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## AENEAS

### innovActive ENERgy storage systems onboArd vessels

#### Deliverable 5.2: Development of a downscaled real-time platform for testing

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## Project Abstract

AENEAS aims to contribute towards climate-neutral and environmentally friendly water transport through three new next generation clean energy storage solutions. Eventual impact is an increase of the global competitiveness of the EU waterborne transport sector by European technology leadership for energy storage solutions for diverse waterborne applications.

AENEAS will develop three innovative electric Energy Storage Solutions (ESS) for waterborne transport, which are advanced beyond the traditional battery systems, including Semi Solid-state batteries (SSSB), Supercapacitors (SC) and a Hybrid system which combines SSSB and SC.

The solutions enable (partial or full) electric shipping, considering conditions specific ships might encounter, including adverse conditions outside sheltered waters or going upstream on rivers. AENEAS will evaluate them for a range of applications and end uses in short-sea shipping and in-land waterways. At the same time AENEAS will define the pathway for the three ESSs for application in different ship types, achieving an understanding of the ESSs and their applicability for diverse waterborne transport.



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## Public Summary

This document is a part of Task 5.2 in WP5 and is based directly on the simulation and control model development of ship power systems and Energy Storage Systems (ESS) performed in D5.1. The deliverable D5.2 provides the preparation for the transition from simulations to laboratory testing using a downscaled real-time hardware-in-the-loop (HIL) platform. The developed platform is structured to enable validation of ESS technologies, including semi solid-state battery (SSSB), Supercapacitor (SC), and hybrid ESS, in a controlled environment that closely emulates shipboard power system dynamics. Key components include the integration of physical ESS modules or emulators, power converters, amplifiers, programmable loads, control interfaces, and measurement, all coupled with digital real-time simulations (DRTS) of ship power systems.

This work provides that the critical hardware, software, and safety elements are in place, and that the HIL platform supports realistic use-cases and detailed assessment of system performance. The deliverable also provides detailed documentation of scaling strategies, hardware-software interfacing, and experimental setup, creating the platform for the experimental testing and implementation activities planned in D5.3. The outcomes of D5.2 provide the technical foundation and an important link from simulation to experimental validation in the next phase.

Hence, the goals of this deliverable can be summarized in preparing a downscaled power hardware-in-the loop (PHIL) platform for:

- Testing the overall performance of ESS modules in the shipboard power system of three use cases,
- Validating applied control techniques that are developed in previous task,
- Validating the design of ESS and power converters in virtual models.

# 1 Introduction

## 1.1 Rationale of this deliverable

This deliverable, “Development of a downscaled real-time HIL platform for testing,” is a result of task 5.2 in WP5 and an important step in moving from computer-based simulations to real laboratory testing. Real-time HIL simulation models enable the testing and validation of complex systems by providing accurate, dynamic representations of physical components in a controlled, virtual environment, ensuring reliability and performance before deployment. HIL testing can be done as controller hardware-in-the loop (CHIL) or power hardware-in-the-loop (PHIL). In which, CHIL simulation focuses on verifying the developed control system and the device under test (DUT) is the control system. In PHIL testing, the focus is on testing and validating the performance of power device(s) and the DUT is power device(s).

Building on the HIL simulation models, and control strategies developed in D5.1 and D2.3, D5.2 focuses on hands-on testing preparation, where real hardware works together with real-time simulations. HIL simulations are useful for understanding how systems and controls behave, only a real PHIL platform can show us the practical issues, connection challenges, and safety questions that come up when real devices and equipment are used in different complex situations.

D5.2 focuses on the design, setting up, and integration of this downscaled real-time PHIL platform. This includes introducing the components of the PHIL setup, PHIL working principle, setup configuration, setting connections for the physical ESS modules (such as SSSB, SC, and hybrid combinations), power converters, programmable loads, control systems, and measurement all linked with real-time computer simulations. The deliverable also explains how everything fits together, how the hardware and software talk to each other and ready for the next stage.

By preparing this PHIL platform in the lab, D5.2 provides the strong technical base and understanding needed for the full hands-on testing that will happen in D5.3. This makes sure that all the key parts are in place for moving from simulation to practical testing of ESS.

## 1.2 Contributors and roles

UVA led the downscaled real-time PHIL platform development, contributing to power electronics, control systems, and HIL/PHIL integration. UVA also supported the overall technical framework, ensuring alignment with previous simulation models. CEA supported the operational strategies. SIE ensured that operational profiles and system requirements were compatible with the simulation software, facilitating realistic and relevant test scenarios. FM provided critical input based on functional testing of the modules in WP4, supporting the verification and evaluation of platform functionality and use cases.

## 1.3 Link with D5.1 simulation results and D5.3 validation

This deliverable, D5.2, acts as a link between the simulation and modelling work carried out in D5.1 and experimental validation that will be performed in D5.3. The real-time HIL simulation models, control strategies, and system behaviours developed and validated in D5.1 form the technical basis for the design and setup of the downscaled PHIL platform in D5.2. By converting these simulation results into hardware and laboratory configurations, D5.2 ensures

that the operational scenarios, control algorithms, and performance criteria identified earlier can be thoroughly assessed in a controlled real-time testing environment. The outcomes of this work provide a foundation and all necessary preparations for the PHIL-based experimental testing that will be performed in D5.3.

## 1.4 Structure of the document

This document is structured as:

- Section 1 provides an introduction, including the rationale of this deliverable, a summary of contributions from project partners, and the alignment of D5.2 with previous (D5.1) and upcoming (D5.3) deliverables.
- Section 2 defines the objectives and scope of the work, explaining the transition from HIL models to hardware implementation, the integration of ESS component designs from earlier work packages, and the overall purpose of establishing a downscaled PHIL platform for validation.
- Section 3 describes the hardware setup and components, covering the physical ESS modules (SSSB, SC, hybrid or emulators), power converters, power amplifiers and loads, control interfaces, and the measurement involved in the platform.
- Section 4 details the downscaled system design, explaining the scaling strategy and presenting three specific use cases, each reflecting a different ESS configuration.
- Section 5 discusses the architecture of the PHIL platform, focusing on component-level testing, the functional arrangement of power and signals, the interaction between real and simulated elements, and signal conditioning.
- Section 6 concludes with a summary of the work achieved in D5.2 and describes the transition towards experimental validation activities in D5.3, followed by list of references, acknowledgements and disclaimer, an abbreviation list, and list of figures and tables.

### Attainment of the objectives and explanation of deviations

The low technology readiness level of solid state battery (SSB) led to difficulties for system-level design and prototyping, raising doubts about the feasibility of achieving a TRL7 onboard demonstration in the near future (by 2027). As a result, according to the agreement of the consortium and the project officer, the project strategically included the design of semi solid state battery (SSSB) module in WP4, which offers a more mature pathway for onboard demonstrations. Consequently, the tasks in WP5 have been carried out using SSSB technology, which has resulted in some delays in the preparation of Deliverable D5.1

## 2 Objectives and scope

### 2.1 Bridging HIL models to hardware Implementation

A key objective of D5.2 is to ensure a smooth and technically robust transition from simulation-based HIL models, developed in D5.1, to their realization in a physical hardware environment. This step is essential for validating not only the theoretical performance of ESS and control strategies but also their real-world feasibility, reliability, and safety when interfaced with actual power electronic components and hardware.

In D5.2, this linking process involves translating the validated HIL simulation models including ESS behaviour, control strategies, and ship power system dynamics into hardware compatible configurations. This requires careful consideration of scaling strategies, real-time interfacing techniques, and adaptation of control and logic for physical devices. The integration of real ESS modules or emulators, power converters, programmable loads, and measurement systems is carried out in a way that maintains closeness to the original simulation scenarios, while supporting the practical limitations and constraints of laboratory hardware.

Through systematically mapping HIL models to hardware implementation, D5.2 provides a setup for subsequent laboratory validation. This process not only enhances reliability in the developed models but also builds the foundation for a safe and effective experimental testing in the next phase.

### 2.2 Integration of ESS component designs from WP2–WP4

The development of the downscaled real-time PHIL platform in D5.2 is based on the validated ESS component designs and methodologies delivered in earlier WPs. WP2 provided detailed models and design specifications for ESS modules and associated subsystems, which serve as the foundation for the physical configurations implemented in D5.2. WP3 contributed electro-thermal models and performance data, capturing critical characteristics such as electrical behaviour, heat generation, and state-of-charge dynamics, which are essential for accurately representing ESS operation during hardware-in-the-loop testing. WP4 provided the ESS prototypes and module designs and operational requirements, all of which are directly reflected in the hardware and test scenarios configured for the PHIL platform.

Throughout D5.2, careful attention has been given to ensuring that the ESS modules, emulators, and supporting systems are fully compatible with the requirements, interfaces, and operational scenarios defined in WP2–WP4. This integration approach ensures that the laboratory platform accurately replicates the dynamic performance and control strategies validated during earlier phases. Using these established component designs and data sets, D5.2 offers a practical environment for validating ESS technologies in real-time PHIL environment.

### 2.3 Purpose of downscaled PHIL for validation

The purpose of establishing a downscaled PHIL platform in D5.2 is to provide a practical and flexible link between simulation-driven validation and full-scale experimental testing of ESS technologies. Based on the structured model development strategy from D5.1, which enabled detailed real-time simulation and control of power system components, the PHIL platform

advances this work by allowing real hardware such as ESS modules, power converters, and control units to be physically integrated into a controlled laboratory environment.

This setup makes it possible to reproduce dynamic behaviours, operational challenges, and integration issues that may arise in actual systems, but at manageable voltage, current and power levels suitable for lab testing. The PHIL approach also enables direct, real-time interaction between hardware and simulation models, ensuring that measured signals and control responses accurately reflect true system performance. This approach enables the emulation and analysis of real operational conditions, particularly dynamic power management, using prototyped ESS modules. This is important for identifying issues that may not be fully visible in purely simulated or CHIL testing.

Moreover, the downscaled PHIL platform is designed with scalability allowing for different ESS configurations, operational profiles, and hardware-software combinations to be tested systematically. Also, this platform allows adding more power devices including ESS modules and power converters to the test. It supports continuous validation, where both component and system-level behaviours can be evaluated and optimized before transitioning to the full implementation and experimental phase in D5.3.

### 3 Hardware setup and components

To find the limitation of the PHIL setup, first it is necessary to describe the specifications of the components. This section provides information about the physical ESS and battery emulator, power converters, power supplies and amplifiers, real-time simulators and control interfaces, and measurements and protections.

Power system architecture of the three different use cases that discussed in D 5.1 are provided in Figure 1. Although they have different architecture, the main components are almost the same. However, there is a need for reconfiguration of the PHIL platform for every use case. In the following, the components of the PHIL platform are introduced in general.

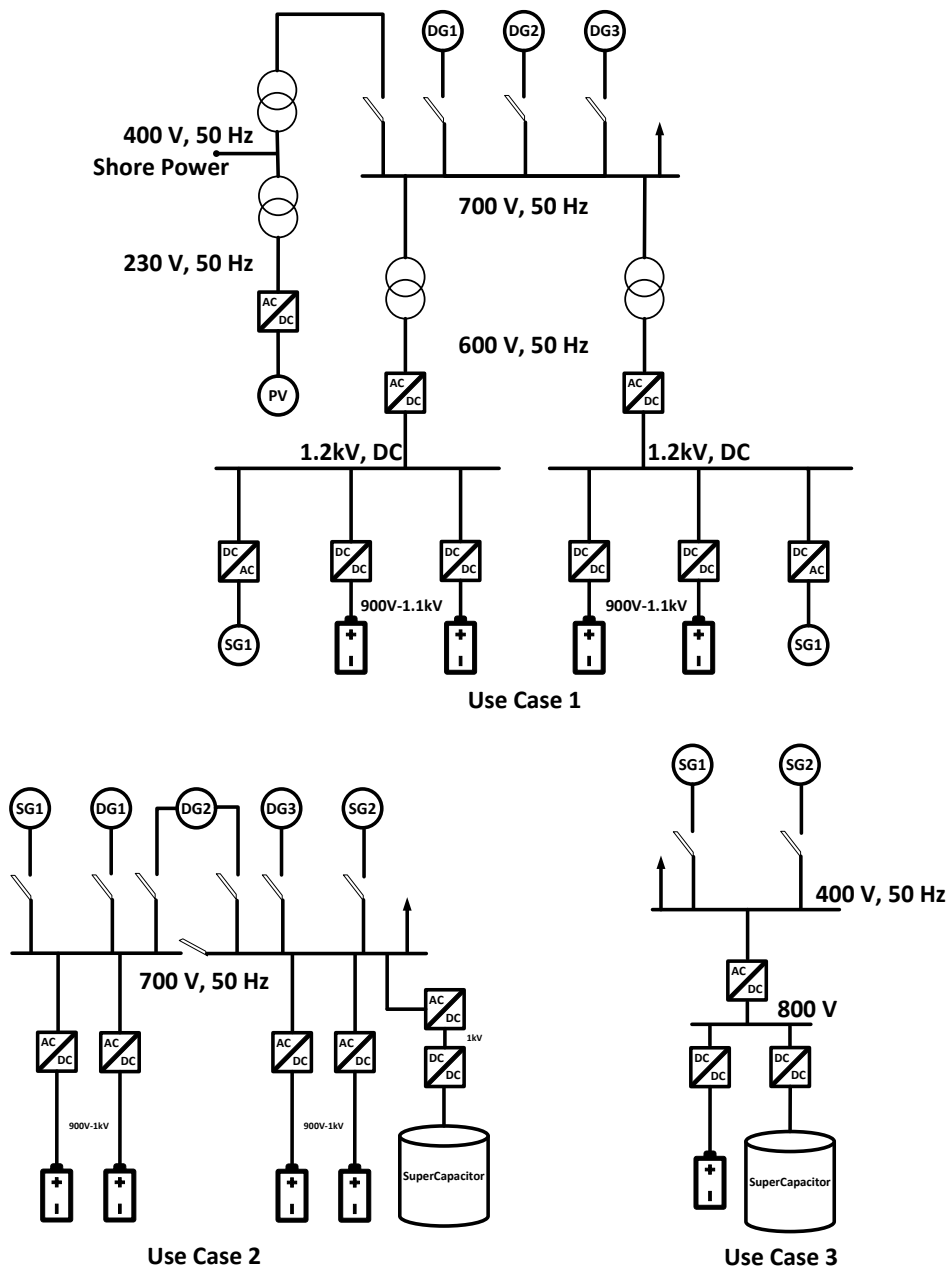


Figure 1: Shipboard power system for three use cases

### 3.1 Physical ESS (SSSB, SC, hybrid modules or emulators)

#### 3.1.1 Semi solid-state battery (SSSB)

The SSSB module is the first ESS under the test, and it is shown in Figure 2.



Figure 2: SSSB module

Basic electrical and thermal specifications are provided in Table 1. The battery pack is equipped with a BMS board which can communicate with other controllers through CAN port. The BMS can be powered both internally and externally, by configuring the provided switch. The main tests should be designed according to the maximum and minimum values for pack voltage and currents. The temperature of the cells is accessible through the CAN port and need to be considered during the operation.

Table 1: SSSB Specification

Parameter	Value
SSSB Minimum Voltage (V)	48
SSSB Maximum Voltage (V)	67.2
SSSB Nominal Voltage (V)	57
Maximum Charge Current (A)	34
Maximum Discharge Current (A)	-34
Minimum Cell Temperature (°C)	-20
Maximum Cell Temperature (°C)	50
Maximum Capacity at C/3	106Ah

#### 3.1.2 Semi Solid-state battery (SSSB) and Supercapacitor (SC)

The downscaled real-time PHIL platform in D5.2 integrates ESS modules for realistic hardware-based validation. For hybrid ESS configurations, integration of the SSSB and SC modules will be tested as a hybrid setup.

### 3.1.3 Energy storage emulator

For components not yet physically accessible or when specific operating conditions need to be simulated, hardware emulators are used to represent the expected behaviour of the ESS modules. This approach provides the flexibility to proceed with test scenarios even in the absence of the physical device.

The energy storage emulators are IT6006C-800-25 from ITECH that are bidirectional programmable DC power supplies, which is shown in Figure 3.



**Figure 3: Bidirectional programmable DC power supply (IT6006C)**

As the IT6000C series offers two-quadrant operation, it integrates the source and sink function in one unit and enables regenerative capability. Electrical specifications of the unit are provided in Table 2. This device is capable to provide constant voltage (CV), constant current (CC), I-V simulation, and adjustable output impedance modes. Considering these modes, it is possible to emulate the behaviour of the DC generation units including photovoltaics (PV) and battery energy storages. Supported interfaces for this unit are USB/CAN/LAN/digital IO, and RS232.

**Table 2: IT6006C specification**

Parameter	Value
Output Voltage Range (V)	0 - 800
Output Current Range (A)	0 - 25
Maximum Power (kW)	6

## 3.2 Power converters (DC-DC, DC-AC)

As T 5.2 and T 5.3 focus on validating the applied control techniques and testing the overall performance of ESS modules integrating with power converters, the PHIL platform includes a combination of DC-DC and DC-AC power converters to manage energy flow between the energy storage modules, grid emulator, and other system components, as the original power system architecture for the use cases is provided in Figure 1.

Both DC-AC and DC-DC converters are integrated with filters to minimize harmonics, support stability, and ensure high-quality waveforms for both AC and DC buses. This arrangement closely emulates real operational conditions.

All converters are coordinated through the platform’s **DSP** and CAN communication systems, ensuring real-time data exchange and precise execution of control strategies. The measurement circuits in the setup provide critical feedback for performance monitoring and safe operation.

This carefully designed converter setup allows the PHIL platform to flexibly and safely evaluate **ESS** integration, control performance, and dynamic interactions under a range of test scenarios, closely aligning laboratory results with realistic operating environments.

### 3.2.1 DC/DC converter

Bidirectional DC-DC converters are used to link the ESS modules (including SSSB, SC, and hybrid configurations) or battery emulators to the main DC bus, depending on the use case power system architecture. These converters manage both charging and discharging operation, providing CV or CC functions to test different control algorithms. In the PHIL platform, the battery emulator (or ESS module) is connected to the DC-DC converter with relevant filtering, ensuring safe and accurate operation.

The DC-DC converter utilized in this PHIL setup is Danfoss VACON NXI series that is shown in Figure 4.



**Figure 4: VACON NXI DC-DC converter**

The electrical specification for this converter is provided in Table 3. As it can be seen in Figure 1, DC-DC converters are the main interface power converters in all use cases and control the power flow of the ESS module. Through the digital IO ports and/or CAN port of the converter, it is possible to communicate with BMS of the ESS module and main controllers of the system.

**Table 3: DC-DC Converter specification**

Parameter	Value
Minimum Output Voltage (V)	465
Maximum Output Voltage (V)	800

Nominal Output Voltage (V)	550
Input Voltage Range (V)	0 - $V_{out}$
Maximum Output Current (A)	34.3
Maximum Input Current (A)	31
Maximum Switching Frequency (kHz)	16

### 3.2.2 DC-AC converters

For DC-AC conversion and AC bus interfacing, the PHIL platform may use two Danfoss converters including VACON NXI series three-phase grid-connected inverters and FC302 industrial drives. These inverters act as a key interface between the DC bus and the AC side, enabling bidirectional power flow through L (or LCL) filter and synchronize with the grid emulator with PLL. The inverters can operate with customized control, supporting dynamic test scenarios and accurate replication of grid-connected conditions. VACON NXI and FC302 are shown in Figure 5, and their specifications are provided in Table 4 and Table 5, respectively.



**VACON NXI grid-connected inverter**



**FC302 with Customized control board**

**Figure 5: DC-AC converters**

**Table 4: VACON NXI grid-connected inverter specifications**

Parameter	Value
Minimum Input Voltage (V)	465
Maximum Input Voltage (V)	800
Nominal Input Voltage (V)	550
Output Voltage Range (V)	0 - $V_{in}$
Maximum Output Current (A)	4.3
Maximum Input Current (A)	4.4
Maximum Switching Frequency (kHz)	16

**Table 5: FC302 industrial drive specifications**

Parameter	Value
Minimum Input Voltage (V)	400
Maximum Input Voltage (V)	800
Nominal Input Voltage (V)	550
Output Voltage Range (V)	0 - $V_{in}$
Maximum Output Current (A)	9.9
Maximum Input Current (A)	11
Maximum Switching Frequency (kHz)	16

### 3.3 Programmable power supply, amplifier, and load

The PHIL platform is equipped with four-quadrant programmable power supplies, capable also operating as amplifiers or loads to emulate a wide range of operational scenarios. A four-quadrant switching device is capable of providing all these functionalities. In this work, two Regatron TCS.ACS devices are utilized, which the single device is shown in Figure 6. In the following, each operational mode of these devices is explained.

**Figure 6: Regatron TCS.ACS**

#### 3.3.1 Power Supply

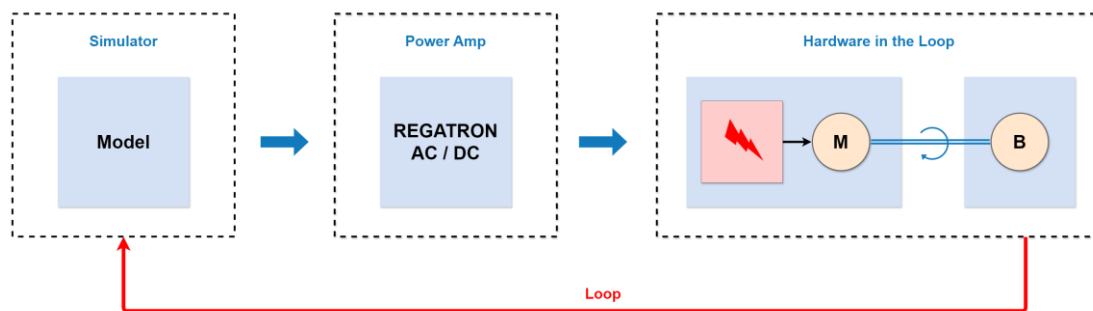
In this mode the device can be used as a programmable power supply that can be set for both DC and AC applications. The electrical rating for a single module is provided in Table 6. It can be programmed either in voltage controlled or current controlled modes, based on the use case scenario.

**Table 6: Four-quadrant Regatron TC.ACS specifications**

Parameter	Value
Power Range (kVA)	0 - 50
AC RMS Voltage Range (V)	3 x 0 - 305
AC RMS Current Range (A)	3 x 0 - 72
DC Voltage Range (V)	0 - ±830
DC Current Range (A)	0 - ±40

### 3.3.2 Power Amplifier

Power amplifiers are used to amplify control signals from an electrical model in real-time simulator to emulate higher voltage and current levels, making it possible to simulate electrical components in the laboratory setup in a PHIL setting. PHIL simulation integrates physical hardware and software models in a closed loop system, offering versatile opportunities to analyse the behaviour of complex systems in different scenarios. As shown in Figure 7, this system includes a real-time simulator driving a power amplifier connected to the physical components. The TC.ACS device works as a power amplifier in this setup.



**Figure 7: Power hardware-in –the-loop principle [1]**

### 3.3.3 Load

In this mode the device represents a programmable load that can be configured to simulate a variety of load profiles, including dynamic and steady-state demands. This allows for testing rapid load changes, in which loads can be adjusted for resistance, inductance, or capacitance as required by the specific test case.

The devices operating both as the power amplifiers and programmable loads are integrated with the control and monitoring systems of the PHIL platform. Real-time adjustments, data logging, and safety interlocks are managed via the DSP and measurement circuits, allowing for precise control and replicability of test conditions. This combination of power amplification and flexible loading capabilities ensures that the PHIL platform can provide realistic, reliable, and repeatable validation of ESS modules, converters, and system integration strategies.

## 3.4 Control interface

There are several control interfaces in a PHIL setup, in which the main control systems in this setup are real-time simulator that controls power amplifier, and microcontrollers that control power converters and manage communications between different devices such as BMS board, power converters, power amplifier, and real-time simulator.

The control interfaces are connected to the PHIL platform using a combination of CAN bus, analog/digital I/O, and other industrial communication protocols. This ensures reliable and high-speed data transfer between the controllers, real-time simulator, and physical devices including Danfoss FC302 inverters, DC-DC converters, grid emulator, and measurement systems. The modular setup makes it possible to switch between different test scenarios with minimum reconfiguration and enabling PHIL experiments within the same platform. In addition, the measurement and monitoring boards are fully integrated into the control framework, providing real-time data acquisition, and system monitoring for all test scenarios.

### 3.4.1 Real-time simulator

In this platform, the Typhoon HIL 402 and OPAL-RT 4510 are utilized to run digital models of the shipboard power systems that cannot be tested physically. They operate in fast computation steps (typically 1–5 microseconds), which is critical for accurately capturing the dynamic behavior of power electronic devices and control systems, based on the accuracy level that is needed for the test. The simulator's flexible analog and digital I/O, along with support for protocols such as CAN and Ethernet, allows for seamless communication and closed-loop interaction with external controllers, power converters, and measurement circuits.

When there is a need to focus on detailed modelling of power converters and switching devices, Typhoon HIL 402 is utilized. And in the case that the whole power system needs to be emulated, OP 4510 is utilized to emulate the main DC or AC bus of the shipboard power system.

### 3.4.2 Controllers

To implement control systems and power management, the platform utilizes both the dSPACE MicroLabBox and Texas Instruments C2000 DSP boards. The dSPACE MicroLabBox allows for rapid development, testing, and deployment of high-level control algorithms including supervisory and protection controls for power converters and ESS modules. The TI C2000 DSP is employed for fast, low-level control tasks such as converter switching, current/voltage regulation, and high-speed protection logic. Both controllers can interface directly with the real-time simulators via configurable analog/digital I/O and communication protocols.

The coordinated use of both dSPACE and TI C2000 DSPs allows for a hierarchical control structure within the PHIL platform. This controller platform supports that all operational scenarios, protection requirements, and control strategies can be thoroughly tested, adjusted, and validated, supporting the evaluation of ESS performance.

### 3.5 Measurement and protection systems

Accurate measurement and protection systems are fundamental to the safe and effective operation of the downscaled real-time PHIL platform. The platform integrates sensors and monitoring circuits to capture all critical electrical and thermal variables in real time. The measurement circuit includes current and voltage sensors, and BMS boards. Analog signal conditioning circuits ensure that sensor outputs are compatible with the input requirements of the controllers and real-time simulators. Measurement channels are digitized and made available for both control loops and data logging, allowing real-time monitoring of variables such as voltage, current, and temperature.

The protection of the PHIL setup is critical to ensure safe and reliable operation. This involves implementing robust safety measures such as overcurrent, overvoltage, and thermal protection mechanisms to safeguard the hardware environment. As PHIL system integrates DRTS with physical power components, requiring precise coordination between the simulation platform and power amplifiers to prevent instability or equipment damage. Protective features like fault detection, isolation switches, and emergency shutdown protocols are essential to mitigate risks from electrical faults or unexpected system behavior. Additionally, proper grounding and galvanic isolation between power devices and signal measurement board need to be considered ensuring accurate test results while maintaining operator safety and equipment longevity. These protective functions are already installed on the introduced components such as power amplifier and power converters. However, additional fuses and breakers will be added to ensure safe and reliable operation in different test conditions.

## 4 Architecture of the PHIL platform

To design the downscaled PHIL platform, the first step is to test the introduced components separately, to be sure that they can operate safe and proper in the different case scenarios. Next, different architectures of the PHIL testing will be designed to reach the whole system testing. A summary of the testing process is provided below.

- Component level testing:
  - Components are tested in isolation before being introduced into the PHIL system.
  - Data is collected and compared against reference models from simulation (D5.1) to validate accuracy and consistency.
- Integration mode:
  - The components will be integrated based on the designed PHIL setup, minimizing the risk of faults or damages during PHIL experiments.

### 4.1 Component level testing

Component level testing is essential step within the PHIL platform development, designed to ensure that each individual subsystem such as ESS, power converters, power amplifier, and control hardware meets the required performance, safety, and reliability criteria before full system integration. This approach supports the identification and mitigation of issues at the earliest possible point, thereby enhancing the reliability and repeatability of subsequent system-level testing.

## Tested Components:

- ESS modules:
  - SSSB and SC modules will be tested independently, verifying its electrical (voltage/current) and thermal characteristics under controlled charge and discharge cycles with the bidirectional DC power supply.
  - Parameters that are sensed with the BMS board of the module will be measured to be sure that the BMS can communicate with other devices accurately.
- Power converters:
  - DC/DC and DCAC converters will be tested for voltage and current regulation, efficiency, dynamic response, and power quality measurements. The converters will be connected to the programmed DC and/or AC power supplies.
  - Component testing includes closed-loop control validation, communicating with external devices, and the assessment of safe operating boundaries.
- Measurement and protection circuits:
  - All voltage and current sensors, ADCs, and peripherals of control system will be calibrated and tested for signal integrity, noise immunity, and response time.
  - Fault detection and rapid shutdown functions are validated using simulated overcurrent and overvoltage conditions.
- Control hardware:
  - Each controller is tested for reliable I/O communication, correct execution of control functions, and response to real-time signals from measurement and protection systems.
  - Controller hardware-in-the-loop (CHIL) experiments will be conducted in advance to confirm performance of the closed-loop control system.

## 4.2 PHIL platform

After component level testing, a more realistic test with all the components of the shipboard microgrid is required to verify the performance of ESS, power converters, and proposed control and power management systems. As it is difficult to have a real shipboard power system in the lab, a PHIL setup should be established, in which the hardware and physical power components are connected to real-time simulated components through a power amplifier.

PHIL is usually developed with downscaled specifications considering limitation of the hardware test setup in the laboratory to reduce the risks of testing even in extreme conditions and costs. This method is mainly validating the dynamic behaviour related to control and power management of the system [3].

### 4.2.1 Functional principle and amplification

Based on the test specification, PHIL configurations can be different. One or more power components can be the DUT, and rest of the system can be simulated in a digital real-time simulator (DRTS). DUT and DRTS are hardware and software parts, respectively, in which they are connected to each other through an interface. Despite CHIL, in PHIL, amplification is necessary. Also, CHIL introduces discrete time behaviour only, but PHIL introduces additional errors that can cause inaccuracy and instability issues.

Various interface algorithm for connection between DUT and DRTS are damping impedance method, partial circuit duplication method, and ideal transformer method (ITM). ITM, which is the most famous interface algorithm, requires an amplifier to amplify the signal fed out from DRTS to the required power level and then fed back to DRTS using a sensor [2].

A generic circuit is shown in Figure 8 that includes a voltage source with series impedance and a DUT that can be a load. The voltage source is representing an AC or DC bus in a power system e.g. a diesel generator that is not available in the laboratory. To replicate this circuit, a general diagram for the corresponding PHIL setup with ITM interface is provided in Figure 9.

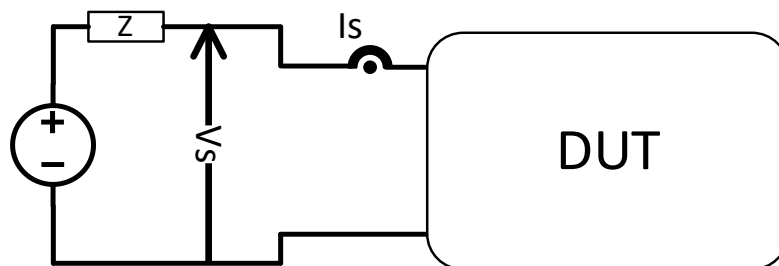


Figure 8: Generic circuit for testing

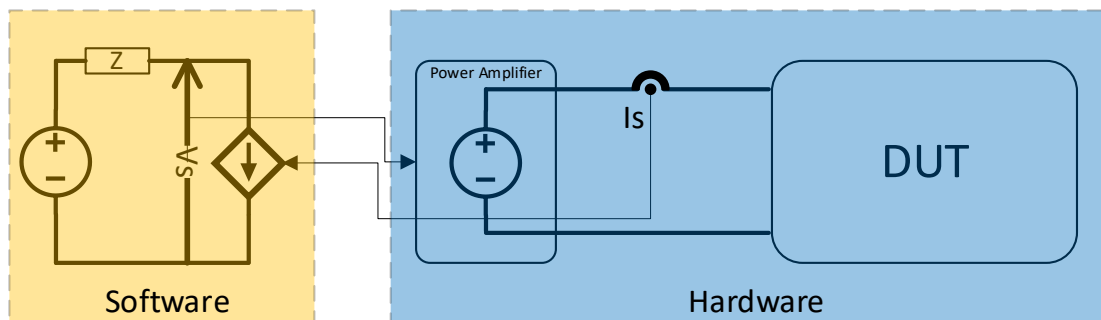


Figure 9: PHIL illustration

Based on Figure 9, PHIL setup consists of two main parts, hardware and software. In software part, an AC or DC bus that is connected to a power system e.g. grid or a diesel generator is implemented in DRTS. The hardware part includes power amplifier and DUT. The DUT can be one or more power devices. For example, it can be only one ESS module, or the ESS connected to a power converter. The output voltage signal in DRTS is measured and applied to the power amplifier, and amplified to higher voltage levels, based on the downscaled voltage rating. To close the loop in the setup, the conducted current is sensed ( $I_s$ ) and fed to the ADC port of DRTS. This current will flow inside the model with determined gain to be matched with the design and be synchronized with the hardware part. In short, voltage of DRTS is amplified and applied to DUT, and the current of the DUT is inserted as a current source in the simulation. It is the basis of a PHIL setup that is going to be designed for all three use cases.

It should be noted that the interface algorithm can be either voltage type or current type, in which in voltage type the power amplifier will amplify the voltage and sense the DUT current, and in current type, the power amplifier will amplify the current and sense the DUT voltage.

### 4.2.2 Stability and accuracy

When a system is decoupled at a specific power exchange point and an interface is added to complete the power flow loop, it introduces delays and bandwidth limitations that can compromise stability. Ideally, an interface with infinite bandwidth and zero delay is preferred, but in practice, this is unattainable due to conversion times in ADC and DAC, DRTS computation, and amplifier response, all of which contribute to delays and restricted bandwidth [2]. Therefore, stability analysis is required to ensure stable operation of the closed-loop system. This stability analysis can be done theoretically using Nyquist and Routh–Hurwitz criteria and/or with simulation.

To analyse the stability of the system, transfer function of amplifier and delays should be considered. Usually, a low pass filter (LPF) is inserted on feedback current to achieve stability, although it reduces accuracy of the PHIL result. Also, additional transfer functions can be designed and inserted to achieve stability, while maintaining a reasonable level of accuracy.

A PHIL configuration for the Thevenin model of a circuit is shown in Figure 10. The DUT is a resistor ( $R_h$ ) in the hardware part, and a resistor ( $R_s$ ) is also inserted into the DRTS model in the software part. To be more specific, the DAC and ADC of DRTS are also shown. The sensed voltage in the software part is converted to an analogue signal and sent to the analogue port of the power amplifier. On the other side, the sensed current in the hardware part is fed to the ADC of RTDS and converted to a digital signal. An optional digital LPF is considered in this design to improve the stability of the system. Hence, the sensed current is applied to the dependent current source in the software to complete the PHIL arrangement.

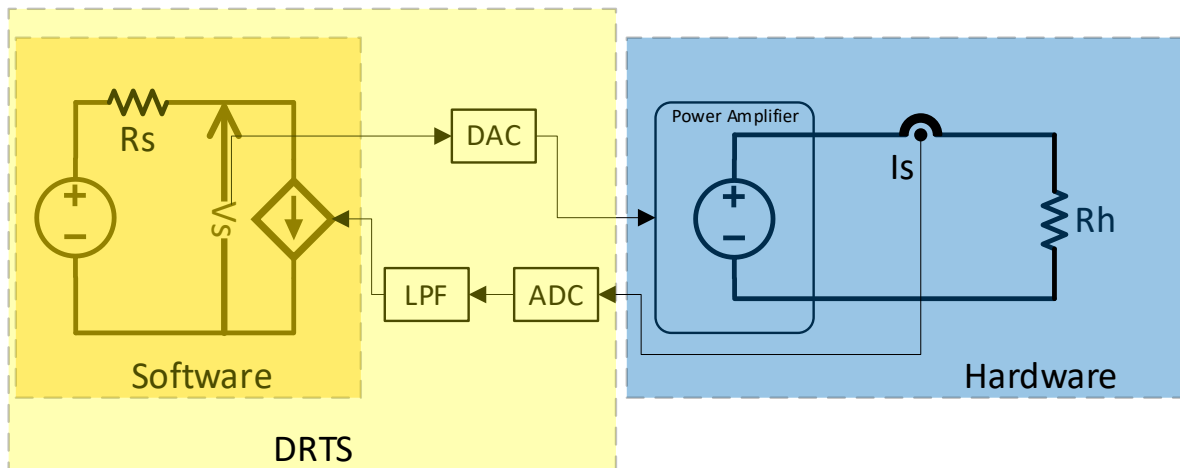
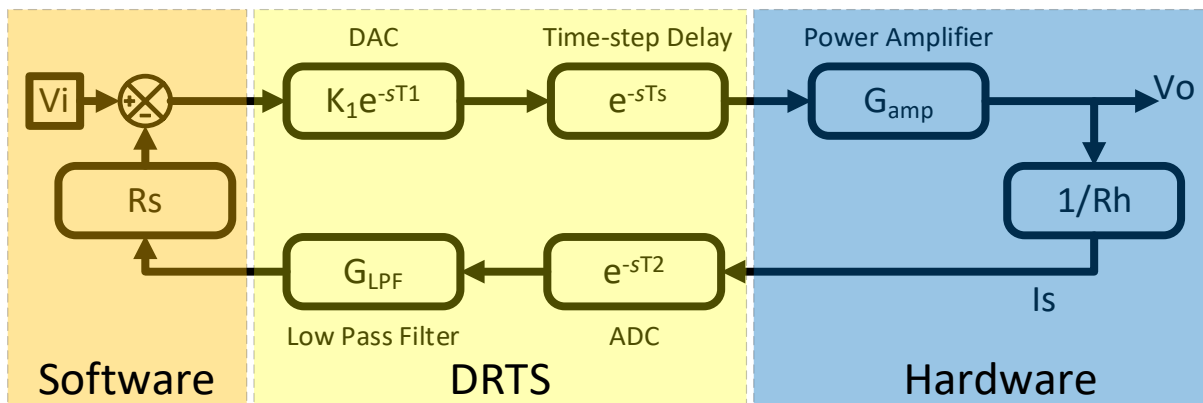


Figure 10: PHIL configuration for a Thevenin model

The control block diagram of the proposed PHIL system is depicted in Figure 11. As it is a voltage type ITM, voltage signal in the simulation is converted to an analogue signal through DAC of DRTS with one time-step delay, and then, applied to the power amplifier and amplifies based on the power amplifier transfer function ( $G_{amp}$ ).  $T_1$  and  $T_s$  are DAC computational time delay and simulation time-step delay, respectively. The sensed current is fed back to the ADC of DRTS and processed by digital LPF.  $T_2$  is the conversion time of ADC that cause a delay in the system, and  $G_{LPF}$  is the LPF transfer function. The filtered signal is then applied to the circuit in the simulation inside the DRTS.



**Figure 11: Control system block of the PHIL setup**

It should be noted that, the ADC and DAC delays play an important role in the system stability and their transfer functions should be considered. Besides the gain of the power amplifier transfer function, delay of the power amplifier needs to be taken into the account as well. Usually, this information can be found in the documentation of the devices, however, a frequency analyser can extract the frequency response of ADC, DAC, and power amplifier.

In addition to the LPF, a controller can be implemented in DRTS and software part to stabilize the PHIL loop and increase the stability margin of the system. In overall, the primary issue is the time delay in the PHIL arrangement and its impact on stability, while the secondary challenge is achieving near real-time outputs with tolerable inaccuracies.

### 4.3 PHIL setup in the lab

Considering introduced components in section 3, the PHIL setup can be made up of:

- Regatron TCS.ACS as power amplifier
- ESS modules with DC-DC and DC-AC converters as DUT
- OPAL-RT and Typhoon HIL as DRTS

All major subsystems are modular and can be reconfigured to represent different shipboard architectures or to test multiple operational scenarios.

A key strength of the PHIL platform developed in this deliverable is its flexible and seamless integration of both real hardware components and digitally simulated elements, supporting a wide variety of experimental scenarios. The architecture enables precise coupling of physical devices (such as ESS modules, power converters, and programmable loads) with real-time simulation models of the shipboard power system, allowing for dynamic interactions between the virtual and physical domains.

#### 4.3.1 Real elements

- Physical ESS modules: SSSB, SC, and hybrid modules are connected to the DC-DC converter and participate in the experiments as real hardware under test.
- Power Converters: Danfoss grid-connected inverters (DC-AC) and bi-directional DC-DC converters are used to manage energy flows between the storage modules, DC bus, and power amplifier.

- Power supply, amplifier, and programmable loads: Hardware loads and the power amplifier introduce realistic operational demands and grid-side dynamics.
- Controllers and measurement circuits: dSPACE MicroLabBox, Texas Instruments C2000 DSP, and sensors are all present as physical hardware, executing real-time control and protection functions.

#### 4.3.2 Simulated elements

- Ship power system: Ship power system (including generators, diesel engine) is simulated in DRTS. This simulation generates dynamic voltage, current, and load profiles for coupling with the hardware.
- Virtual ESS modules: In scenarios where scaling is needed beyond the available physical hardware, ESS modules, i.e., SCs are represented virtually and their behaviour emulated by the simulator, with amplification as needed through hardware emulators.
- Supervisory and mission profiles: Operational profiles, system-level management, and various test scenarios are run in software and communicated to the hardware layer in real time.

#### 4.3.3 I/O coupling and signal exchange

To ensure safe, accurate, and high-speed interaction between real and simulated elements, the PHIL platform uses I/O coupling strategies:

- Analog and digital interfaces: Real-time data (voltage, current, temperature, status flags) is exchanged through high-speed analog/digital I/O lines between Typhoon HIL, controllers, power electronics, and measurement systems.
- Communication protocols: CAN bus and other industrial protocols are employed for data transfer, especially for commands, feedback, and supervisory signals.
- Isolation and signal conditioning: All I/O channels are protected with isolation and signal conditioning circuits to prevent ground loops, protect against voltage transients.
- Closed-loop operation: Measurements from the hardware are fed back into the simulation environment, allowing real hardware and virtual elements to influence each other dynamically, as in a real integrated shipboard power system.

## 5 Downscaled PHIL system design

### 5.1 Scaling strategy for downscaled system

The scaling strategy for the PHIL platform is designed to emulate the essential dynamics and operational challenges of a real shipboard power system in the laboratory environment. This approach involves translating the physical parameters and system architecture of the shipboard system into accessible voltage, current, and power levels while ensuring that all critical relationships and behaviours are preserved.

According to Similitude Theory, two systems have the same behaviour (under the same experimental conditions) if their dimensionless variables have the same values. Then, it is possible to compare the systems with each other by comparing their dimensionless quantities [3]. In this work, voltage and current scaling factors, namely  $S_v$  and  $S_i$  are introduced to reduce the scale of the system based on the laboratory limitations. They represent the downscaled value for voltage (current) to the original value of the voltage (current). These scaling should be done based on the PHIL architecture and the use case topology, however, as these systems have several similarities with each other, a general guideline is provided here.

#### **Voltage and current downscaling:**

- The main shipboard DC bus, typically operating at 1-1.2 kV, needs to be downscaled to the maximum voltage of 800 V DC in the laboratory setup.
- The maximum phase voltage of the AC bus is 432 V, 50 Hz, in line with the TC.ACS.
- Output voltage of all energy storage modules (SSSB, SC) are less than 75 V DC;
  - SSSB: 48–67 V, up to 34 A
  - SC: up to 75 V, up to 120 A
- In most cases, the inverters output current and ESS module are limiting the current rating of the system at 4.1 A (SSSB and inverter) or 11 A (SC and Danfoss FC302). So, based on the topology selection and availability of the inverter, these values will apply.

#### **Functional and topological preservation:**

- The downscaled platform reflects the shipboard topology by mapping all major subsystems generators, inverters, DC-DC and DC-AC converters, ESS modules, and loads onto laboratory hardware.
- Programmable power amplifier and loads are used to reproduce generator dynamics and operational scenarios, enabling realistic use-case-based validation.
- The use of virtual modules and battery emulators allows the system to flexibly represent different ESS configurations and supports easy expansion for test cases.

#### **Mapping of use cases:**

- The testbed can be configured to reproduce downscaled use cases, each directly reflecting the operational and architectural features of the original shipboard system.

- This mapping ensures that key system behaviours, power flow pathways, and control interfaces remain representative. All voltage and current levels, as well as system boundaries, have been selected to ensure full compatibility with the control, measurement, and protection schemes described in Chapter 3.

## 5.2 Use case 1: SSSB

The shipboard power system for use case 1 is shown in Figure 12. As discussed earlier, due to the unavailability of power system components such as diesel generators (DG), shaft generators (SG), and power converters, and the limitation of power devices ratings, there is a need for a downscaled PHIL setup.

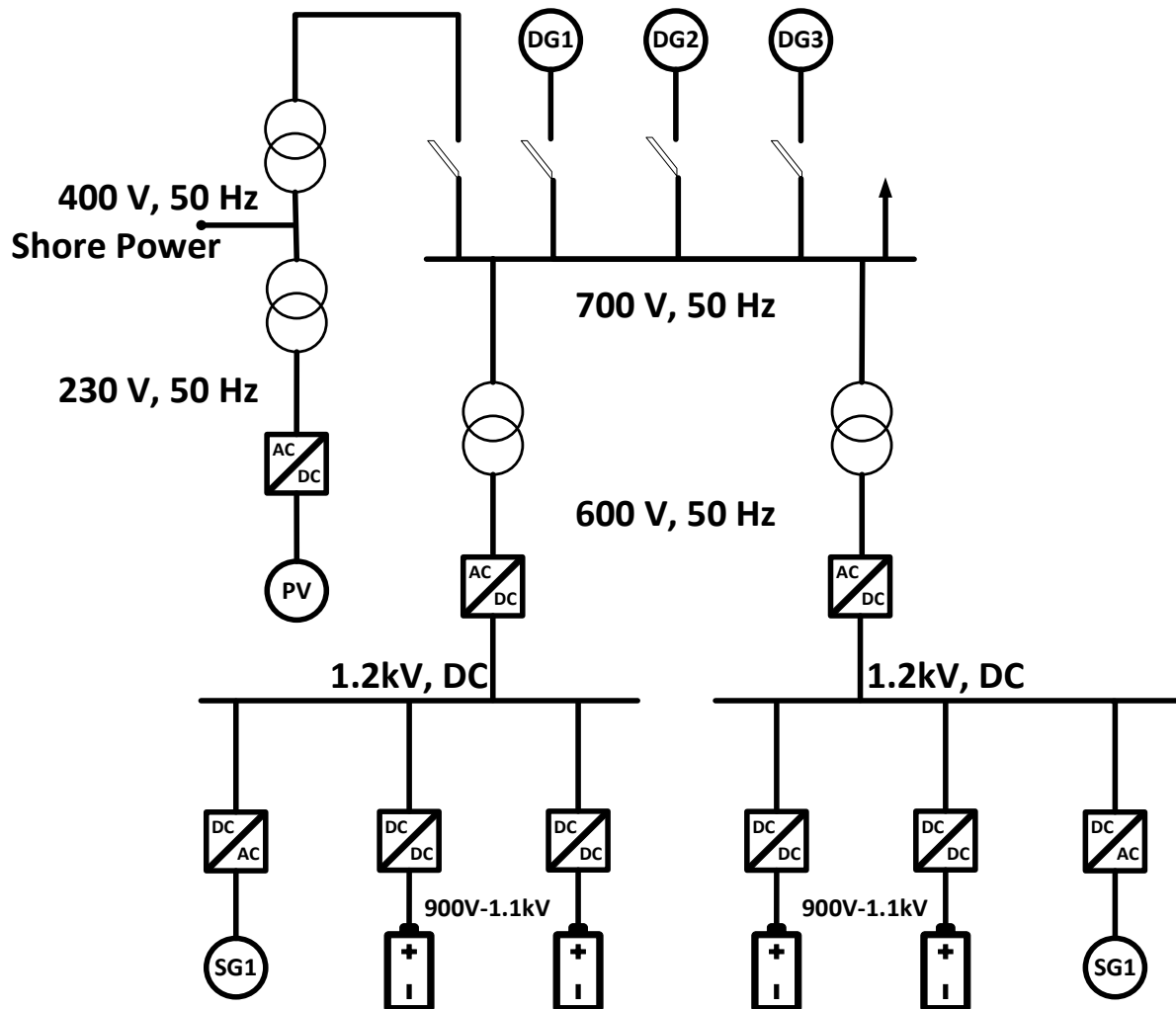


Figure 12: Shipboard power system for use case 1

Considering all the introduced limitations and PHIL principles, the PHIL configuration for the use case 1 is provided in Figure 13. A step-by-step PHIL testing will be done to achieve the whole system. First, the SSSB module will be tested independently, connected to the power amplifier that is emulating the whole shipboard power system. Next, DC-DC converter will be added, and at the end, the DC-AC converter will be included to finalize the PHIL configuration.

The downscaled voltage of every bus is shown in the PHIL arrangement. This downscaling is done considering the scaling strategy and limitations of the available power devices. In this

configuration, Danfoss VACON NXI inverter can be used, so the maximum output current in the AC bus should be set to 4.1 A to prevent damaging the SSSB module and the inverter. Limitations in this use case can be summarized as:

Parameter	Value
Maximum Current for AC bus	4.1 A
Maximum Output Voltage of SSSB	67 V
Maximum Output Voltage of DC-DC	550 V
Maximum RMS Output Voltage for AC bus	305 V

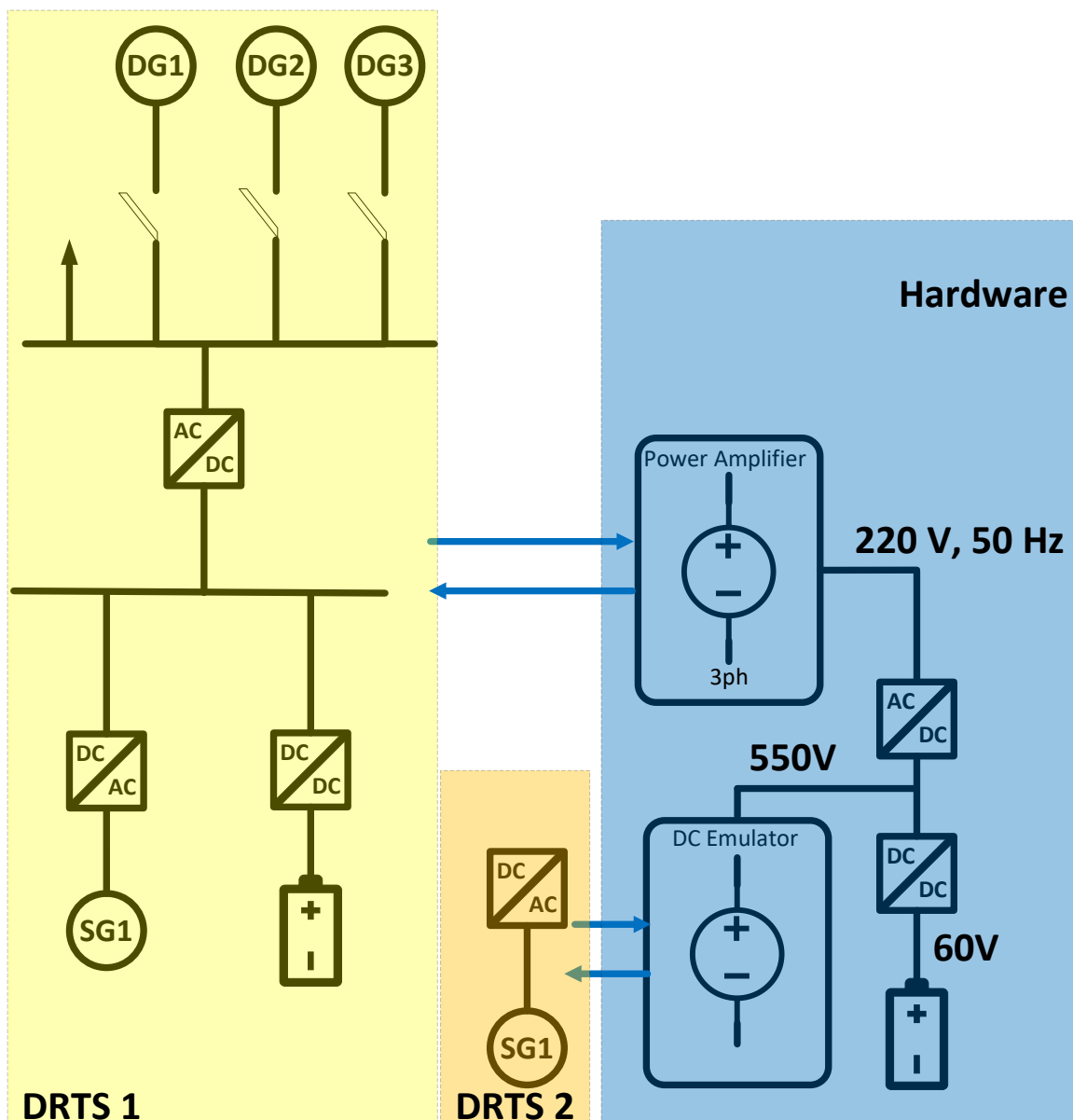


Figure 13: PHIL arrangement for use case 1

### 5.3 Use case 2: SC

The shipboard power system for use case 2 is shown in Figure 14. As discussed earlier, due to the unavailability of power system components such as diesel generators, shaft generators, and power converters, and the limitation of power devices ratings, there is a need for a downscaled PHIL setup.

Considering all the introduced limitations and PHIL principles, the PHIL configuration for the use case 2 is provided in Figure 15. A step-by-step PHIL testing will be done to achieve the whole system. First, the SC module will be tested independently, connected to the power amplifier that is emulating the whole shipboard power system. Next, DC-DC converter will be added, and at the end, the DC-AC converter will be included to finalize the PHIL configuration.

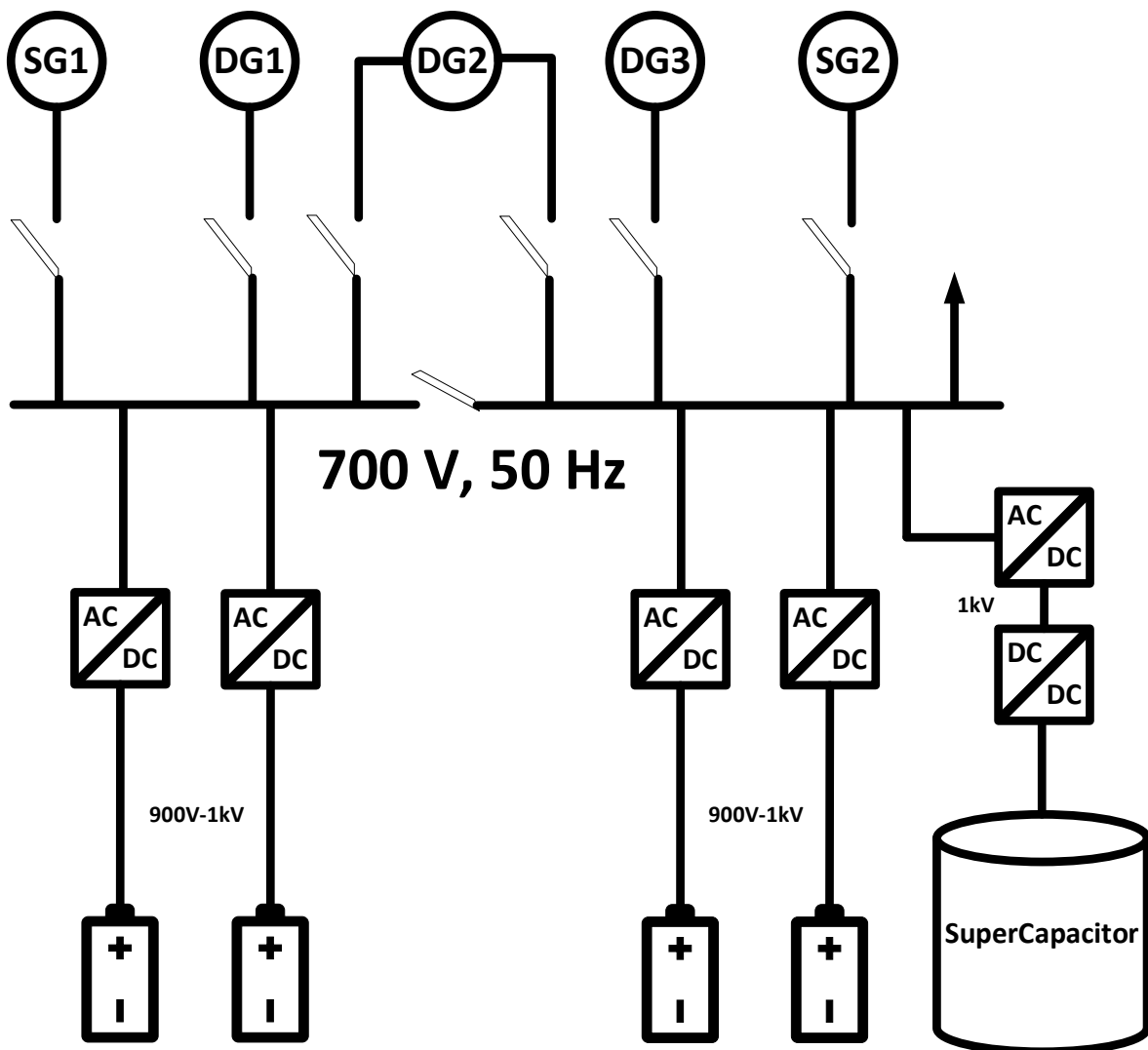


Figure 14: Shipboard power system for use case 2

The downscaled voltage of every bus is shown in the PHIL arrangement. This downscaling is done considering the scaling strategy and limitations of the available power devices. In this configuration, Danfoss FC302 inverter can be used, so the maximum output current in the AC

bus should be set to 11 A to prevent damaging the SC module and the inverter. Limitations in this use case can be summarized as:

Parameter	Value
Maximum Current for AC bus	11 A
Maximum Output Voltage of SC	75 V
Maximum Output Voltage of DC-DC	550 V
Maximum RMS Output Voltage for AC bus	305 V

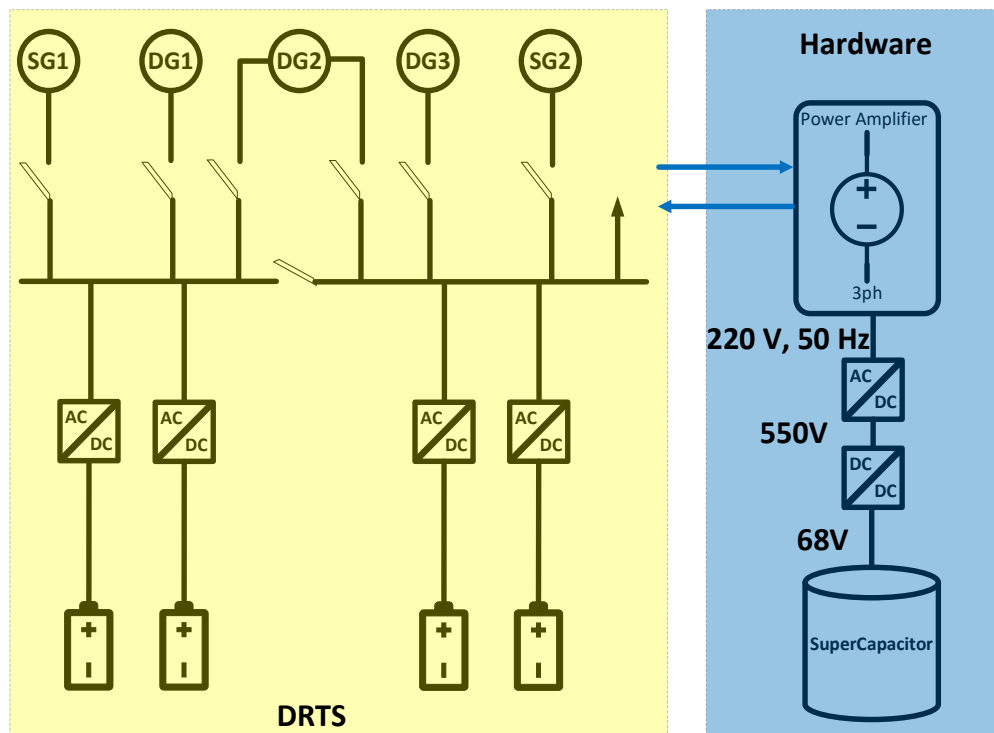
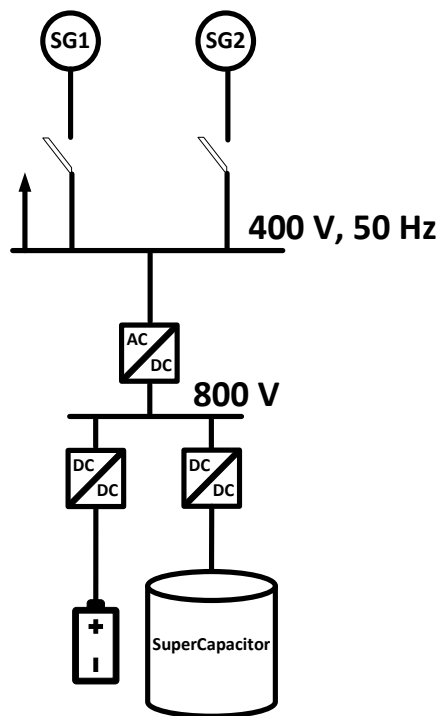


Figure 15: PHIL arrangement for use case 2

### 5.4 Use case 3: Hybrid

The shipboard power system for use case 3 is shown in Figure 16. As discussed earlier, due to the unavailability of power system components such as diesel generators, shaft generators, and power converters, and the limitation of power devices ratings, there is a need for a downscaled PHIL setup.



**Figure 16: Shipboard power system for use case 3**

Considering all the introduced limitations and PHIL principles, the PHIL configuration for the use case 3 is provided in Figure 17. In this use case, there is no power converters involved, and the SSSB and SC modules are connected to two separate power amplifiers that emulate the common DC link in the shipboard power system. Therefore, two RTDS devices are utilized, that can communicate with each other to ensure proper and synchronized operation. Limitations in this use case can be summarized as:

Parameter	Value
Maximum Current for SSSB (or SSSB)	34 A
Maximum Current for SC	Not Finalized
Maximum Output Voltage of ESS modules	68 V

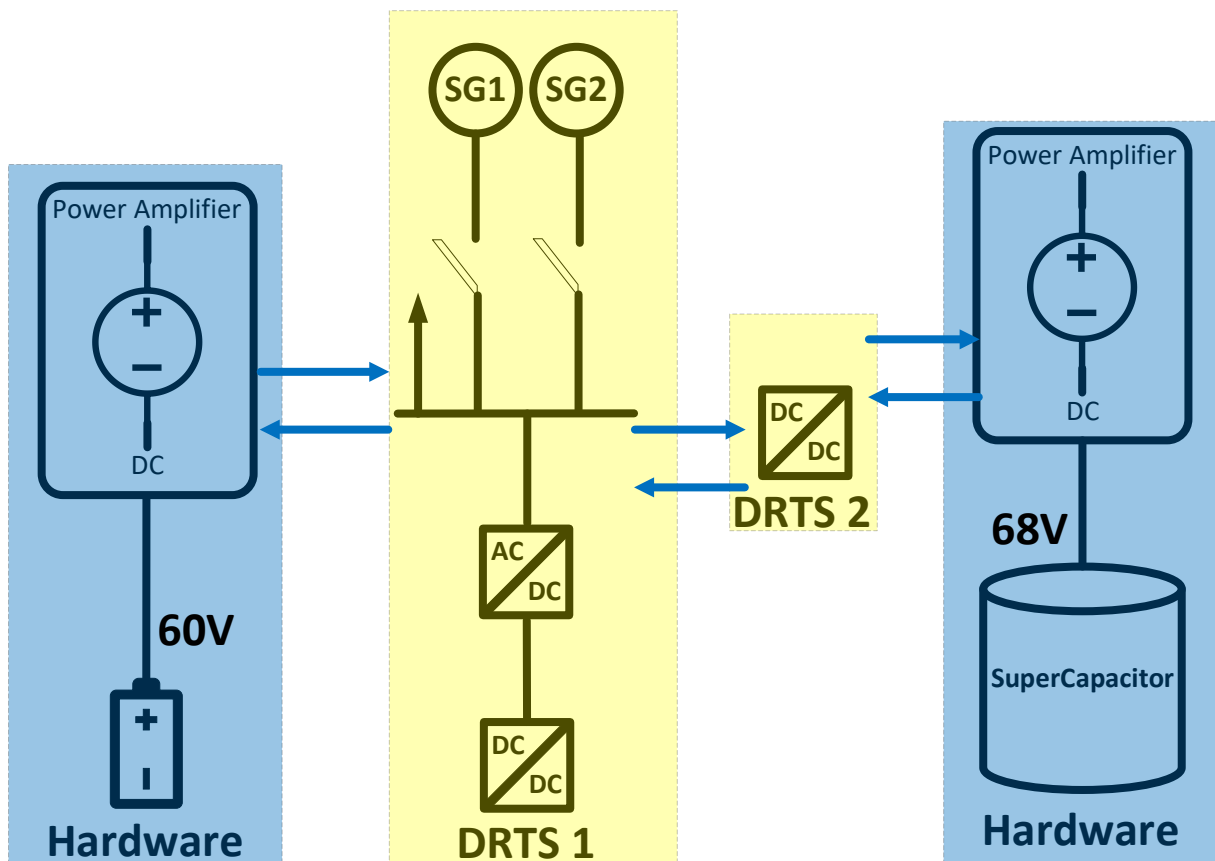


Figure 17: PHIL arrangement for use case 3

## 6 Conclusion, future work, and transition to D5.3

### 6.1 Summary of D5.2

This deliverable, D5.2 represents an important step in the transition from pure simulation to laboratory validation within the WP5. Using the simulation models, control methods, and ESS designs from earlier work (D5.1 and WP2–WP4), D5.2 has set up a flexible PHIL platform. This setup can connect both real hardware and digital simulations, and it can be adjusted or expanded as needed.

D5.2 describes the step-by-step process used to select, configure, and connect the main hardware components such as SSSB, SC, hybrid ESS modules (and their emulators), power converters, programmable loads, control platforms, and measurement systems. The PHIL setup was designed to emulate shipboard power systems but works safely at lower voltages and currents that are suitable for lab testing, using careful scaling.

D5.2 achieved the following:

- Design process and working principles of PHIL platform to test different shipboard power systems.
- Connecting HIL simulation models to real hardware (DUT) through power amplifier, so that results from simulations can be tested and used in hardware setup.
- Building the PHIL setup for all three use cases, each one matching a real shipboard energy storage scenario but using lab equipment, to see how the systems interact and perform, and to test the overall performance of ESS modules.
- Preparing the PHIL setup in a way that the developed control systems can be tested and validated withing the PHIL platform.
- Preparing the PHIL setup in a way that the design of ESS and power converters in virtual models can be tested and validated withing the PHIL platform.
- Utilizing real-time simulator and control tools (Typhoon HIL, OPAL-RT, dSPACE MicroLabBox, and TI C2000 DSP) to find out how these digital systems can communicate with each other.
- Setting up of I/O coupling and measurement infrastructure to provide accurate data exchange between simulated and physical systems.

### 6.2 Transition to next tasks

The setup of the downscaled PHIL platform has been completed in D5.2, so WP5 can now move on to D5.3. In D5.3, the main focus will be to use the developed PHIL arrangements from D5.2 to perform real-time HIL experiments and tests with the integrated energy storage modules, converters, loads, and control system.

The transition to D5.3 will involve:

- Final integration and configuration of ESS prototypes (such as the SC and hybrid modules as soon as available).
- Fine-tuning the test plans and operating scenarios, so that tests match both the simulation results.
- Running lab tests that cover normal operation, changes in load, and possible faults, to fully check how the system performs, how stable it is, and how well it can be controlled.

- Validation KPIs and comparing results with earlier simulations (D5.1) and module testing from WP4.

The experimental results from D5.3 will complete the feedback loop between simulation, hardware, and real operation.

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#	Partner	Partner full name
1	FM	FLANDERS MAKE
2	CEA	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES
3	ABEE	AVESTA BATTERY & ENERGY ENGINEERING
4	SIE	SIEMENS INDUSTRY SOFTWARE SAS
5	UVA	VAASAN YLIOPISTO
6	I2M	I2M UNTERNEHMENSENTWICKLUNG GMBH
7	GRIM	GRIMALDI EUROMED SPA
8	INLS	INLAND SHIPPING SRL
9	FV	FUNDACION DE LA COMUNIDAD VALENCIANA PARA LA INVESTIGACION, PROMOCION Y ESTUDIOS COMERCIALES DE VALENCIAPORT
10	AUTH	ARISTOTELIO PANEPISTIMIO THESSALONIKIS
11	SOER	FUNDACION CENTRO TECNOLOGICO SOERMAR
12	FMAR	FORMARE- POLO NAZIONALE PER LO SHIPPING SRL
13	ISSN	INSTITUTE FOR SUSTAINABLE SOCIETY AND INNOVATION
14	FS	CONSTRUCCIONES NAVALES P FREIRE SA

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## List of abbreviations

<b>Abbreviation</b>	<b>Description</b>
AC	Alternating Current
ADC	Analog-to-Digital Converter
BMS	Battery Management System
CAN	Controller Area Network (communication protocol)
HIL	Hardware-in-the-Loop
CHIL	Controller Hardware-in-the-Loop
PHIL	Power Hardware-in-the-Loop
PV	Photovoltaics
CV	Constant Voltage
CC	Constant Current
DAC	Digital-to-Analog Converter
DC	Direct Current
DC-AC	Direct Current to Alternating Current Converter
DC-DC	Direct Current to Direct Current Converter
DRTS	Digital Real-Time Simulator
DSP	Digital Signal Processor
DUT	Device Under Test
ESS	Energy Storage Solution
FC302	Danfoss FC302 Industrial Drive
HIL	Hardware-in-the-Loop
ITM	Ideal Transformer Method
I/O	Input/Output
KPI	Key Performance Indicator
LCL Filter	Inductor-Capacitor-Inductor Filter
LPF	Low Pass Filter
OPAL-RT	OPAL-RT Real-Time Simulator
PHIL	Power Hardware-in-the-Loop
PMS	Power Management System
RTDS	Real-Time Digital Simulator
SB	Supercapacitor Bank (or Module)
SC	Supercapacitor
SSB	Solid-State Battery
SSSB	Semi Solid-State Battery
TI C2000	Texas Instruments C2000 Digital Signal Processor
DG	Diesel Generator
SG	Shaft Generator



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## 9 Annex 1: List of devices used in the PHIL setup

Bidirectional programmable DC power supply (IT6006C)



VACON NXI DC-DC converter



VACON NXI grid-connected inverter



VACON NXI grid-connected inverter



FC302 with Customized control board

FC302 DC-AC Converter



VACON NXI grid-connected inverter



FC302 with Customized control board

