. From this environment, selected parts of the simulated models can be implemented on the hardware and executed in real time. RICOSO itself realizes a programmable bidirectional AC/DC inverter, serving as the core power-electronics element of the prototype.

Figure 2.1 – RICOSO Hardware (© Benjamin Zweig)

Accompanying the hardware exists a software control library that was expressly designed for the RICOSO architecture. The integrated system provides the infrastructure to develop and test controls for power-system inverters quickly, reliably, and safely. It supports the model-based approach for designing, testing, and tuning control strategies, using a single bidirectional high-performance AC/DC converter as the Device Under Test (DUT). This setup allows developers to iterate rapidly: after compiling new firmware, the updated code can be loaded onto the target hardware for immediate validation of tuned control algorithms. The tight coupling of simulation, real-time hardware execution, and the control library makes RICOSO a versatile tool for advanced research in motor drives, renewable-energy converters, and grid-connected power-electronics applications.

Figure 2.2 depicts the control structure of the Rapid Inverter Control Prototyping Solution (RICOSO). It consists of a System-on-Module made by AMD/Xilinx, a Kria K26. It features an AMD/Xilinx UltraScale+ MPSoC (Multiprocessor System-on-Chip), which is made up of an ARM Cortex-A53 quad core CPU, an ARM R5 dual core CPU and a Field Programmable Gate Array (FPGA). The A53 CPU hosts a Real-Time (RT) patched Linux based operating system, which is used to run RT control applications, implementing e.g. user defined control algorithms. The FPGA implements all low-level features, such as safety features, Pulse-Width-Modulation (PWM), communication with measurement system and external control systems. Inside the UltraScale+ MPSoC, CPU and ARM share an internal Advanced eXtensible Interface 4 (AXI4) bus, which allows bi-directional data transfer between the two units. The R5 can be used to deploy additional control or analysis applications that run independently from the control algorithms running on the A53.

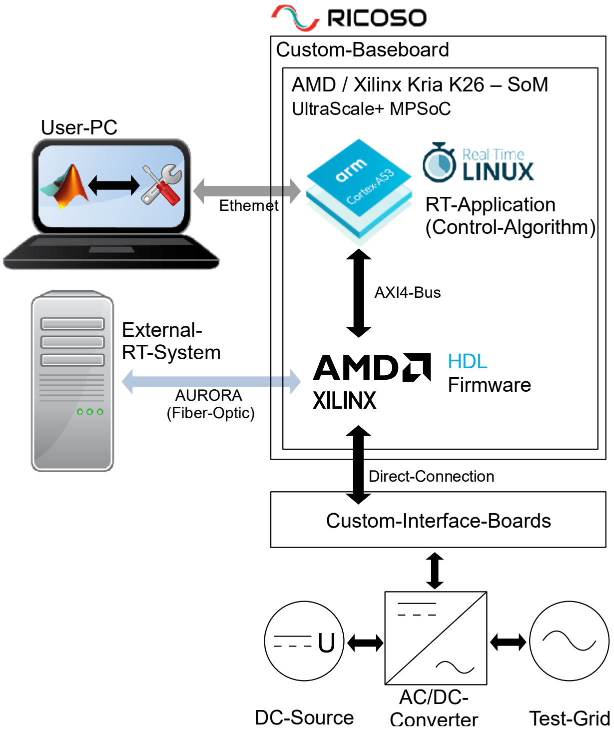

Figure 2.2: RICOSO Control System

The SoM itself is seated on a custom baseboard, developed by the Fraunhofer IEE, see Figure 2.3. It extends the SoM by adding additional input-output-interfaces (IO), such as Fiber optic, USB, Ethernet and CAN. Furthermore, the baseboard allows the usage of custom extension/interface boards, which are used to connect the SoMs FPGA to external hardware, such as measurement systems and PWM drivers.

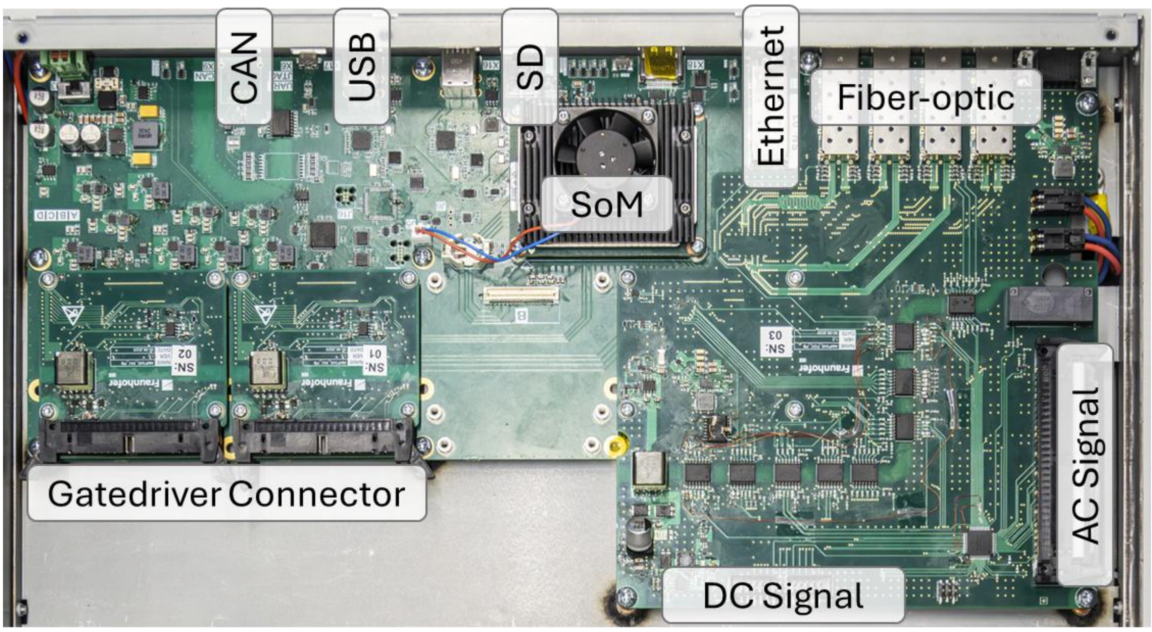

Figure 2.3: Control Board, with SoM and Interface Cards

The system allows for two possible modes of operation, internal, using Matlab/Simulink to deploy a control algorithm directly to the A53 CPU, which communicates over AXI4 with the FPGA. And external, here an external control system is used and connected via fiber-optics, and the AURORA Protocol. In this mode the external system receives measurement data from the RICOSO system and in turn sends duty cycles for each phase back. Using the external mode, it is possible to integrate the RICOSO system into more complex laboratory environments.

Figure 2.4 shows a block diagram of the RICOSO test inverter. The inverter is implemented as a 4wire system with three phases and an active neutral conductor. A three level TNPC topology is used which, in combination with the specially tuned AC filter (DM and CM-Filter), is intended to achieve a large signal bandwidth of 2 kHz.

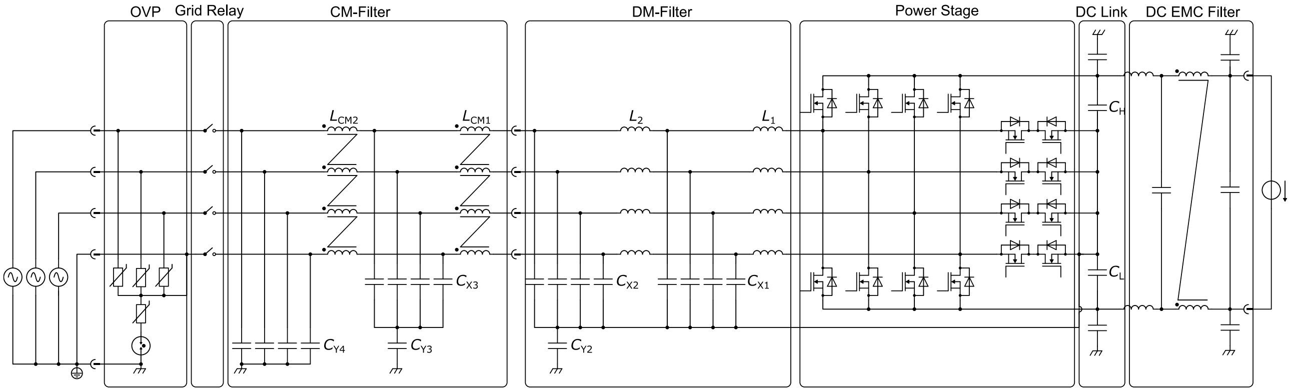

Figure 2.4: Four Leg Inverter Topology

The individual modules and circuit boards of the test inverter were assembled and tested separately. The assembly of the complete inverter system (see Figure 2.5) and testing in conjunction are finished. Figure 2.6 shows the output voltage curve for the three phases during controlled operation. The next step involves increasing the voltage and power to their nominal values and operating the system on the low-voltage grid. The fourth leg enables independent neutral point control, enhancing voltage balance and performance under unbalanced or single-phase loads.

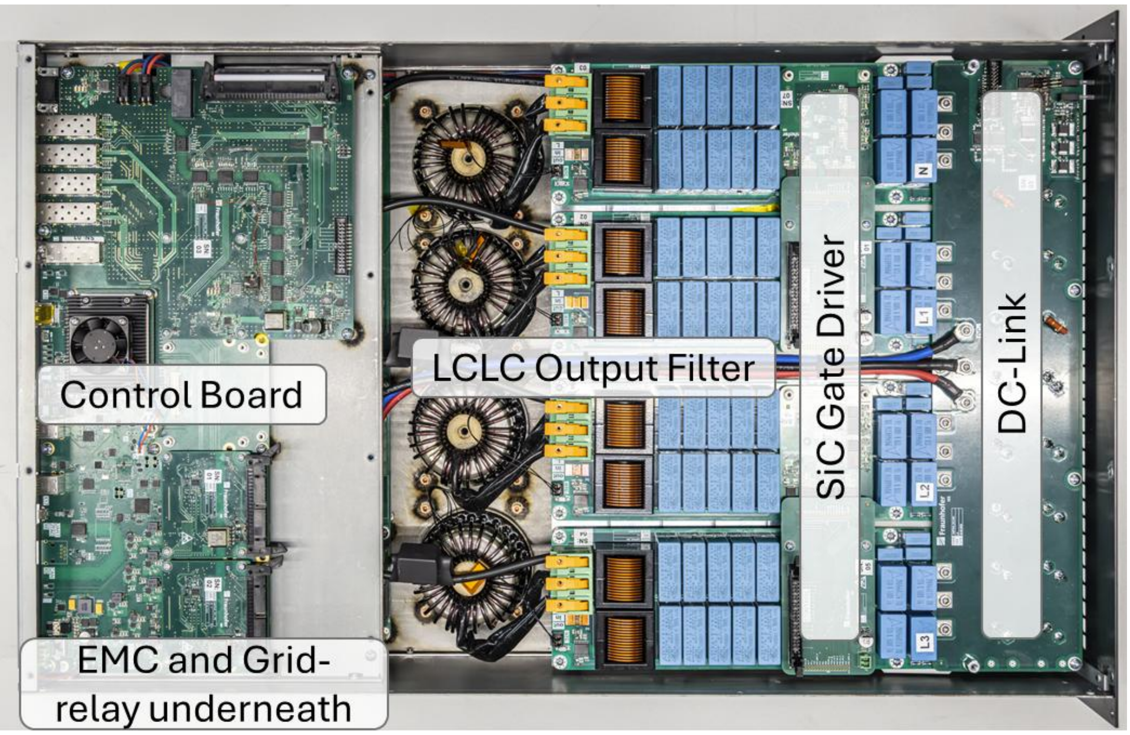

Figure 2.5: Commissioning of the Inverter Prototype

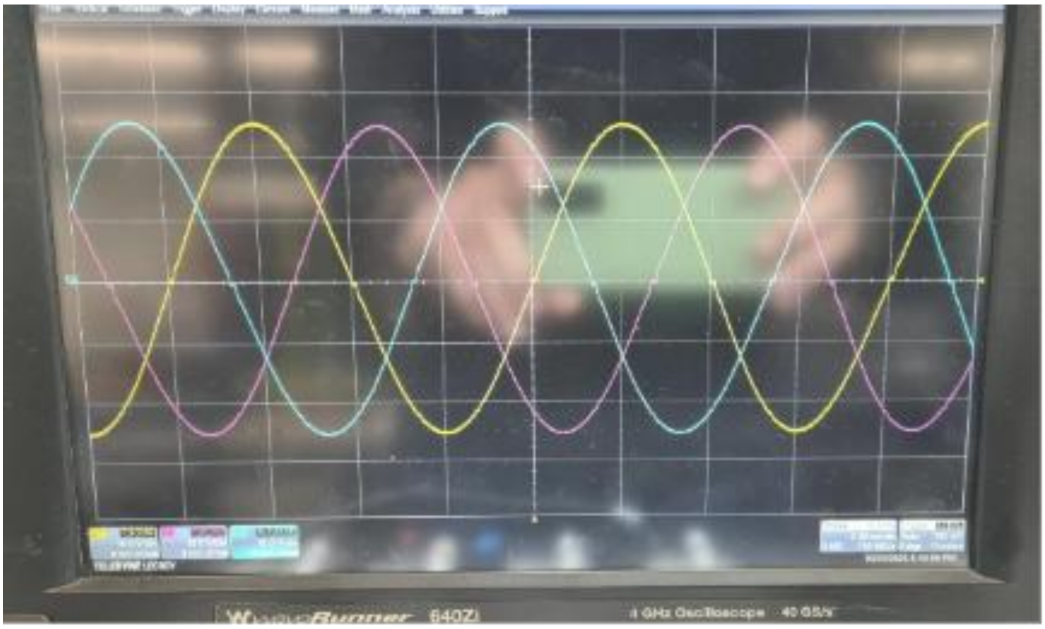

Figure 2.6: Three-Phase Output Voltage

3 Real-Time AGI

3.1 AC AGI model implementation

The AC-AGI developed by the University Kassel was implemented in the Opal Real-Time Simulator. Figure 3.1shows the RICOSO AC AGI model implementation in *Matlab/Simulink*.

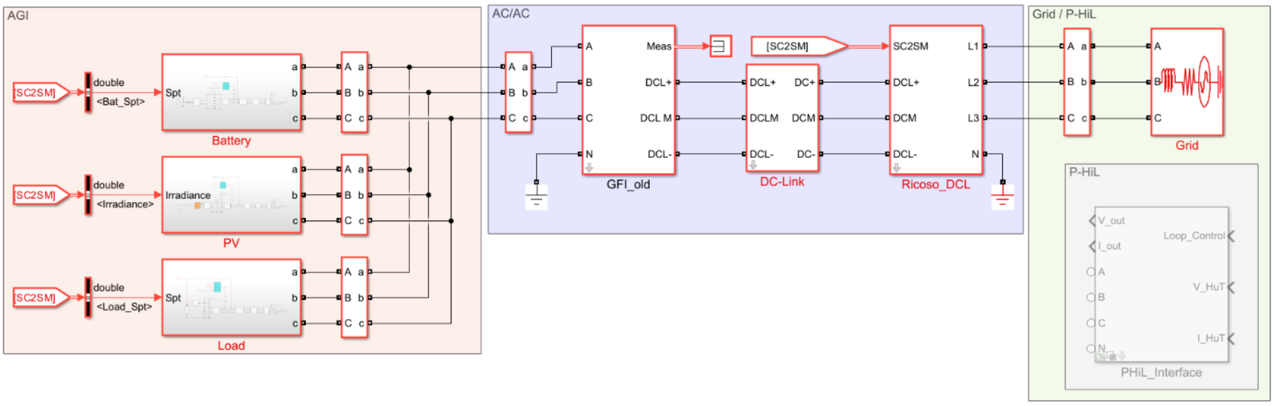

Figure 3.1: RICOSO AC-AGI model

On the left side in the red box is the three-phase AC-AGI model including a battery, PV system and a constant PQ load. The green area on the right side represents a simplified model of a grid connection point. In a next step, this simulated grid will be replaced by a P-HiL interface. Both areas are coupled by two DC/AC inverters in a back-to-back configuration connected at the DC-link, which is modelled in the purple area. The island grid is being supported by a Grid-Forming inverter. The second inverter serves to stabilize the common DC-link voltage using a closed-loop control algorithm (DC-Link voltage controller), which is depicted in Figure 3.2. The inverters are modelled based on the Rapid Inverter Control Prototyping Systems (RICOSO), which is freely programmable within certain limits using the Model Based Design approach [3]. Besides the modelling of the DC-Link voltage controller, the RICOSO_DCL block also includes the modelling of the RICOSO hardware, which will not be discussed in more detail here.

The DC-Link voltage controller algorithm is a cascaded control with a voltage controller in the outer loop and a current controller in the inner loop. Here, the voltage controller generates the current setpoint $I_{\mathrm{d,spt}}$ (in the d/q coordinate system) from the DC link voltage error $U_{\mathrm{DCL,err}}$, using a PI controller. This is sufficient, since the d-axis current I_{d} directly defines the active power flowing between the AC- and DC-side, and thus the voltage across the capacitor DC-Link.

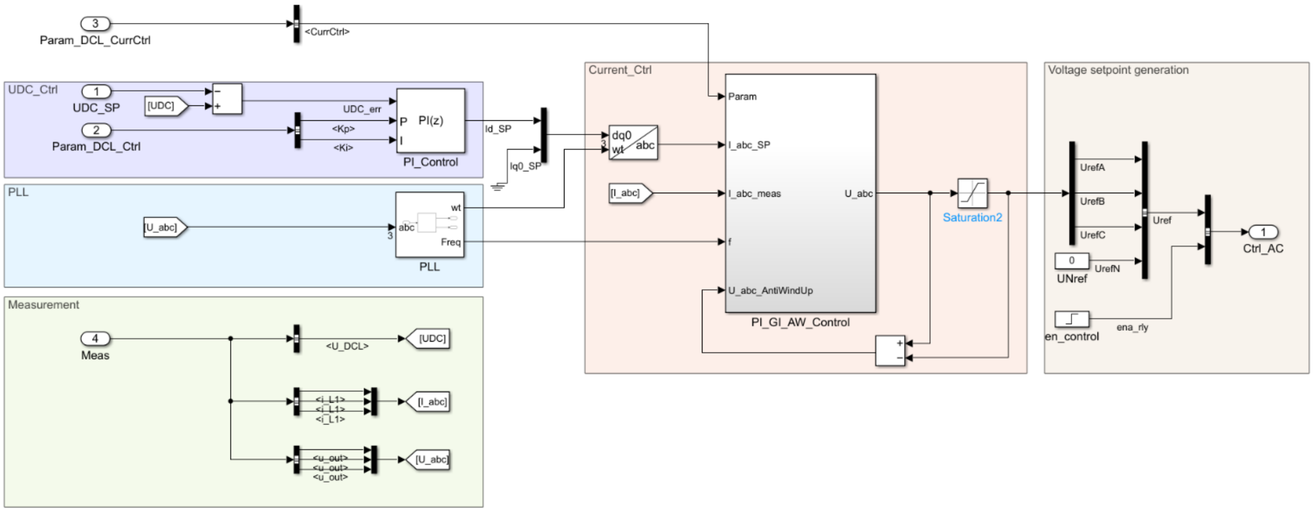

Figure 3.2: DC-Link voltage control

For the inner loop current control in all three phases abc, the inverse d/q transformation (Park transformation) is required. This involves defining the setpoints for I_q and I_0 to zero. For the inverse d/q transformation, the phase angle ωt of the three-phase grid is required, which is determined using a phase-locked loop (PLL). For the PLL to follow the grids frequency quickly enough, a sufficiently short settling time must be guaranteed. The current controller PI_GI_AW_Control consists of a PI controller, a *Generalized Integrator* (GI) and an Integral Anti-Windup and is depicted in Figure 3.3.

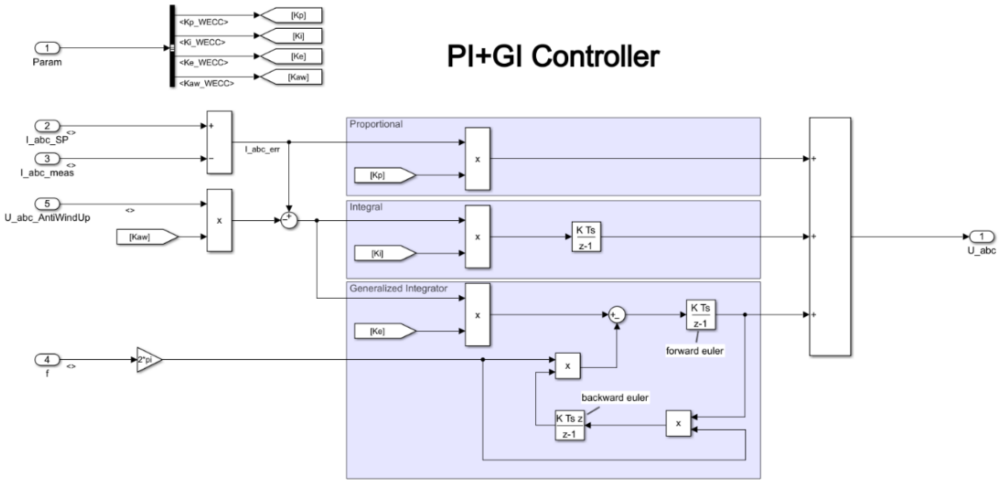

Figure 3.3: Current Controller

Here, the PI component provides proportional and integral correction for low-frequency (DC) errors, while the resonant component (GI) provides unlimited gain at the fundamental frequency and selected harmonics, to eliminate stationary errors with sinusoidal references. Together, they form a PI + resonant controller, which enables precise tracking of AC references. Thus, the current controller generates the voltage setpoints as controller output variable.

3.2 P-HiL interface

To integrate the emulated AC AGI model with the real AC test grid, the damping impedance method (DIM) is used as the interface algorithm, as shown in Figure 3.4. This method combines the ideal transformer method (ITM) and partial circuit duplication (PCD), offering high stability and accuracy. In this setup, the voltage v'_1 in the real-time simulator (RTS) represents the voltage at the simulation point where the inverter is connected. This voltage is provided to the power amplifier as its voltage reference v_2.
The measured voltage at the test grid v'_2 is fed back into the simulation via the interface algorithm as a voltage source. Additionally, the current measured at the power amplifier is also input into the DIM as a current source, decoupled by the damping impedance Z^*. Maximum stability is achieved when $Z^* = Z_2$. For decoupling of the power amplifier and the test grid air coils are used with a linking impedance of $Z_{12} = 580\ \mu\mathrm{H}$.

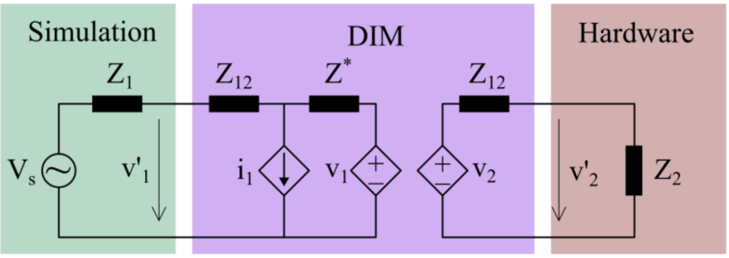

Figure 3.4: Damping Impedance Method (DIM)

3.3 Simulation results

For simulation the P-HiL interface is not used, but the three-phase grid model. The grid model shows the test scenario voltages from section 1.4 defined in Table 1.1. However, the first second of simulation is used to reach steady state operation and at t=1s the scenario voltage is started. The results show that AC events on the test grid does not have any impact on the AC AGI grid. The decoupling works as intended and active power balancing is working. A more detailed analysis will be done in following laboratory tests and the results will be provided in Deliverable 4.3.

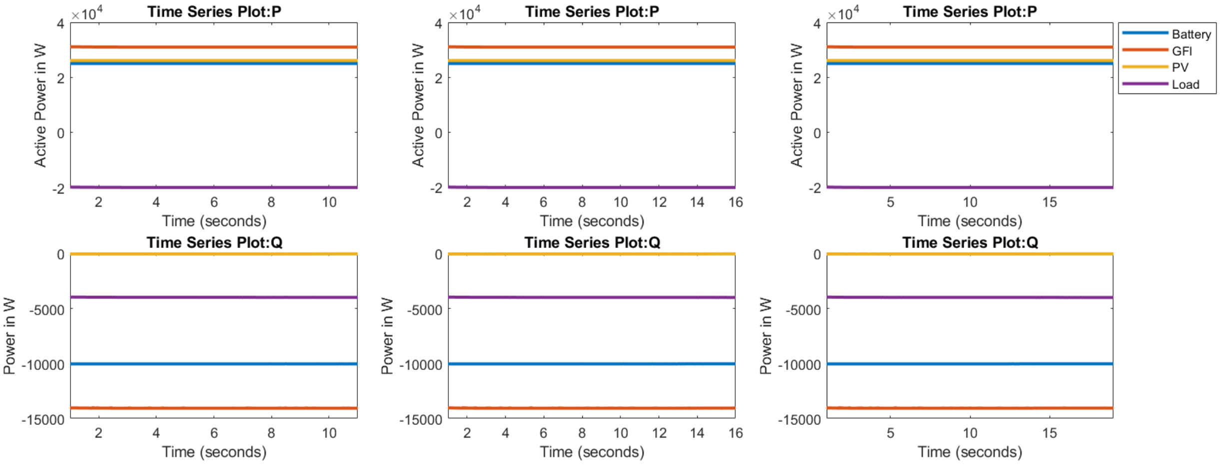

Figure 3.5: AC-AGI Simulation results of active reactive power

4 Fraunhofer Sandbox

4.1 Fraunhofer Sandbox as validation environment

Within AGISTIN, the Fraunhofer Sandbox (Sandbox = real LV grid setup in controlled lab environment) serves as the central laboratory validation environment for the implementation and commissioning of advanced grid interface concepts under controlled but realistic grid conditions. In WP4, its role is to provide a flexible and reconfigurable infrastructure in which e.g. storage-related converter systems, bidirectional charging concepts, grid-forming and grid-following setups, and higher-level supervisory functions can be integrated step by step and prepared for systematic validation. By combining real electrical hardware, programmable converter platforms, real-time simulation and power interfaces in one coherent setup, the Sandbox bridges the gap between simulation-based development and laboratory implementation. This makes it particularly suitable for validating integrated storage and converter-based solutions in representative grid-connected and islanded operating conditions.

The Sandbox represents a configurable LV grid environment with adjustable electrical boundary conditions and a modular structure for the connection of distributed assets. Representative local grid conditions can be reproduced by means of configurable topologies, variable line types and line lengths, and defined coupling impedances between converter-based units and further grid components. In addition, the environment is designed to combine physical devices such as storage converters, charging interfaces, loads and photovoltaic units with digitally emulated grid sections and dynamic components through real-time simulation (RTS) and Power-Hardware-in-the-Loop (P-HiL) coupling. This hybrid structure is essential for AGISTIN, as it enables real storage-related hardware to interact with emulated industrial grid sections and reproducible network dynamics without requiring the full external system to be physically installed.

A key strength of the Fraunhofer Sandbox for AGISTIN is that it provides not only electrical infrastructure, but also a system-level validation environment for dynamic and interoperable operation of converter-dominated grids. The setup is suitable for grid-connected and islanded operation, controlled system split and resynchronisation procedures, dynamic load changes, and the parallel operation of multiple (programmable) converter systems with different control functions. This is directly relevant for the AGISTIN laboratory test cases, in which battery converters, EV charging emulators and additional converter-based assets can be combined and assessed with respect to voltage and frequency stability, system support capabilities and interaction with connected industrial grid sections. The Sandbox therefore forms the technical basis for AGISTIN-specific commissioning activities, including the preparation of rapid control prototyping (RTS) systems, communication interfaces, higher-level control integration and the staged extension toward AGI-oriented validation workflows. The following subsections describe these infrastructure elements and commissioning steps in more detail.

4.2 Physical and digital infrastructure

The physical and digital infrastructure of the Fraunhofer Sandbox was configured in AGISTIN as a hybrid laboratory environment combining real electrical equipment, programmable converter systems, RTS and P-HiL interfaces within one common validation setup. Its objective is to provide not only a representative LV test grid, but also a controllable and extendable environment in which physical storage and converter hardware can be coupled with emulated grid sections and dynamically parameterised operating conditions. This supports the staged implementation of AGISTIN use cases ranging from converter-level investigations to coordinated multi-component validation scenarios with storage, charging interfaces and higher-level control interaction.

At the electrical level, the Sandbox provides a configurable LV grid section with several connection points for distributed assets and adjustable boundary conditions. The test centre includes buildings/test households with adjustable loads and PV systems, which can be interconnected through configurable LV cables to realise different grid topologies and varying impedances. This allows representative local grid conditions to be reproduced in a structured and repeatable way. In the AGISTIN context, this is particularly relevant because the investigated storage and AGI concepts must be assessed under changing electrical boundary conditions rather than in a fixed feeder configuration.

A central infrastructure element for AGISTIN is the integration of programmable converter hardware based the RICOSO RCP. The selected setup includes an RCP system (see chapter 2) with a rated output of $\sim 40\,\mathrm{kVA}$, which can be equipped with grid-forming and grid-following functions and can emulate a bidirectional electric vehicle charging interface. In addition, the broader test environment allows parallel operation with further converter systems and bidirectional charging hardware, enabling an extension toward multi-converter and storage-related scenarios. This converter layer forms the interface between the physical power hardware and the AGISTIN-specific control functions and provides the flexibility required to adapt converter behaviour during commissioning and validation.

To complement the physical grid, the Sandbox also includes RTS and P-HiL infrastructure. In the selected AGISTIN test configuration, three P-HiL systems with $90\,\mathrm{kVA}$ amplifiers each are connected to the setup, allowing industrial grid sections and further external components to be represented in emulated form. This hybrid architecture enables realistic interaction between real hardware and emulated network behaviour without requiring a full physical replication of all external assets.

The infrastructure is further complemented by high-performance measurement, logging and digital configuration capabilities. Current and voltage values can be acquired at relevant nodes using dedicated data loggers, while the real-time environment supports test parameterisation and semi-automated execution of scenarios. In addition, the setup provides the basis for integrating communication links, controller access points and switchable components required for plant-level supervision and AGI-oriented coordination. As such, the Sandbox infrastructure in AGISTIN is not limited to electrical hardware but represents a combined cyber-physical environment for the commissioning of converter control, storage integration and supervisory control functions within one consistent validation workflow.

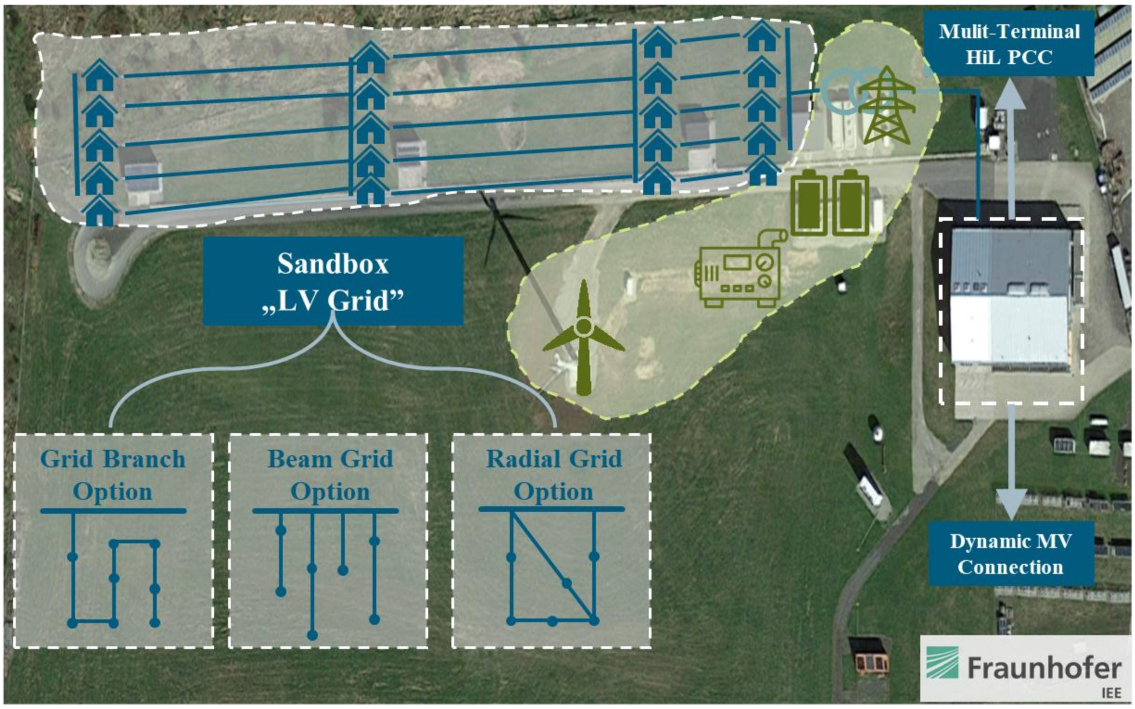

Figure 4.1 – Experimental test site Fraunhofer Sandbox

Figure 4.2 Testhousehold #1 (legt), Testhousehold #1 inside (middle), RLC loads (right)

The setup in its base consists out of (see also Figure 4.2):

- Low voltage test site
    - 20 house connection with 20 kVA each, incl. heat pumps, rooftop solar generators, ev charges, smart meters, …
    - Selectable cable sizes (length and diameter) & topologies (e.g. grid branches, beam grids, radial grids)
    - Adjustable RLC loads
    - LV/MV transformer with smart tap changer
    - LV/MV resynchronization unit
- Medium voltage test site
    - PV-Battery system and Battery system
    - 20 km MV cable emulator
    - Diesel Gen-Set
    - Wind-Turbine
- Extensions

  - 3 x 90 kVA LV power hardware-in-the-loop terminal
  - MW AC Grid emulator
- Multi MW PV / DC emulator

Superordinate controller for voltage support and transformer loading mitigation

Within this cyber-physical infrastructure, AGISTIN deploys a superordinate controller that coordinates distributed assets in the Sandbox LV grid. This controller operates on aggregated measurements (e.g. household voltages, LV/MV transformer loading) and generates setpoints for underlying converter-based units such as storage converters and EV charging emulators. In this way, it forms the link between the physical Sandbox hardware and AGISTIN's higher-level grid support objectives, in particular voltage stability and transformer overload mitigation under realistic operating conditions.

The superordinate controller consists of two complementary, trigger-based modules:

- a reactive power controller that supports voltage during band violations, and
- an active power controller that reduces LV/MV transformer overload.

Both controllers share a common event-driven principle: the control output is only changed when a trigger is generated. This reduces sensitivity to measurement noise, avoids unnecessary and continuous actuation, and yields stable, incremental corrections that are well suited to the mixed physical–digital environment of the Sandbox and to P-HiL operation.

Reactive power controller supporting voltage during band violations

The reactive power controller supervises the voltage in a target LV grid section and adjusts the reactive power of participating converters in discrete steps:

- When the voltage is inside the allowed band, the controller remains idle and the reactive power setpoint is held constant.
- When the voltage drifts above or below the band, an internal clock starts. The further the voltage is from the band, the faster this internal clock runs.
- Each time the timer fills, a trigger is generated and the controller nudges reactive power up or down by a small fixed step in the direction that counteracts the deviation.
- Once the voltage returns to the allowed band, the controller stops corrective triggers and gradually releases reactive power back toward zero (or a defined neutral value).
- For increased robustness, the voltage used for control can be calculated as the average of several measurement points in the target grid section, e.g. across multiple households or feeder locations.

This trigger-based concept allows the Sandbox to reproduce and analyse voltage support behaviour for different grid topologies, line impedances and converter placements in a structured and repeatable way.

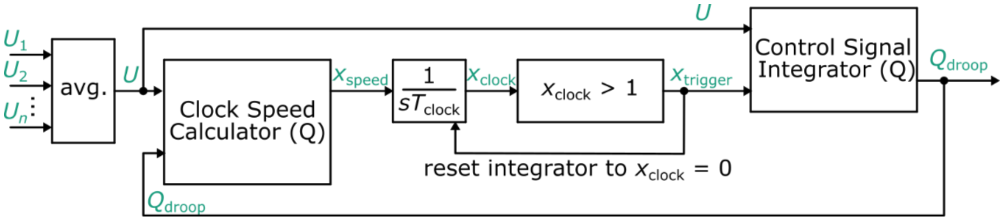

Figure 4.3 Reactive Power Controller overview

Active power controller (transformer overload reduction)

The active power controller monitors the LV/MV transformer loading and limits active power consumption when thermal limits are approached:

- When the transformer loading first crosses its upper threshold, the limiter activates and steps the allowed active power per household (or controllable asset) down from 100% in small increments until loading returns to a safe range.
- While loading remains within the safe band, the current power limit is held constant, avoiding oscillatory behaviour.
- If loading drops below the lower bound of the band, the limit is stepped back up in small increments.
- If loading falls well below a deactivation level, the limiter switches off and the allowed power is reset to 100%.

This strategy enables systematic investigations of overload mitigation concepts in the Sandbox for different loading scenarios, combinations of converters and operating modes (grid-connected and islanded).

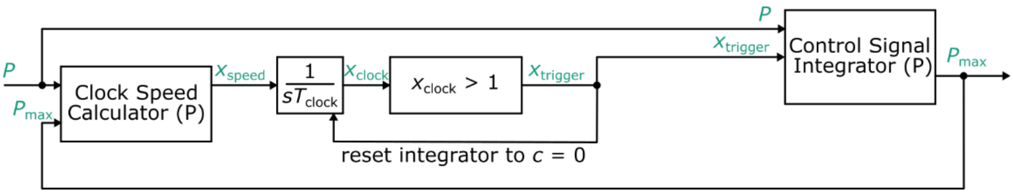

Figure 4.4 Active Power Controller overview

Implementation in the Bachmann PLC environment

Both controllers are implemented in a Bachmann system environment using a MATLAB toolbox. The control algorithms are modelled in MATLAB/Simulink and then deployed to a Bachmann PLC, which acts as the central superordinate controller within the Sandbox infrastructure:

- The same control logic can be validated stepwise: first in offline simulation, then in RTS/P-HiL setups, and finally in the full hybrid Sandbox configuration.
- Interfaces to measurement systems, converter controllers and communication networks in the Sandbox can be configured modularly, allowing flexible allocation of control responsibilities to storage converters, EV charging emulators, RLC loads and other assets.
- Control parameters (e.g. voltage band limits, transformer thresholds, step sizes) can be efficiently adjusted during commissioning and test campaigns, supporting rapid control prototyping and AGI-oriented validation workflows.

In combination with the physical and digital components of the Sandbox, the superordinate controller thereby provides a central building block for AGISTIN's system-level validation of converter-dominated grid operation.

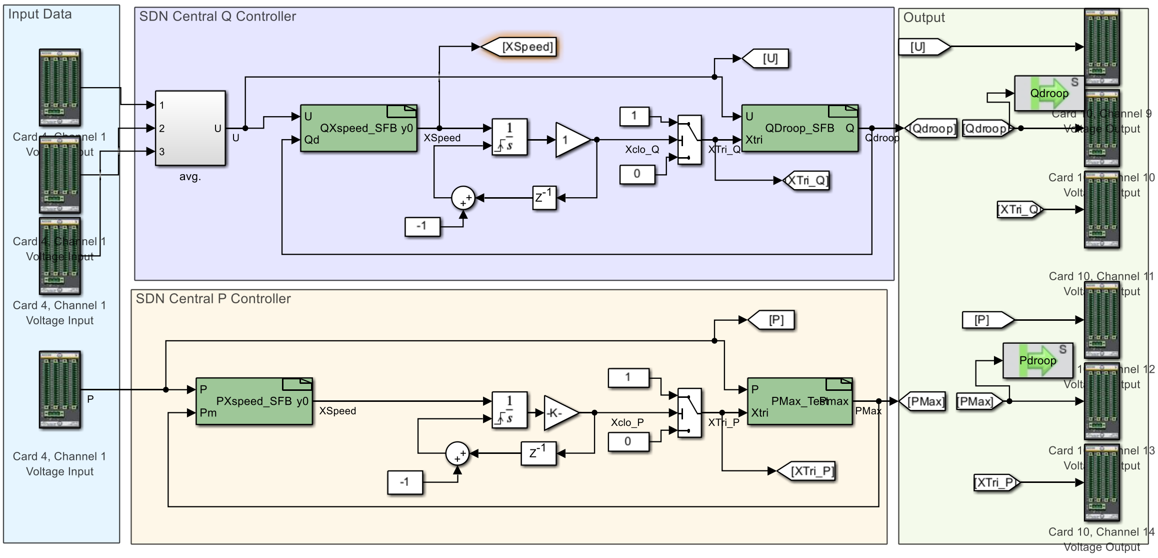

Figure 4.5 Implementation in Bachmann PLC

4.3 AGISTIN-specific commissioning and extensions

For AGISTIN, the Fraunhofer Sandbox was not used as a fixed laboratory setup, but was commissioned and extended as a project-specific validation environment. The main objective of this commissioning phase was to adapt the existing hybrid infrastructure to the requirements of the AGISTIN laboratory test cases, in particular for the integration of storage-related grid interface concepts, bidirectional charging functionality, and coordinated control approaches. In line with the validation concept, the setup was therefore complemented by additional measurement channels, communication paths, switchable components and control interfaces required for the staged implementation of the planned use cases.

A central activity was the integration of RCP systems based on the RICOSO platform. Within AGISTIN, these systems were prepared to implement converter control functions in real time and to emulate different grid plant behaviours, for instance under grid-forming and grid-following operation. This provided the required flexibility to adapt converter functions to individual laboratory test cases and to combine or emulate battery converters, charging interfaces and further programmable devices in a common electrical environment. At the same time, the rapid prototyping layer created the basis for transferring control concepts from model-based development into the laboratory setup in a structured and traceable manner.

In parallel, the commissioning activities addressed the preparation of higher-level control integration. According to the AGISTIN validation approach, the Sandbox had to support not only local converter control, but also plant-level coordination and advanced grid controller access. For this reason, communication interfaces to the real-time environment and the programmable power hardware were prepared in such a way that supervisory control functions could access measurement values, provide set-points and interact with local control layers. This included the integration of real-time-capable controller systems and generic controller templates for plant-level control, as well as the adaptation of HiL-related controls and interfaces to the AGISTIN setup.

To demonstrate and verify the commissioning process, a dedicated laboratory setup was established to analyse the procedures and integration possibilities of several devices in a system-oriented context. For this purpose, a decentralised islanded grid setup was realised, consisting of two RICOSO RCP systems operated with grid-forming control and an additional grid load. The purpose of this setup was not to assess the final technical performance in detail, but to verify the implementation procedure, the interoperability of the involved components, and the suitability of the planned test case workflow. In this context, the selected test case focused on the behaviour of multiple grid-forming converters under current-limiting operation triggered by excessive loading. This provided a representative example for validating the commissioning sequence, the interaction of distributed converter controls, and the practical applicability of the envisaged AGISTIN laboratory procedures.

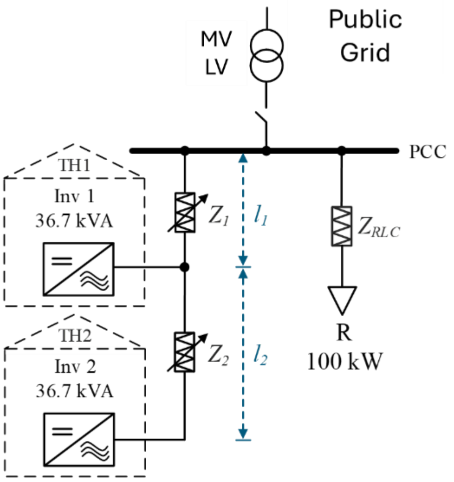

Figure 4.6 – Validation setup of the Fraunhofer Sandbox for decentralised islanded grid operation.

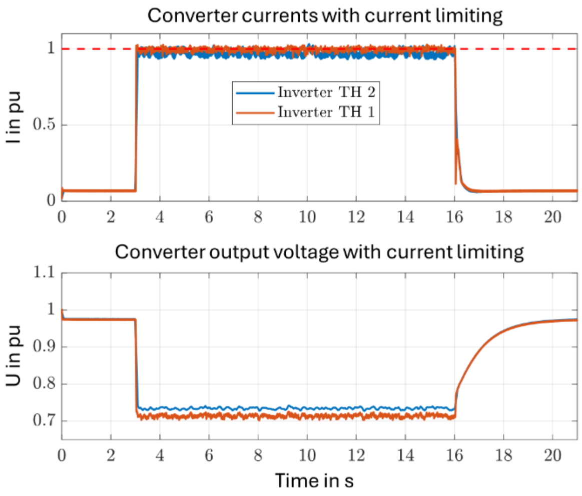

Figure 4.7 – System behaviour of a decentralised islanded grid with distributed grid-forming converters under current-limiting operation.

Overall, these commissioning and extension activities turned the Sandbox into an AGISTIN-specific validation platform, in which converter control, communication-assisted coordination and hybrid power system emulation could be prepared jointly before the execution of the detailed validation campaigns.

4.4 Relevance for the validation process

The Fraunhofer Sandbox is relevant not only as a laboratory installation, but as the enabling environment for the overall validation process. Its main contribution is the possibility to transfer AGI concepts from model-based development into a reproducible cyber-physical setup in which converter controls, storage integration, communication paths and emulated grid behaviour can be commissioned jointly. This is fully aligned with the AGISTIN validation approach, which foresees the preparation of dedicated test scenarios, the integration of additional communication and controller components, the use of RCP inverters and P-HiL systems, and the implementation of plant-level control structures for real-time testing.

A key advantage for the validation process is the possibility to realise different electrical boundary conditions and operating states in a structured way. By combining configurable grid topology, programmable converter hardware, real-time simulation and measurement infrastructure, the Sandbox supports the stepwise commissioning of the AGISTIN laboratory test cases, including grid-connected and islanded operation, system split and resynchronisation, interoperability investigations and interaction with emulated industrial grid sections. This allows the validation workflow to progress from scenario preparation and control implementation to integrated laboratory operation without changing the basic validation environment.

The Sandbox is therefore particularly valuable for the validation process because it supports process-oriented validation in system-context rather than isolated component testing. It enables repeatable setup adjustments, traceable integration of higher-level control functions, and controlled comparison between different operating modes and controller configurations. In this sense, the Fraunhofer Sandbox forms the methodological backbone of the AGISTIN laboratory validation process, while the technical findings obtained with this setup are discussed separately in D4.3.

5 Conclusion & Outlook

The AGISTIN project has successfully demonstrated the potential of advanced energy storage technologies and innovative grid interface solutions to support the rapid integration of renewables in industrial power systems. Through the development and validation of novel storage concepts—such as aqueous batteries and the use of irrigation systems for energy storage—as well as the implementation of flexible, programmable converter platforms, the project has addressed key challenges related to grid stability, flexibility, and cost reduction for large industrial users.

The comprehensive validation activities, carried out in realistic laboratory environments like the Fraunhofer Sandbox, have confirmed the technical feasibility and operational benefits of these solutions. The results show that the tested technologies can provide fast dynamic response, reliable grid-forming capabilities, and effective support for both grid-connected and islanded operation scenarios. The modular and hybrid validation approach has enabled the systematic assessment of storage integration, converter control, and supervisory coordination under a wide range of operating conditions.

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