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Power Hardware-In-the-Loop for Electrical Systems: from Research Experience to Guidelines for Industrial Testing

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ABSTRACT

Power Hardware-In-the-Loop (PHIL) testing is a powerful approach that combines the flexibility of numerical simulations with the high fidelity of hardware tests to allow experimental validation of electrical equipment in a close-to-reality laboratory environment. This is enabled by using specially designed software and hardware that serve as an interface between the modeled environment and the equipment under test. Using PHIL for testing and validation can help significantly reduce time-to-market for novel energy solutions by both reducing the number of design/prototyping iterations, which in turn reduces the development costs, and the need for timely and costly field tests later during the system validation stage. The PHIL as a technology has been studied over the last 20 years, focusing mostly on the software/hardware interfaces and on system stability challenges. However, there has not been a consensus yet on how a PHIL system should be designed, validated and operated to maximize its benefits. The present work provides answers to these questions. Starting from the existing research experience and use cases, the present paper introduces practical guidelines for PHIL modeling, design, laboratory implementation and validation, and it identifies a few remaining open topics that need to be addressed to enable wider adoption of PHIL for testing and validation of electrical equipment in industrial environments.

INDEX TERMS Electric power systems, Power Hardware-In-the-Loop, industrial applications, power amplifier, system testing, real-time simulation.

I. INTRODUCTION

A wide range of new energy solutions for power systems is proposed every year varying from energy storage systems, to renewable energy sources or to components for the transportation infrastructure. The fast pace of these developments challenges system operators to validate new technologies before their adoption. While compliance to grid codes can be easily assessed with standard laboratory testing, the real system-level performance can be validated only in the field. For some consolidated technologies (e.g. photovoltaics), the learning curve is already in advanced stage and only limited testing is needed. However, for less mature technologies (e.g., electrolyzers, new battery chemistries) relatively limited information is available about their field performance and overall system impact.

Setting up a full scale demonstrator is the only established present practice to increase the operational know-how. However, this may lead to several issues as: (i) high testing costs associated to long installation time and the need for specialized workforce on the field; (ii) low testing flexibility due to the limited possibilities to change the demonstrator configuration and its properties, and the need to extend the testing campaign duration until all desired scenarios are covered; (iii) liability issues because the hardware under test is still at prototype stage and could eventually provoke large disturbances in the grid or at local customers. This could require insurance policies to cover unexpected damage to adjacent equipment.

The concept of Power Hardware-In-the-Loop (PHIL) has been introduced in the early 2000s [1] to reduce testing costs, time, and risks, while maintaining a high performance assessment accuracy and continued to get more traction since then [2]–[4]. Indeed, PHIL combines the fidelity of full-power hardware tests with the flexibility associated to numerical simulations by interfacing, via specialized power amplifiers, the hardware under test, also called hardware of interest (HOI), with a real-time model of its operational environment. The system model (e.g. a model of a power grid), also commonly known as a model of interest (MOI), is running on a real time simulator (RTS). The real time simulator provides to the power amplifier setpoints (typically in the form of digital signals) that are converted to corresponding voltages and currents in the real physical system.

The presence of a power amplifier as an interface between the MOI and the HOI is a distinct feature of PHIL compared to Control Hardware-In-the-Loop (CHIL) and enables the flow of instantaneous power at the interface point as in the real system, thus reproducing the real coupling case between the HOI and its operational environment. Any HOI that respects the voltage and current ratings of the power amplifier can be connected at its output. Moreover, a chosen variable (e.g., current or voltage) should be measured and provided as feedback to the simulator [5], closing the loop as shown in Fig. 1. This approach allows the assessment of

the HOI performance by applying equivalent test conditions as in the field testing.

The concept of PHIL has been expanded and further refined over the last ten years by providing basic guidelines for its usage [3], [4]. Recently, the working group IEEE P2004 developed the Recommended Guidelines for PHIL testing [6], establishing the foundation for a common understanding of PHIL. However, a final step toward the standardization of PHIL is still currently missing.

The present work gathers current experiences on PHIL, analyzing more complex testing architectures, and introducing guidelines for modeling, setting-up and executing stable and accurate PHIL testing. This document aims to further advance the IEEE P2004 work, focusing on providing more practical guidelines and highlighting aspects of PHIL testing that still remain open. The targeted audience for this paper is represented by newcomers to the PHIL world in industry and academia that would like to understand and start PHIL testing. The main contributions of this work can be summarized as:

- Providing an overview of the PHIL systems current state-of-the-art, including examples of existing large-scale PHIL infrastructures.
- Introducing a workflow and recommendations for PHIL system modeling and testing, in order to guide PHIL newcomers to perform a safe, stable, and accurate testing.
- Introducing new PHIL systems architectures, involving more HOIs and MOIs in the same testing setup.
- Identifying the challenges and research open points to be solved for expanding the implementation of PHIL systems in industry.

Following this introduction, a comprehensive review of the user experience with PHIL-based testing is given in Section II. Section III provides an overview of the existing methods and offers a guideline for mathematical modeling of PHIL systems. Novel PHIL architectures are introduced in Section IV, focusing on multi-port, multi-system, multi-modal concepts. Section V gives a thorough review of existing recommendations and applicable guidelines relevant for PHIL applications, while Section VI provides a step-by-step recommended guideline to set up and perform PHIL

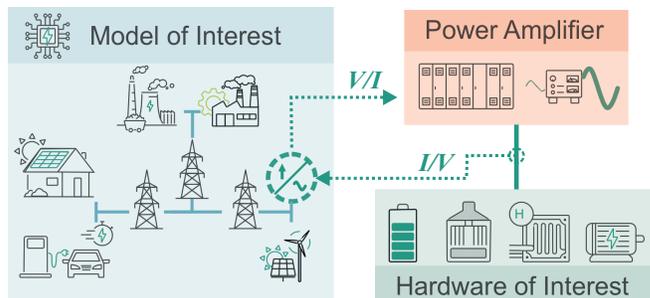


FIGURE 1. Power Hardware-In-the-Loop concept.

testing. Section VII presents multiple PHIL test cases covering different industrial applications, that have followed the testing guideline principles. The technical challenges in PHIL-based testing, as well as PHIL systems' inherent limitations are discussed in VIII. An overview of remaining open topics in the PHIL field is presented in IX. Section X concludes this paper.

II. Evolution of PHIL in scientific literature

In the academic world there is a clear increasing trend of using PHIL for experimental validation of electrical components as shown in Fig. 2. Initial works on PHIL are dated at the beginning of 2000s, where the main research topic was testing electric drives and machines [1], [23]. Nowadays, the papers with the PHIL as main topic has grown to more than 40 papers per year in 2024, with a yearly linear increase.

As Table 1 shows, the focus changed greatly over time. The initial focus was on motors and electric drives applications, targeting the performance validation of machine under external disturbances [1], [7]–[9], [23], [24] while even earlier works [1], [25] introduced the concept and focused more on the basic aspects. However, with the global attention shifting to renewable energy production and integration, the focus of PHIL-related research has moved towards grid connected components as, for example, the validation under realistic conditions of energy storage systems that are used to counteract the higher power variations caused by renewable resources [10]–[13]. Finally, in most recent years, the results of more complex and accurate real-time-based simulations using the PHIL approach have been published mostly in the domain of electric power grids and power electronics-based control approaches [14]–[16], [18]–[22].

III. Mathematical Modeling of PHIL Systems

As described above, the PHIL system entails the interface between the RTS and the hardware of interest by means of power amplifiers. In the practical implementations digital-analog conversion and additional filtering layers are also present. These interfaces do not exist in the real physical systems reproduced in PHIL, but they are inherently introduced by the testing methodology and as such can produce "artifacts". Thus, it is necessary to account for their presence and to quantify their effect on the accuracy of the results and eventually on stability [17], [26], [27].

Several techniques have been proposed to develop mathematical models that describe the stability limits for PHIL testing and highlighting the following elements as critical factors to be carefully addressed:

- **Inaccuracies in representing delays in the continuous domain:** PHIL modeling has been mostly performed since the beginning in a continuous domain for mathematical simplicity [3], [17], [28]. This enables an indicative assessment of the PHIL system stability but with clear limitations. Indeed, the delays cannot be represented accurately (e.g. resorting to Padé approx-

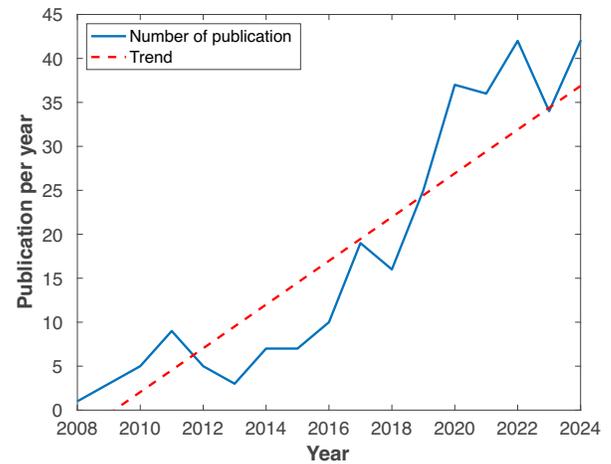


FIGURE 2. Number of published papers for each year from 2008 using Web of Science database. Research performed in Web of Science with the query *TS=(“power hardware in the loop” OR “power-hardware-in-the-loop”)*

imations) when describing discrete systems, possibly affecting the model accuracy especially in the high-frequency range. Discrete-domain modeling can effectively improve the delay representation, e.g., for power electronics, and, thus, the PHIL model accuracy [29]. Recent efforts focused on multi-rate discrete PHIL modeling, where the continuous-time domain part of the loop is represented in the discrete domain, but at time-steps smaller than the ones used for the numerical simulation [26].

- **Hardware of Interest representation:** classical modeling approaches considers only HOI passive components (e.g., external filters), ignoring the dynamic contributions from the hardware controllers (e.g., in case of power electronics converters) [17]. A recent work [30] showed how the HOI control impacts the PHIL system stability and accuracy, highlighting the need for including the hardware control in the HOI model.
- **Stability analysis assessment:** several mathematical approaches have been proposed to model and assess the PHIL system stability. A common mathematical approach is the impedance-based stability method [31] using Nyquist criterion [17], which allows the stability assessment without the HOI model knowledge, relying on HOI data-driven models [32].

A. Example of modeling: PHIL testing of a power converter

A modeling approach to assess the stability and accuracy of a PHIL configuration for testing a power electronic converter is presented in [30]. The model has been built under the following assumptions, as shown in Fig. 3:

- The analysis was performed in the discrete Z-domain instead of the continuous domain, because system components such as the RTS and the converter controller are

TABLE 1. Evolution of the PHIL applications in literature from 2007

References	Year	Application	Simulation time step	Time frame of interest	Size of simulated grid	Hardware power scale factor	Hardware voltage scale factor
[7]	2007	Superconducting Motor	1.5 & 50 μ s	minutes	756 nodes	1	1
[8]	2008	Electric Drives	50 μ s	hundreds ms	1 Bus	1	1
[9]	2010	Large Motor Drives	50 μ s	hundreds ms	1 Bus	1	1
[10]	2013	Unintentional islanding		hundreds ms	Small	1	1
[11]	2017	Frequency response of Energy Storage	50 μ s	hundreds ms	24 Buses	5-50e3	500
[12]	2017	Flywheel Energy Storage	50 μ s	minutes	24 Buses	1	1
[13]	2018	Heat Pump and Energy Storage Systems	50 μ s	minutes	1 Bus	1	1
[14]	2018	Distribution Voltage Regulation		minutes	14 Buses	10	1
[15]	2019	Solid State Transformers Primary frequency support		hundreds ms	Small	100	1
[16]	2020	Flywheel Frequency Response	24 μ s	hundreds ms	18 Buses	1	1
[17]	2021	Power electronics grid integration	50 μ s	ms	1 Bus	1	1
[18]	2021	Energy Storage Integration	50 μ s	minutes	1 Bus	3 & 7	5 & 8
[19]	2021	Variable Speed Diesel Generator with Supercapacitor	50 μ s	hundreds ms	Small	1	1
[20]	2021	Virtual Motors	15 μ s	seconds	Small	1	1
[21]	2024	Asynchronous Grids	24 μ s	hundreds ms	18 Bus	10	1
[22]	2024	Virtual Synchronous Machine validation in flywheels	24 μ s	hundreds ms	Small	1	1

more suitable for being modeled in the discrete domain. The Tustin discretization method was employed.

- The Hardware of Interest is a grid-following power converter connected to the grid via a LCL-filter, whose control includes an ideal PLL and a PI-based current controller. A current-controlled grid-following converter has been preferred instead of more complex configurations to make the modeling approach easier to understand.

The procedure for modeling the PHIL system for the purpose of stability analysis is described in the following steps. The use of the superscript * is meant for reference values.

1) Grid Model

The grid is represented as a Thévenin equivalent with a voltage source V^* and a line impedance Z_s :

$$Z_s = Z\{R_s + sL_s\} = R_s + \frac{2L_s}{T_s} \frac{1 - z^{-1}}{1 + z^{-1}} \quad (1)$$

This is arguably an oversimplified grid model, but it helps to understand the overall PHIL system modeling approach.

2) Converter Model

An average model can be used to describe the converter, employing an ideal voltage source U_h connected to a LCL filter impedance. The transfer function describing the dy-

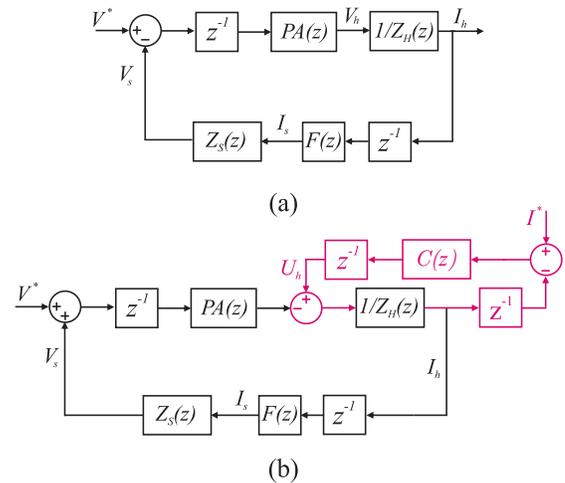


FIGURE 3. PHIL system block diagram: a) without converter control loop b) with converter control loop

dynamic behavior of the converter as modeled in Fig. 3 is given by:

$$\frac{I_h(z)}{I^*(z)} = \frac{C(z)Y(z)z^{-1}}{1 + C(z)Y(z)z^{-2}}, \quad (2)$$

where $C(z)$ is the converter controller (i.e., a proportional-integral controller), $I^*(z)$ is the converter reference current, and $Y(z)$ is the line admittance inclusive of the admittance of the converter's LCL output filter. Thus, $C(z)$ and $Y(z)$ can be formulated as:

$$C(z) = Z\left\{K_p\left(1 + \frac{K_i}{s}\right)\right\} = K_p\left(1 + K_i\frac{T_s}{2}\frac{1+z^{-1}}{1-z^{-1}}\right) \quad (3)$$

$$Y(z) = Y_h(z) + Y_s(z)$$

$$Y_h(z) = Z\left\{\frac{sC_fR_f + 1}{as^3 + bs^2 + cs + d}\right\}$$

$$Y_s(z) = Z\left\{\frac{1}{R_s + L_s s}\right\} = \frac{1 + z^{-1}}{R_s + 2\frac{L_s}{T_s} + (R_s - 2\frac{L_s}{T_s})z^{-1}} \quad (4)$$

where the LCL-filter elements are defined for brevity as:

$$\begin{aligned} a &= C_f L_c L_g \\ b &= C_f L_c R_f + C_f L_g R_f + C_f L_c R_g + C_f L_g R_c \\ c &= L_c + L_g + C_f R_f R_c + C_f R_f R_g + C_f R_c R_g \\ d &= R_c + R_g \end{aligned} \quad (5)$$

Finally, the internal loop $CC_{loop}(z)$ of the power converter can be determined as

$$CC_{loop}(z) = \frac{Y_h(z)z^{-1}}{1 + Y_h(z)C(z)z^{-2}} \quad (6)$$

3) Filtering Stage

To filter out the noise from the feedback signal and for increased stability margin, a first-order linear filter $F(z)$ has been considered with the following transfer function

$$F(z) = Z\left\{\frac{1}{1 + T_f s}\right\} = \frac{1 + z^{-1}}{1 + \frac{2T_f}{T_s} + \left(1 - \frac{2T_f}{T_s}\right)z^{-1}} \quad (7)$$

4) Power Amplifier

The power amplifiers used in PHIL can be either linear or switched-mode power amplifiers. In linear power amplifiers (also called analog power amplifiers), power semiconductors are operated in their linear region (hence the name), which enables these amplifiers to achieve very high bandwidths (in the range of tens of kHz), high slew rates (several tens of V/ μ s) and low output impedances (in the range of m Ω), but at the same time makes them very inefficient (class B amplifiers have a maximum efficiency of approximately 78.5%, which is achieved only at the maximum output voltage and

with resistive load). Furthermore, linear amplifiers are not capable of regenerating energy back to the input power source, and their operation with reverse power flow leads to very high losses in the power semiconductors. Unlike linear power amplifiers, the switched-mode power amplifiers (also called digital power amplifiers) operate by modulating the switching of the power semiconductors in such a way that the amplifiers output voltage or current follows the setpoint. As a result, the switched-mode power amplifiers feature significantly higher energy efficiency (higher than 90%), bidirectional power flow and smaller size and weight, compared to the linear power amplifiers, with their bandwidth and slew rate reaching the levels of linear power amplifiers [33], [34].

A switched-mode power amplifier in the PHIL system can be modeled with a second-order transfer function given by

$$\begin{aligned} PA(z) &= Z\left\{\frac{1}{s^2 + a_{PA}s + b_{PA}}\right\} = \\ &= T_s \frac{1 + 2z^{-1} + z^{-2}}{A_{PA} + B_{PA}z^{-1} + C_{PA}z^{-2}} \end{aligned} \quad (8)$$

where A_{PA} , B_{PA} , and C_{PA} are coefficients derived from the Tustin transformation. Typical values of these coefficients for switching power amplifiers are $A_{PA} = 20640$, $B_{PA} = 40000$, and $C_{PA} = 19360$, if a sampling time of $T_s = 50 \mu$ s is considered. In the case of linear power amplifiers and high-performance switched-mode power amplifiers, the transfer function is reduced to $PA(z) = 1$ due to the fact that these power amplifiers are able to reach the desired setpoint within 5 μ s, that is usually an order of magnitude lower than the RTS sampling time in CPU-based simulations. This assumption does not apply in case of FPGA-based solvers, where the sampling time can be reduced to 4 ns.

5) PHIL system model for stability analysis

The equivalent transfer function of the closed-loop PHIL system including the converter control and plant dynamics can be determined as follows. The forward path transfer function of the system can be written as

$$FW(z) = -CC_{loop}(z)PA(z)z^{-1}, \quad (9)$$

where the closed-loop transfer function $\frac{I_h(z)}{V^*(z)}$ of the PHIL can be written as

$$\frac{I_h(z)}{V^*(z)} = \frac{FW(z)}{1 - FW(z)Z_s(z)F(z)z^{-1}} \quad (10)$$

The mathematical approach illustrated in Fig. 3 has been presented and validated in [30], where all the details of the mathematical validation can be found.

IV. New PHIL systems architectures

Power Hardware-In-the-Loop was initially conceived for testing a single hardware unit connected to a simulated system at a single point of connection [3], [4]. A first

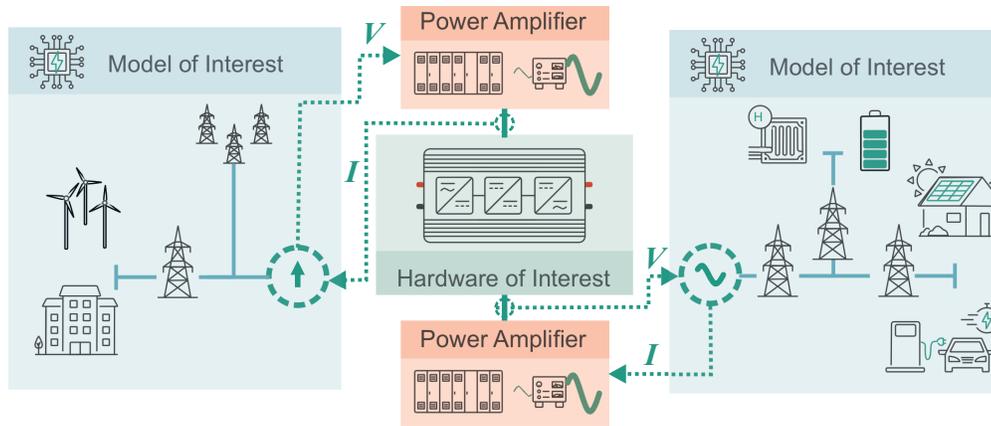


FIGURE 4. Multi-Model, Single-Hardware PHIL architecture (MMSH). A multi-port hardware is coupled with several simulation environments by means of separate PHIL systems.

reason is that the PHIL was historically meant to substitute laboratory testing, such as type-tests, and this involved only one machine or converter interacting with the rest of the system; second, the RTS and power amplifier technologies were still rather immature and offered limited computational and testing capabilities.

The improvements in RTS and power amplifier technologies together with the reduction of costs per simulation core and kVA, enabled the realization of more complex forms of PHIL system architectures, involving additional points of connection between the hardware and the simulation model. New PHIL system architectures are identified and classified in this section.

A. Multi-Model, Single-Hardware Architecture (MMSH)

Usually, shunt-connected devices (e.g., photovoltaics, batteries) can be tested with a single-point of connection with the rest of the PHIL system. However, several series devices (e.g., power lines, transformers, breakers, power electronic converters) require a multi-port connection, to correctly emulate the behavior of the environment (e.g. power grid, load, etc.) on all of their connection ports (e.g. primary and multiple secondaries of a transformer). To properly test these devices, a Multi-Model, Single-Hardware (MMSH) PHIL system architecture needs to be adopted. This architecture assumes connecting one HOI to two or more power amplifier ports. Each of these ports is connected to the simulator using an independent power interface.

As an example of MMSH architecture, Fig. 4 shows a possible PHIL system architecture to test a power electronics converter connected between two independent distribution feeders. A three-stage power electronics converter, such as a Solid State Transformer (SST), is connected to the rest of the PHIL system at two points. In this specific case, a voltage-type PHIL interface algorithm is implemented in the primary side due to the grid-following characteristics of the SST primary side. A current-type PHIL interface algorithm connects the secondary side of the SST with the supplied

distribution grid (right MOI). Any other voltage- and current-type interface algorithm can be used for this PHIL system architecture. If a disturbance occurs at the secondary side of the SST, its effect can be seen in the grid connected to its primary side, and vice-versa.

Applications: series elements testing, such as power lines (e.g., superconductive), transformers, breakers, power electronics systems (uninterruptible power supplies, wind turbines Type-4 converters, SSTs).

B. Single-Model, Multi-Hardware architecture (SMMH)

The Single-Model, Multi-Hardware (SMMH) architecture assumes multiple individual HOIs being interfaced to a single MOI. As can be seen in Fig. 5, this kind of architecture allows the testing of the interaction between different HOIs in realistic conditions [35]. This feature is particularly important during testing the control and plant interactions between power electronics converters (e.g., between wind turbines converters in wind farms) To be noted that the testing

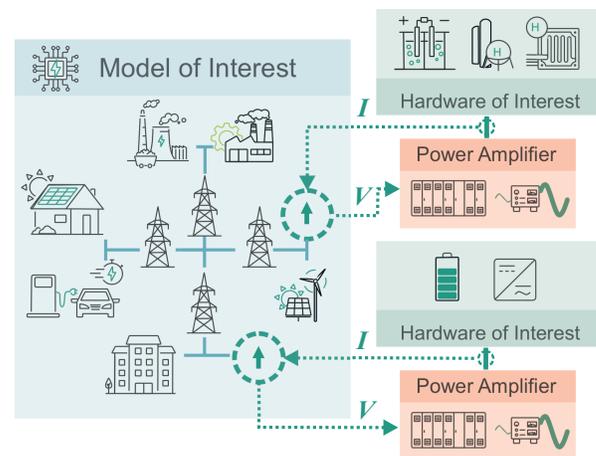


FIGURE 5. Single-Model, Multi-Hardware PHIL system architecture (SMMH). Several separated HOIs are connected to the same MOI by means of separated PHIL systems.

scenario and the interaction dynamic between these HOI systems is strictly dependent on the PHIL system dynamics. Faster dynamics such as high frequency resonances and harmonics may be filtered out by slow power interfaces (i.e., limited-bandwidth power amplifiers or low-bandwidth filtering).

Applications: microgrid high-level controller, harmonic oscillation and instability analysis, fast reconfigurable networks.

C. Partial-PHIL

High-voltage PHIL testing (e.g., for HVDC), is very challenging to be performed in laboratories due to the need for (extra) high-voltage facilities and high-power supplies. The current state-of-the-art offers mostly Simulation-in-the-Loop or Control Hardware-In-the-Loop solutions, in order to test control strategies such as voltage balancing [36], protections [37], [38], and modulation schemes [39]. However, these approaches do not assess losses and cooling performance realistically, switching dynamics and dead-times, effect of energization of auxiliary power supplies, etc.

To partially reduce these problems, and perform a more realistic assessment of high-voltage power electronics devices, the concept of Partial-PHIL system is introduced as in Fig. 6 [40]. The idea is to model the full converter in the digital real-time simulator in conjunction with a replica controller in the loop, except for a single submodule, which is realized with low-voltage hardware and connected to a power amplifier. The Partial-PHIL system enables the assessment of the real performance of a single submodule, for example one of a modular multi-level converter (MMC), and then to improve the hardware design of the submodule before full assembly. With the digital real-time simulator and the replica controller in the loop, it is possible to replicate exactly identical voltage, current, and switching profiles of the submodule under test as in a real MMC. This approach brings clear advantages, permitting testing in low-voltage environments while still retaining the accuracy of testing full-power rating modules.

Applications: high-voltage multi-level converters, such as MMC or Cascaded H-Bridge converters.

D. Distributed-PHIL

PHIL test laboratories are costly facilities that are typically tailored to specific testing needs: higher voltage or power, faster dynamics, etc. Laboratories may also need to test specific components, which are difficult to be moved, such as transformers, long cables, or breakers.

The researchers in digital real-time simulation have recently piloted the creation of distributed real-time labs, where the electrical variables are exchanged over internet in real time between the laboratories that are hundreds kilometers apart, with reduced delays (tens to hundreds of milliseconds). This concept has already been proven in the digital real-time simulation field [41]–[43], where simulated

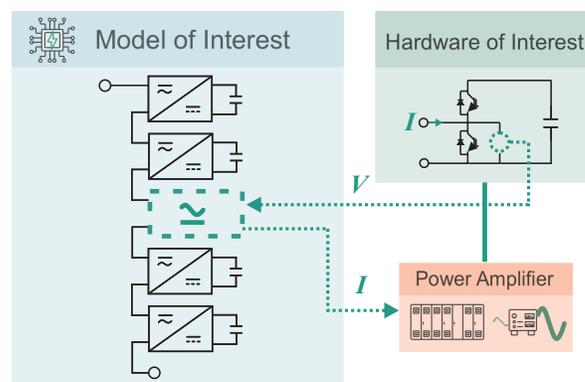


FIGURE 6. Partial PHIL System - validation of a full-scale low-voltage single submodule.

variables are exchanged among labs, investigating delay and stability analysis. The concept of distributed-PHIL is relatively new [44], [45], with some initial work done on the loop delay and stability analysis [46]. However, safety and accuracy aspects of this approach need to be further developed and standardized.

Applications: IP-protected converter testing, wide-area control strategies.

E. Testing more energy carriers: the Multi-Physics Hardware-In-the-Loop concept

Novel energy technologies are designed to transform energy from multiple energy carriers in order to increase the system-level energy efficiency. For example, waste heat from generators has been used for decades for feeding local district heating networks, and now, technologies such as fuel cells, generate high-temperature heat as by-product of chemical reactions. While the attention of the industry has been focused greatly on this multi-energy carriers technologies, little has been done for testing them in realistic laboratory conditions.

An innovative concept that is currently being introduced is the Multi-Physics Hardware-In-the-Loop. This concept involves the parallel testing of the electrical, thermal, or gas layer of the system under test, in order to validate the performance of each energy layer in a coordinated way (i.e., not independently). To achieve a comprehensive multi-physics testing, a proper testing of the thermal layer needs to be performed. For this reason, the concept of Thermal Hardware-In-the-Loop is introduced, where the MOI is any heating network, varying from a city-wide system to a single cooling loop, and the HOI is any technology tasked to absorb or generate heat Fig.7.

A first attempt at multi-physics Hardware-In-the-Loop was performed in [47], where the thermal and hydraulic layers were emulated together with the electrical one. The setup was able to emulate properly the energy behavior of a small residential house, and to validate a heat pump concept as a system under test. Although the concept has been introduced,

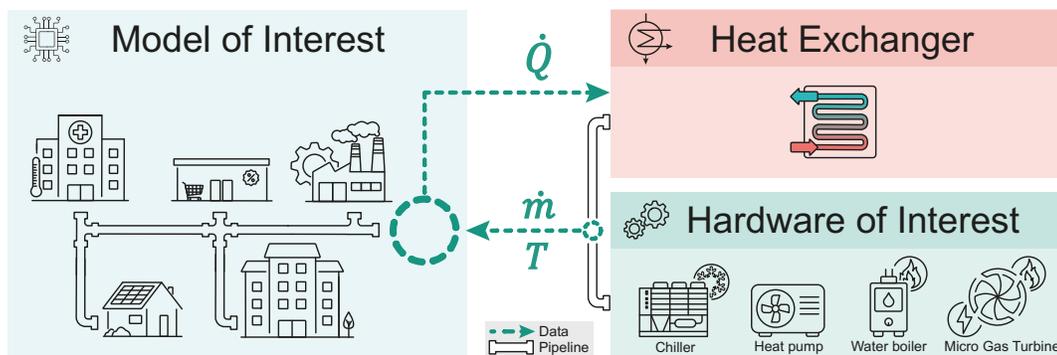


FIGURE 7. Thermal Hardware In the Loop concept, coupling a simulated heating network (MOI) with a thermal resource (HOI).

the following topics still need to be addressed: (i) for the hydraulic and thermal layers, the mathematical approach for the power interface algorithm needs to be formulated, similarly to what was done for the electrical layer (e.g., with the Ideal Transformer Method). (ii) novel hardware for the power interface needs to be designed and built. The dynamics of the thermal and hydraulic actuators are several orders of magnitude slower than the electrical ones. Slower transients (e.g., daily thermal needs for a house) can be easily emulated with current actuator technologies. However, for faster thermal dynamics, such as the ones generated by different power electronic converters operations, this may be challenging.

Applications: co-generation units, cooling systems for power electronics, Heat Ventilation Air Condition (HVAC) units.

V. Recommended Guidelines for using PHIL

This section introduces design and implementation guidelines for safe, stable and accurate PHIL testing. Four topics are addressed: test scenarios, hardware, stability, and interface algorithm choice.

A. Applicability of PHIL based on test scenarios dynamics

The PHIL system concept has been developed to experimentally test hardware in realistic grid conditions. As a consequence, the PHIL testing is strongly dependent on the test scenario where the HOI needs to be tested. As an example, PHIL systems are particularly useful in case of dynamic transients covering from frequency support to fault ride through applications.

The applicability and benefits of PHIL testing can be evaluated for systems, processes and phenomena with the following transient dynamics: quasi steady-state transients, dynamic transients, fast electromagnetic transients:

- Quasi steady-state transients: in several cases, PHIL has been used to validate quasi steady-state phenomena, where transients evolve with slow dynamics. In these cases, PHIL brings only limited advantages to the testing. The slow dynamics allow to reduce a simulation

model complexity (e.g., employing average models), and thus the same scenario can be easily tested in a simulation environment without affecting the testing accuracy.

- Transients dynamics ranging from few milliseconds to few seconds. These dynamics (e.g., frequency and voltage transients, fault ride through capabilities, harmonics) are one of the reasons why PHIL has been conceptualized. These transients cannot be reproduced easily in simulation without making extensive simplifications, and at the same time they are too complex for reduced laboratory test-benches. PHIL offers optimal testing capabilities (more flexible and safer than the on-field testing) providing a realistic assessment of the hardware performance.
- Fast electromagnetic transients: PHIL has clear bandwidth limitations due to the time discretization of CPU-based RTS (usually with a time-step of $50 \mu s$), the limited bandwidth of the power amplifiers (varying from few kHz up to 10 kHz for larger units, up to 200 kHz for smaller ones), and the need for filters for loop stability purpose (typically, in the order of $200\text{-}500 \mu s$ time constants). As a result, transients evolving within a few milliseconds (e.g., DC faults, switching dynamics) are currently challenging to reproduce with PHIL systems. Advanced interface algorithms, integrated with FPGA units, need to be designed to deal with these transients.

B. Hardware topology and scalability

As mentioned above, the advantage of PHIL is its ability to create testing conditions that are close to the real operational environment, which enables system performance evaluation under close-to-reality conditions. However, these conditions do not cover only the MOI, but also the HOI: the hardware that needs to be validated experimentally should have electrical and thermal performance close to the one that will be installed in the field (e.g., similar topology, architecture, switching technology, etc.).

Several papers addressed the problem of scalability of the results from a stability and accuracy point of view [48], targeting an up-scaling of the voltage and power in the RTS,

and working with a reduced-scale hardware in laboratory. However, this brings several issues that affect the accuracy and fidelity of the results.

The following few guidelines can be followed when it comes to hardware aspects of PHIL:

- **Modularity:** the HOI may consist of modular (e.g. high-voltage power converters) and non-modular (e.g., electrical machines) systems, where the properties of the high-power modular systems could be assessed using PHIL based on the assessed properties of the cascaded lower-power modules. For example, MMCs may be studied from the behavior of the single cell, as proposed in the partial-PHIL in Section IVC. Scaling up non-modular systems can lead to an incorrect performance estimation because some properties of these systems, such as for example the dynamic or thermal performance, cannot be scaled easily. On the other side, energy storage systems, for example, show a certain degree of modularity in their power and voltage rating (e.g., battery stacks), that can be easily integrated in the PHIL testing. It is strongly suggested to understand the modularity of the HOI before proceeding to plan a PHIL validation. The PHIL testing offers realistic performance only if the reduced-scale hardware has the same electrical and thermal performance of the full-scale system.
- **Device technology:** in the recent literature, PHIL testing has been used to test high-voltage power electronics devices by using lower-voltage rated semiconductor devices. While in many cases the per-unit design has been respected for the passive components, low voltage rating semiconductors (e.g., low-voltage IGBT, MOS-FET) cannot represent the switching dynamics of high-voltage devices (e.g., 3.3 kV IGBT, Thyristors, GTO, IGCT). As a consequence, an overestimation of the transient capabilities of the power converter may occur. If lower-voltage or current rated devices are necessary due to limited testing capabilities, these semiconductors may still be employed in PHIL testing, but they shall be considered only as ideal switches, ignoring the electrical and thermal switching characteristics (e.g., in the losses calculation).

C. PHIL system accuracy, stability, and sensitivity

The stability and accuracy are strongly coupled in PHIL testing. The accuracy is related to the capacity of the PHIL testing to reproduce the real coupling case, i.e., like in field testing, without any added power interface between the HOI and the MOI. As mentioned in the first part of this paper, the power interface introduces delays and non-linear dynamics. The following are general guidelines that can be used when it comes to stability, accuracy and sensitivity aspects.

- **Stability:** a stable PHIL is mandatory to avoid damages to the hardware of interest. The PHIL stability depends on the loop transfer function, including the

delays introduced by the power amplification and filter stages [32]. Recent works highlighted how multi-rate partitioning the power interface can help increasing the PHIL system stability [49]. The PHIL system stability can be estimated from offline simulations of the PHIL system's transfer function, and it is subject to the knowledge of the HOI parameters. Typically, these parameters are only partially available and can vary during the experiment (e.g., temperature-dependent resistance). For obtaining a stable PHIL testing the following is suggested:

- 1) To perform an online estimation of the HOI impedance during PHIL operation by means of frequency-sweep approaches, and to represent in simulation the HOI as an equivalent Thevenin (or Norton) generator. A more accurate knowledge of the HOI equivalent impedance avoids neglecting important dynamics for the PHIL stability.
 - 2) If the HOI impedance cannot be estimated during operation, it is vital to consider the influence of the control during operation. An offline frequency-sweep for estimating the HOI impedance may overlook some controller dynamics that are present during online operations.
 - 3) If no impedance estimation is possible, the controller dynamics that may create interaction with the power system under considered conditions should be evaluated. This includes converters' power- and current-controllers, phase-locked loop, communication and automatization dynamics (e.g., primary or secondary controllers).
- **Accuracy:** The inherent limitations of PHIL interfaces, such as limited measurement accuracy and limited bandwidth of power amplifiers, can significantly affect the accuracy of PHIL tests [50]. As a consequence, PHIL testing results may differ from the field ones, and this is strongly undesired. For this reason, the PHIL accuracy definition needs to be introduced. If we consider the TF_{PHIL} , TF_{RC} , \underline{TF}_{PHIL} , and \underline{TF}_{RC} the PHIL and real coupling case (i.e., like in the field testing) amplitude and phase, respectively, we can define the amplitude $|A|$ and phase \underline{A} accuracy indexes as:

$$|A(\omega)| = \frac{|TF_{PHIL}(\omega)| - |TF_{RC}(\omega)|}{|TF_{PHIL}(\omega)|} \quad (11)$$

$$\underline{A}^\circ(\omega) = \underline{TF}_{PHIL}(\omega) - \underline{TF}_{RC}(\omega) \quad (12)$$

These two error indexes shall be performed across the whole frequency spectrum and, as indicative guidelines, following acceptance limits shall not be exceeded:

$$|A(\omega)| < 3dB \quad (13)$$

$$\underline{A}^\circ(\omega) < 5^\circ \quad (14)$$

The cutoff frequency, where the PHIL testing differs more than the above values from the real coupling, will

be determined as the accuracy bandwidth of the PHIL testing.

D. Interface algorithm selection

The PHIL interface algorithms allow for the connection between the MOI and HOI. Two main interface categories are available for PHIL testing: the voltage-type (voltage as feedforward signal from MOI to HOI, and current as feedback signal) and the current-type (current as feedforward signal, and voltage as feedback signal). Commonly, the voltage-type is adopted for PHIL testing, due to higher stability characteristics for shunt-connected HOIs (e.g., renewable energy converters, energy storage systems, etc.). Current-type interfaces are used only in case of grid-forming characteristics of the HOI, such as for the solid state transformers case [15]. In the two aforementioned categories, different interface algorithms have been proposed for connecting the HOI with the MOI. These algorithms come under different variants, but three are considered the most used ones [3], [4], [51]:

- **Ideal Transformer Method (ITM):** it is the most straightforward interface method for connecting HOI and MOI. It is based on a feedforward voltage signal (or current for CT-interfaces) from the MOI to the power amplifiers, and a feedback current signal (or voltage for CT-interfaces) from the HOI measurements to the DRTS. It offers high accuracy, since only the signal delay is introduced, but its stability is dependent on the ratio between MOI and HOI transfer functions, as explained in Section III.
- **Partial Circuit Duplication (PCD):** this approach is an extension of the ITM algorithm, where impedances of the same values have been added both in simulation and in hardware. When computing the PHIL transfer function, these impedances contribute positively to the testing stability range. Two problems have been observed in practice: i) it is difficult to precisely match hardware and software impedances, due to non-linear behavior of real impedances (e.g., dependency on temperature and frequency, manufacturing tolerances); ii) the addition of virtual and hardware impedances affects the accuracy of the PHIL testing and can incur extra costs.
- **Damping Impedance Method (DIM):** the DIM method combines the ITM and PCD algorithms, adding an additional damping impedance that supports stability if it matches the HOI impedance. While matching the MOI and HOI works well in theory, shortcomings have been observed in practical application. In case of power electronics testing, the HOI (a power converter) shall be represented as a Norton equivalent [32], making the matching with a fixed impedance challenging.

In summary, while PCD and DIM offer interesting concepts, challenges of practical application have been encountered. The use of an ITM algorithm allows for a straightforward realization of an accurate PHIL system and is widely

used. It is therefore in the focus of this paper. Stability concerns can be solved adding feedforward filters (Section III).

VI. Process Guidelines for PHIL Testing

This section provides a step-by-step guide on how to develop and perform a PHIL testing. The PHIL system design flowchart illustrated in Fig. 8 provides an overview of the steps needed to design a stable and accurate PHIL test system. These steps are finally summarized in the Table 2 together with typical values used in literature.

1) Scenario case development:

As a first step, the PHIL testing goal has to be determined, developing the power system scenario in the MOI where the HOI is connected. As first, the size and the required modeling depth of the scenario needs to be analyzed [52], to understand if the power systems phenomena under study respects the PHIL system dynamic (including MOI, HOI, power amplification and filtering dynamic limitations). It is strongly suggested that the real-time simulation step T_s of the MOI should be at least 20 times higher than the fastest scenario dynamic $f_{ModelMax}$ that is under investigation. If this requirement cannot be initially met, the following two options are available:

TABLE 2. Checklist parameters for PHIL testing and their typical values

Design step and PHIL system property definition	Values
1. Define MOI Bandwidth $f_{ModelMax}$, which represents the highest frequency that shall be controlled in closed loop	Depends on scenario
2. Define output quality at $f_{ModelMax}$, as number of setpoint changes N per period corresponding to $f_{ModelMax}$	$N \geq 20$ (the higher, the better)
3. Calculate required minimum Model Cycle Time T_m	$T_m = \frac{1}{N \cdot f_{ModelMax}}$
4. Calculate the maximum RTS time step T_s	$T_s \leq T_m$
5. Select between CPU- and FPGA-based RTS	Depends on T_s
6. Determine required power amplifier bandwidth f_{amp}	$f_{amp} = 2 \cdot f_{ModelMax}$
7. Estimate maximum allowed open-loop delay time T_{OLdel} at $f_{ModelMax}$ to ensure closed loop stability, where $T_{OLdel} = \text{setpoint} + \text{amplifier} + \text{measurement delays}$	$T_{OLdel} \approx \frac{1}{3 \cdot f_{ModelMax}}$

- a) Reduction of the time step size T_s considering the model size and the computational capacity of the RTS (either CPU- or FPGA-based).
- b) Reduction of the simulation model size in order to fit a smaller time step size T_s .
- c) If any of the above conditions cannot be met, the scenario under study should be rethought.

2) Hardware requirements:

In a next step, the proper selection of hardware devices with respect to available RTS, power rating, bandwidth, voltage, and current limits needs to be performed for the PHIL interface. For the hardware part, I/O ports, respective signal connection terminals, and the safe operating area (SOA) of the power amplification stage, as well as the HOI, have to be considered. Once the hardware has been chosen, the transfer functions of the power interface (power amplifier,

sensors, analog/digital converters) should be determined and stability analysis can be performed using the mathematical approach proposed in Section III.

When defining the required power amplifier bandwidth, it is important to first determine the MOI bandwidth $f_{ModelMax}$, which represents the highest frequency that will be controlled in the tested closed loop in the system. The $f_{ModelMax}$ is typically not the fundamental frequency of the system. A few examples of properly determined $f_{ModelMax}$ are:

- AC applications: The frequency of the highest-order harmonic to be represented by the model.
- Impedance measurement applications: The highest perturbation frequency to be tested.
- Electric machine simulation: The highest frequency of the back electromagnetic force (EMF) to be modeled, the highest frequency of the machine torque ripple, or highest frequency of the current ripple generated by a converter driving the machine, whichever is higher.

Based on the empirical data, it is good engineering practice to select the power amplifier bandwidth f_{Amp} to be 2 times higher than $f_{ModelMax}$. The properties of the power amplifier at f_{Amp} should be:

- Amplifier gain > 3 dB
- Amplifier phase shift: $< -45^\circ$

3) PHIL system stability:

For the evaluation of system properties such as system accuracy and stability, the complete PHIL setup including filtering blocks and the PHIL interface has to be modeled using transfer functions. Then, it is recommended to test the closed-loop PHIL system with a model representation of the HOI connected to the PHIL interface instead of the physical HOI. Stability analysis of respective open-loop and closed-loop systems should be used to evaluate system stability properties according to literature [3], [6] and suggestions in this work. In the initial testing stage, it is strongly recommended to use conservative settings (e.g., lower filter bandwidth). Then, with an iterative process, the constraints can be relaxed until the desired stability limit is attained [17].

4) PHIL system accuracy:

After verifying the stability of the PHIL system, the system accuracy needs to be verified as well. Resulting open-loop and closed-loop transfer functions can be used for an error estimation of the PHIL setup as described in [6], and the indexes in (13). If the accuracy is positively assessed, the PHIL can be performed. Otherwise, the following three options are available:

- a) Adjust the filter bandwidth, reducing the dynamic of the loop, increasing its stability. As a negative effect, the testing accuracy decreases at higher frequency.

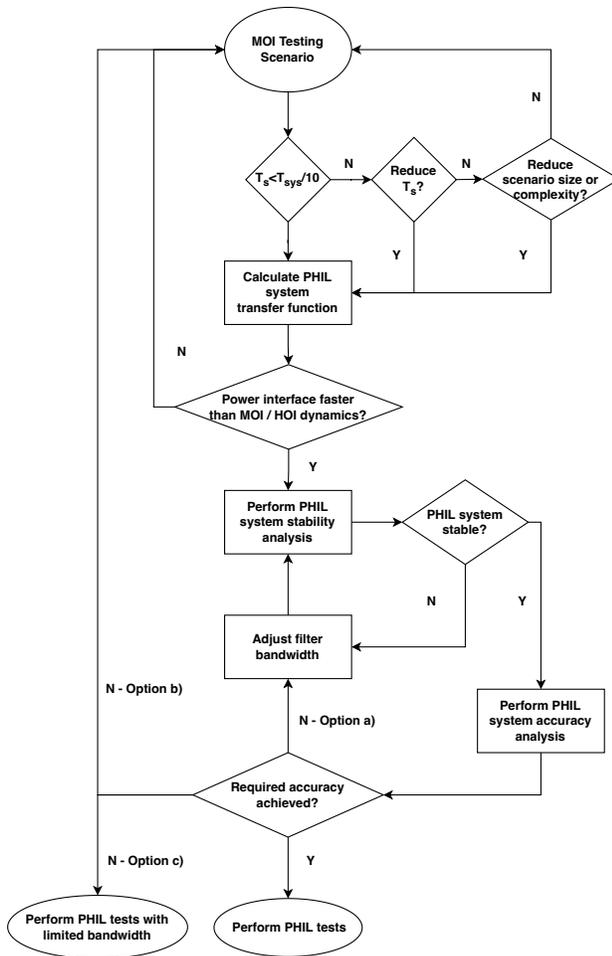


FIGURE 8. Decision Flowchart for developing and performing a stable and accurate PHIL testing

- b) Redesign the scenario under study, reassessing stability and accuracy with the new scenario.
- c) Perform the PHIL testing assuming a limited bandwidth validity.

As a final step, feedforward and feedback signal connections, I/O ports, measurement bus, software and hardware related safety monitoring devices, and protective emergency shut-off circuits have to be verified and validated.

VII. Test cases for PHIL Testing

PHIL is a powerful tool for testing hardware in realistic conditions. However, as mentioned in the previous sections, it is a relatively complex approach that requires several components and controllers. For this reason, it is vital to understand practically in which test case the PHIL brings an additional value to the testing, whereas simulations have modeling challenges or field tests are too complex to be performed.

This section is dedicated to providing an overview of test cases performed in large research centers around the world, where the PHIL plays a vital role in more accurate testing of energy technologies. The list of test cases is arranged following a component-to-system approach.

A. Fast frequency support and virtual inertia

Background: One of the major challenges for future renewable-based energy systems is the decrease of rotating masses in the power system. To address this challenge, novel fast frequency support and virtual inertia strategies have been proposed in connection with energy storage systems.

Laboratory setup: The Power Hardware In the Loop lab in the Karlsruhe Institute of Technology, a 1 MVA PHIL system, composed of five 200 kVA COMPISO power amplifiers, allows for various experiments on AC and DC energy storage systems providing frequency and inertia support. In recent works [16], [53], the KIT team has demonstrated the capability of flywheels to provide frequency and inertia support during disturbances, as well acting as a virtual synchronous machine [22]. This multi power amplifier setup allows also the operation in the previously introduced MMSH configuration, with two MOI representing the primary and secondary side of asynchronous grids offering frequency support [21].

Testing of grid forming and inertia support functionalities has been conducted also at the Norwegian Smartgrid Laboratory featuring an OPAL-RT platform for real time simulation and a 200 kVA COMPISO power amplifier as PHIL interface [54]. However, the focus has been primarily on aspects related to the overall power system impact in terms of frequency nadir and ROCOF, and on the integration of intelligent electronics devices for wide area monitoring.

PHIL Advantages: The following advantages in using PHIL testing for inertia and frequency regulation provisions have been found at the Karlsruhe Institute of Technology and at SINTEF Energy Research :

- **State-of-the-art comparison:** The proposed frequency and inertia support approach has been validated in a realistic grid condition, comparing the performance with other papers proposing similar approaches [16]. As a consequence of the direct comparisons, the advantages and limitations of the proposed control approach have been easily highlighted.
- **Data-driven models:** As explained in recent works [52], [55], the simulation models are valid only for specific scenarios. Simulations are not able to represent all real hardware variables, such as the power consumption of auxiliaries, temperature, and humidity dependency. A data-driven model of the flywheel has been realized by means of PHIL testing using realistic frequency regulation scenarios and then validated with a standard microgrid benchmark [56]. Being realized in realistic conditions, when tested with other power systems, the model shows only minimal power and state-of-charge mismatch, allowing its use in any frequency control-related approaches.
- **System limitations:** The commercial hardware has implemented several control safeguards (such as power ramp-rate characteristics) for avoiding instabilities. In [22], the testing of realistic flywheel settings with power ramp-rate shows the limitation of commercial flywheels in performing inertia support, and the need for unlocking the ramp-rate settings for this service provision.
- **Real time simulation of large power systems with phasor models:** The simulation in real time of large power systems to assess dynamics related to frequency oscillations or reaction to inertia support can be conveniently performed with phasor simulations. This allows to reduce the computational complexity of the model but the phasor model needs interfacing with a more conventional transient model for controlling the power amplifier.

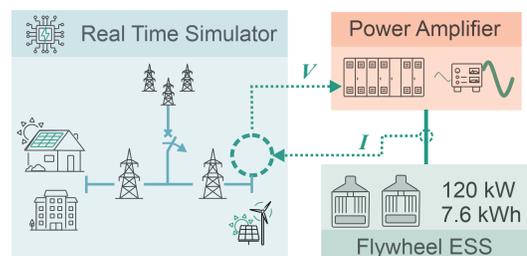


FIGURE 9. PHIL concept for flywheel applications testing

B. Microgrid testing

Background: Modern microgrids exhibit high volatility caused by inverter-based, decentralized energy resources, flexible loads, and storage systems. In contrast to distribution grids, which can compensate for overproduction or increased load demand through the transmission system,

island microgrids must autonomously manage generation and consumption. This results in stronger interactions between local and hierarchical control systems, the communication infrastructure, and protection devices. As highlighted in recent real-world and hardware-based studies below, microgrids must coordinate heterogeneous device behaviors, non-ideal load dynamics, and varying communication delays to maintain stability and power quality under both steady-state and transient conditions. These interactions can only be modeled to a limited extent, making hardware-based validation indispensable.

Laboratory setup: As described in IEEE Standard 2030.8 [57], pure simulations are often insufficient due to unavoidable model simplifications, which prevent reliable representation of proprietary algorithms and internal limitations of real components. Field tests, on the other hand, are costly, inflexible, and associated with risks. Laboratory platforms such as the Electric Energy Systems Laboratory at NTUA [58] and the Smart Energy System Control Laboratory at KIT [59] bridge this gap by combining digital real-time simulations with microgrids via SMMH-PHIL, featuring reconfigurable AC/DC topologies that are galvanically isolated from the public grid. Observation and control of the network elements occur via real communication and automation systems between the components. These structures enable safe yet technically rigorous testing of both stable and critical operating conditions of microgrids.

PHIL Advantages: Several publications from NTUA and KIT demonstrate that the combination of real microgrids and new PHIL architectures, particularly SMMH, reveals dynamic interactions that simulations systematically underestimate:

- **Interoperable operation between microgrid and local controllers:** Modern microgrids are characterized by cross-layer coordination among DER primary control, secondary control and demand-side management, and tertiary EMS control. New PHIL architectures enable simultaneous observation of interactions across all layers. According to Salcedo et al. [60], some interactions between the Supervisory Microgrid Controller and local DER Controller can only be seen in PHIL, and these interactions are very important for making sure the microgrid is stable and resilient. According to Wiegel et al. [61], the microgrids must be validated as cyber-physical systems because the real controller behaviors, interactions between real controllers, and communication delays often dominate system dynamics.
- **Validation of microgrid dynamics:** Many DER manufacturers do not disclose internal algorithms, latencies, or limits. When modeling such components, the impact of the specific implementation is often underestimated or ignored entirely. However, proprietary synchronization algorithms, time-varying latencies, switching delays, and saturation effects are essential for stable microgrid operation, as the behavior of entire networks

is often governed by the internal logic of individual DER units due to system size and coupling structure. PHIL makes it possible to systematically identify these modeling blind spots. Results from [62] show that interactions between grid-forming and grid-following resources during transient events (islanding/grid transitions, faults) are fully observable and validly comparable only in CHIL/PHIL environments. This finding is supported by [63], which shows that the level of DER performance expected from simulations cannot be met in real-component tests because of nonlinear load behavior, resonance amplification in generators, and temporal delays.

- **Enabling standardization of validation procedures in real microgrids:** Using reference and benchmark systems together with defined PHIL test procedures, as described in [64], provides a consistent and reproducible basis for evaluating microgrids and components. This allows cross-manufacturer interoperability testing of microgrid and device controllers under identical boundary conditions. In [61], this approach is extended by integrating the SMMH architecture, real-time simulators, and a microgrid that is fully observable and controllable from within the RTS environment. This creates a comprehensive development and testing environment for rapid prototyping of central and hierarchical grid-control and EMS systems.

C. High power testing

Background: PHIL studies provide a versatile and powerful platform for testing and validating high power system components and control strategies in a highly controlled yet realistic environment. This reduces the risk, cost, and time associated with deploying new technologies at high-power rating and ensures robust performance under real-world conditions as alternative to expensive field testing.

Several PHIL studies performed at Florida State University Center for Advanced Power Systems (CAPS) demonstrated applicability and flexibility of the PHIL concept in the kV/MVA range, validating a 3 MW, 13.8 kV, 60 Hz diesel generator for data center load applications, i.e., its capability in handling constant power load demands [65]. The successful PHIL testing enabled revising the rating and consequently yielding a reduced number of generators required to carry data center loads, reducing costs significantly

Laboratory setup: Clemson University's eGRID (Electrical Grid Research, Innovation, and Development) Lab, located in North Charleston, South Carolina, is a state-of-the-art facility dedicated to advancing power systems and grid technologies [66]. It houses a 15 MW PHIL Grid Simulator that leverages the electrical infrastructure of the Dominion Energy Innovation Center and allows wind turbine generator (WTG) manufacturers to test both mechanical and electrical characteristics of their machines in a well-controlled and calibrated environment [67]–[69]. Moving

many electrical testing scenarios previously available only by field demonstrations into a controlled environment, the HIL Grid Simulator gives WTG manufacturers a platform to ensure new innovations meet even more stringent global electrical standards. This increases reliability and lowers the cost of energy delivered. The 15 MW PHIL Grid Simulator provides electrical testing beyond fault ride-through testing for the Center to provide a complete suite of electrical testing solutions to the power conversion industry as a whole (not just the wind industry) at the multi-megawatt level. The PHIL setup at Clemson University is shown in Fig. 10.

CAPS is located in Tallahassee, Florida, USA, and the center has a state-of-the-art PHIL facility dedicated to advancing terrestrial and shipboard power systems. The PHIL-interfaces available are three 5 MW, low and medium voltage AC and DC amplifiers and a 5 MW dynamometer with a speed range of up to 24 krpm. All power amplifiers are interfaced to and controlled by real-time simulators. Overall, the amplifiers enable several nominal voltage setups including 4.16 kV AC/700 A, 13.8 kV AC/200 A, 1 kV DC/2500 A, and combinations of four 6 kV/200 A DC setups.

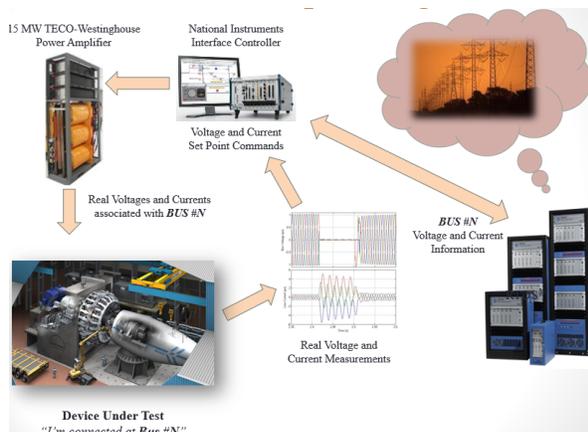


FIGURE 10. PHIL setup at Clemson University's eGRID.

PHIL Advantages: The CHIL and PHIL are being extensively utilized at the eGRID and CAPS facilities for robust evaluation of various use cases aiming towards achieving the following objectives.

- **Grid Modernization:** Developing technologies and strategies to update the aging infrastructure of the electrical grid to meet contemporary demands.
- **Renewable Energy Integration:** Exploring methods to efficiently incorporate renewable energy sources into the grid, addressing challenges related to intermittency and variability.
- **Smart Grid Technologies:** Innovations in smart grid technologies, including advanced metering, demand response, and intelligent grid management systems.
- **Power Electronics:** Research on advanced power electronics for improved control and efficiency in power transmission and distribution.

- **Cybersecurity:** Enhancing the security of the electrical grid against cyber threats, ensuring resilient and secure operation.
- **Superconducting technologies:** Validation of superconducting technologies, such as motors and fault current limiters.
- **Motors:** research on high-power, high-speed generators and motors for naval applications.

D. Emulation of electric drives

Background: Another example of an application where PHIL can significantly simplify testing procedure and introduce additional flexibility is high-power inverter testing. The inverters for Electric Vehicles drive trains and industrial drives are traditionally tested using motor-generator groups, which, due to spinning masses, require implementation of specific safety measures in the test laboratory. Additionally, one motor-generator group is only suitable for testing inverters with rated powers within a certain range. More flexible testbenches are needed to accelerate inverter development.

Laboratory setup: High-power inverters can be tested using PHIL (to simulate the operation of an electrical machine) instead of motor-generator groups [70]–[72]. The model of an electrical machine is executed in a real-time simulator and the setpoints are then sent to the power amplifier to reproduce voltages and currents of the simulated machine. An example of the experimental waveforms of the startup and load transients of a real 22 kW induction machine compared to the same machine simulated in PHIL is illustrated in Fig. 11 [72].

PHIL Advantages: Using PHIL for high-power machine emulation permits flexible validation of machine controllers and components:

- **Multi-machine emulation:** it can significantly simplify the test setup by replacing several motor-generator groups with one PHIL system simulating a wide range of electric machines (including different types of electric machines). This is done by simply changing the simulation models to simulate different types of machines (or by loading different parameters sets to simulate the same type of machine with different properties), while using the same test setup hardware.
- **Sensor testing:** the PHIL emulation of machines allows to implement easily different types of position/speed feedback devices (e.g. resolver or encoder) as a part of the simulated machine model.

All this makes PHIL approach very practical and attractive because it significantly reduces the hardware requirements for the test equipment and the time required for reconfiguration, while enabling significantly higher versatility of the test system.

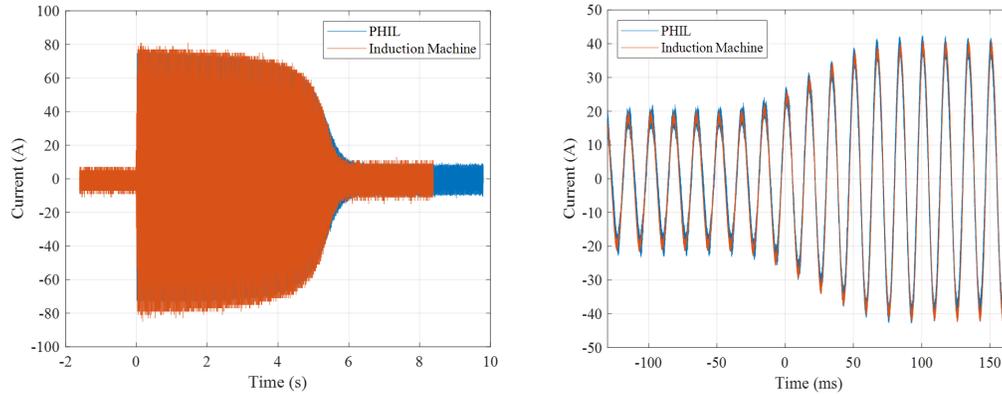


FIGURE 11. Transient response of a 22-kW induction machine vs. the same machine simulated with PHIL: (left) direct-online start transient, and (right) load step transient from 9 kW to 18 kW.

E. On-board microgrids for More Electric Aircraft

Background: By using PHIL systems, the functionality verification process for the on-board microgrid of the more electric aircraft (MEA) is significantly facilitated.

Laboratory setup: The effectiveness of the PHIL-based test benches for aerospace applications for the emulation the electrical machines and the autotransformer rectifier showed good match between the emulated waveforms and the experimental waveforms was presented [73] and [74]. A setup comprising of two 250 kW power supply and 2x200kW COMPISO power amplifiers from EGSTON power was adopted for the testing of electric machine for hybrid aircraft propulsion in [75]. The DC Power supply is used to emulate the battery for the drive. A PHIL setup emulating the on-board microgrid, while measuring online the small-signal behavior of the power electronics subsystems for stability analysis, was presented in [76]. Located at the DNV GL Flexible Power Grid Lab (FPGL), the setup features a 200 kVA EGSTON digital power amplifier. At the University of Nottingham Ningbo China, a PHIL facility comprising of a 30 KVA Puissance+ linear amplifier and a PLECS RT Box real time simulator is used to emulate a downscaled 400 Hz ac electrical power distribution system of the aircraft, followed by the implementation and verification of a control-based stabilizing technique [77]. As for the system-level evaluation, a down-scaled on-board microgrid including the power generation, distribution and the energy storage was tested by the real-time simulator with the programmable sources [78]. Cost-effective PHIL implementations using back-to-back switching converters have been successfully demonstrated for automotive traction inverter testing [79]; such approaches are promising for adaptation to aerospace power systems.

PHIL Advantages: PHIL testing for on-board microgrids has the significant advantage of reducing the testing time. While it is true that aerospace follows strict protocols which ultimately imply a copper-bird testing, validating the HOI with a PHIL system connected to an on-board micro-grid

allows to verify safely several critical operational conditions. Additionally, the interaction between the converter under test and the whole power system can be preliminarily analyzed within the PHIL system. Given the very low inertia of the future aerospace electrical power system, PHIL testing in this phase can help identify potentially dangerous issues before further development takes place as well as to help optimize the design of the whole system (e.g., optimizing storage/magnetics/capacitors).

VIII. Critical considerations in applying PHIL

PHIL test systems are relatively complex systems and users of these systems need to be aware of several important aspects that can affect applicability or accuracy of PHIL tests. The most important aspects that require more attention are discussed in this section.

A. Scalability

The PHIL testing is mainly limited by the power amplifier sizing, which is typically limited to several MVA in low-voltage applications (1 kV RMS or 1.5 kV dc). However, higher voltage and higher power applications are currently of high interest for the academic and industrial community. The results of PHIL tests performed using reduced-scale prototypes connected to simulated networks of significantly larger size are presented in several papers. This approach is typically used to test wind power plants [80], [81], HVDC systems [82]–[84], and high power electric drives [71].

Although some performance characteristics can be easily captured, the main concern with this trend lies in the fidelity of the testing as a result of power converter scaling-up. The improper scaling-up can introduce significant inaccuracies in test results, because some converter properties such as switching characteristics, dynamic and thermal properties cannot be accurately scaled-up.

Open points: the fidelity of tests based on scaled-down HOI with respect to the full-scale hardware needs to be verified. Using reduced-scale PHIL system components may

neglect certain phenomena or dynamics, and thus provide a wrong performance assessment. In some cases, a well-built simulation or CHIL testing could produce more accurate results.

B. PHIL experimental dynamics

Power Amplifiers in PHIL systems are used as an interface between the MOI and the HOI. As already mentioned in Section III, power amplifiers used in PHIL systems can be either linear power amplifiers, or switched-mode power amplifiers [85]. Due to their operation principle, linear power amplifiers can achieve very high bandwidths, but suffer from low efficiency and cannot regenerate energy back to the input power source. On the contrary, switched-mode power amplifiers feature significantly higher energy efficiency (higher than 90%), bidirectional power flow and smaller size and weight.

All these aspects need to be taken into account during PHIL testing (especially if phenomena involving fast transients are tested), because amplifier limitations (limited bandwidth in particular) can compromise the test accuracy in these cases.

Open points: Additional research is needed to characterize the effects of power amplifier limitations on simulation testing accuracy of highly dynamic systems and phenomena (e.g. faults). There is need for new power amplifier technologies, able to cover high-frequency and high-power levels (e.g., for testing medium frequency transformers).

C. Non-idealities in the PHIL interface

Several linear and nonlinear elements of PHIL system, such as power amplifiers, measurement systems, or digital/analog converters, that are vital for the PHIL operations, are not present in field testing. Therefore, non-idealities of these items have to be considered when assessing the performance of the PHIL interface while the real coupling case at the power interfaces that exists in the real-world system is intended to be preserved in PHIL system as described in [6]. All components of PHIL test system have intrinsic delays (usually up to few tens of microseconds) deriving from measurement digital conversion (below $1 \mu\text{s}$), fiber optics limited speed (up to $0.3 \mu\text{s}$ per meter of fiber), and power amplifier (from $3\text{-}4 \mu\text{s}$ to $50\text{-}100 \mu\text{s}$ for older models). In addition, active elements like switched-mode power amplifiers, will have a unity gain (i.e., output follows exactly the input) only within a limited bandwidth. Outside this bandwidth, the output signal may show attenuation or resonance phenomena, decreasing the fidelity of testing.

Open points: a detailed characterization of non-idealities of PHIL system is still missing, as well as the analysis of the impact of these non-idealities on the PHIL stability. More advanced mathematical models are needed to characterize non-idealities with higher accuracy. Additional studies are needed to understand the impact of asymmetrical delays in the feedforward and feedback path of PHIL systems.

D. Stability vs. Accuracy

As mentioned above, the PHIL introduces elements for interfacing the MOI and HOI that do not exist in the reality: power amplifiers, sensors, filtering, etc. As a consequence, this introduces a delay between the software and hardware communication. It is well documented, that this affects the PHIL stability [3], [4], [86].

To solve this issue, two approaches have been followed:

- 1) Varying the interface method, choosing more complex approaches such as Partial Circuit Duplication and Damping Impedance methods [51].
- 2) Inserting a feedback (or feed-forward) filter to damp the high-frequency system dynamics, and thus stabilize the loop [30].

Both approaches help to stabilize the PHIL. However, at the same time, they modify the loop plant, introducing transfer functions that do not exist in reality (i.e., in the real coupling case condition). As a result, the accuracy of the PHIL testing is heavily affected, mostly at high-frequency range.

Open Points: further studies are needed to assess properly the impact of filter and interface methods on the testing accuracy. A standardization of the accuracy estimation methodology should be proposed and elaborated in order to make the accuracy of test cases comparable between different laboratories and setups.

E. PHIL modeling

Recent developments in RTS and power amplifier technology has reduced drastically the loop delays and non-idealities. As a consequence, a larger spectrum of scenarios can be analyzed in PHIL, including dynamics that previous modeling techniques could not achieve.

Open Points:

- The impact of the **PLL** is usually ignored in PHIL assessment. However, this has a clear impact on the lower frequency spectrum, introducing inaccuracies. Due to the increased mathematical complexity, the PLL model shall be considered only if it affects the outcome, e.g., impact of angle estimation during fault ride through situations.
- All the previous stability analyses have considered either single-phase or perfectly balanced three-phase systems. More focus is needed on **unbalanced systems**, because these systems better represent real power systems.
- The current mathematical approaches involve the knowledge of the MOI and HOI model. However, in industrial testing, this is usually not known or protected by intellectual property. More work is needed in the **automatic estimation** of the MOI and HOI model (e.g., by means of impedance estimation), and automatic assessment of the stability and accuracy margin.



IX. Research points to be explored for PHIL

The PHIL is still a relatively novel topic when compared to electric drives and renewables. Recent advancements in the power amplifier technologies and real-time simulators have allowed a wider adoption of this approach. However, there are still a few remaining open topics that need to be addressed to enable wider adoption of PHIL for testing and validation of electrical equipment in industrial environments. Some of those topics are summarized in this section.

Testing at medium voltage: the industry is currently focused on designing medium-voltage power converters for grid stability (e.g., MV DC grids) or large electrochemical plants purposes (e.g., electrolyzers, power-to-X). However, their testing in PHIL is challenging, due to the high power and voltage requirements. Two approaches are possible in this case: (i) employing a multi-MW low-voltage converter with a step-up transformer to the desired voltage. This solution has been already applied in several existing PHIL setups [66], [87], [88], and power amplifier companies can offer off-the-shelf products. The main issue with this solution lies in the transformer dynamics and linearity, which requires additional efforts to avoid inaccuracies during testing. To address this, dynamic compensation approaches have been included in the power amplifier controllers to consider the transformer dynamics. (ii) employing a multi-MW medium-voltage converter (e.g., modular multi-level converters) that is connected directly to the System Of Interest (SOI). This approach can potentially increase the accuracy of the tests, but it is still at the early stage of adoption and needs more evaluation. Several facilities with this approach are currently being developed, such as the High Power Grid Lab at the Karlsruhe Institute of Technology [89]. Major concerns on the bandwidth and fault-current interruption (in half-bridge topologies) still need to be addressed and are open points for future research.

Faults: PHIL testing is accurate only within a certain dynamic range. Due to the inclusion of delays and filters in the interface algorithm and the limited transient capability of some switched-mode amplifiers, the faster dynamics generated by faults are difficult to emulate. In particular, DC faults phenomena, extremely important for the development of DC technologies, have a time constant of few milliseconds, which can be difficult to reproduce accurately in hardware. In addition, there is a conservative approach of testing laboratories in performing fault studies, due to the high probability of damaging the equipment during the tests. There is still no general consensus on how to emulate faults with PHIL.

Unbalanced grids: the majority of PHIL tests involve single-phase or balanced three-phase systems. No significant attention has been given to unbalanced systems mainly because of nature and requirements of typical SOIs: electrical drives, power electronics for photovoltaic or energy storage systems. All these systems are usually controlled with a balanced current injection. Recently, more attention has been

given to single-phase fault ride through capability of converters. Initial studies on asymmetrical grid faults [90] provided a first assessment of the testing accuracy. However, the field still lacks a general approach for unbalanced systems studies, particularly during transients.

X. CONCLUSION

Power Hardware-In-the-Loop is a powerful tool that can effectively accelerate the testing of novel energy technologies and their introduction to market. Reproducing realistic grid conditions in the lab in a safe and repeatable way allows for reducing testing time and costs for manufacturers, and alleviating integration concerns for utilities. The PHIL research field is relatively new, with the first publications published only twenty years ago and the first IEEE recommended practice published only in 2025. The present paper offers a recommended guideline for implementing PHIL systems in industrial facilities, considering different scenarios, hardware topologies and scalability, testing accuracy and stability. It introduces a first classification of PHIL testing architectures, including multi-port and multi-system configurations, to expand the classical single-device, single-system testing approach.

While the research field has been extensively explored, particularly regarding the loop stability concerns, a significant work still needs to be done on scalability, dynamics, non-idealities, accuracy, and standardization. This offers fertile ground for new ideas for both academia and industry.

XI. ACKNOWLEDGMENT

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