# Real-time Simulation-based Testing of Modern Energy Systems

## I. Introduction

One can define an energy system as a system that converts one or more energy fluxes into other energy fluxes of a different kind. This definition may describe a relatively small system – for instance a power plant, a chemical plant, the heating and cooling system of a single-family house – as well as one covering larger energy needs – as for instance the needs of a city, of a country, or even of a continent. As energy systems are developed through the centuries, the way we structure these systems goes through changes affected by contextual conditions. Recently, concerns about the availability of traditional fossil energy sources and their environmental effects are revolutionizing the way energy systems are planned, designed, and operated.

Modern energy systems are expected to be multi-modal and incorporate electrical, gas, and heat networks – to achieve maximum usage of every form of energy available – and to include storage capacity [1]. The distributed nature of new resources (generation and storage) and the participation of loads in energy management require fast, reactive control, and protection. In this context the monitoring and control of modern energy systems are expected to be characterized by distribution of functions. At the same time – to ensure optimal coordination – a large use of communication media is envisioned [2]. Interactions between continuous dynamics and discrete events are becoming more relevant due to the increasing number of controllable devices (e.g., power electronic converters in the electrical grids) and the use of networked control schemes. Energy systems, furthermore, are increasingly driven by market competition. Because of these characteristics and because of human involvement, modern energy systems can therefore be classified as complex and concerns about emerging behaviors might be raised [3].

The complexity of such systems poses significant challenges on how these systems are planned, designed, and operated. In this context it is crucial that each piece of the system is tested in a more comprehensive way. In the last decade incremental prototyping tools (mainly Hardware-in-the-Loop (HIL) based) have become a standard practice in industry. In this work we will review and summarize recent developments in specifying validation needs as well as corresponding methods and tools like real-time simulation and HIL-based experiments.

## II. Validation Concepts

As outlined the planning, design, and operation of modern energy systems gets more complex mainly due to its cyber-physical and multi-domain/modal nature. Typically, in the past individual domains of power and communication systems have been often designed and validated separately. Also, existing methods focus mainly on component level issues; system integration topics are usually not addressed in a holistic manner [4]. Instead of this well-known practice a holistic approach and corresponding methods and tools for analyzing and testing modern energy systems on the system level is required.

Over the past years there has been some progress in order to introduce formalized concepts for designing and developing modern energy systems applications like the IntelliGrid method for documenting use cases as well as the Smart Grid Architecture Model (SGAM) for developing suitable architectures [5]. Also, model-driven development of cyber-physical energy systems becomes more popular [5]. However, when it comes to a structured and formalized validation and testing of system-level questions there exist a lack in the concepts. First promising approaches like the ERIGrid holistic testing [6] as well as the JRC interoperability testing approach [7] have been introduced recently which makes it easier to define testing needs and corresponding plans. Furthermore, available validation methods and tools spanning from formal analysis/physical equations over simulations/real-time simulations up to laboratory experiments and field tests need to be aligned with these new design and validation approaches. The following table provides an overview of the suitability of those approaches along the development process.

*Table 1: Suitability of different design and validation approaches along the development process [4].*

| | ***Requirements and Basic Design Phase*** | ***Detailed Design Phase*** | ***Implementation and Prototyping*** | ***Deployment / Roll Out*** |
|---|---|---|---|---|
| Analytical Methods / Software Simulation | + | ++ | O | - |
| Laboratory Experiments and Tests | - | - | ++ | + |
| Real-time Simulation and Hardware-in-the-Loop (HIL) | - | - | ++ | ++ |
| Demonstrations / field tests, pilots | - | - | - | ++ |

- … less suitable, o … suitable with limitations, + … suitable, ++ … best choice

In the following sections we will review recent progresses in the development of real-time simulation and HIL-based methods and tools to support the prototyping and roll-out phases.

# III. Methods and Tools

## A. Real-time simulation

During the last years real-time simulation has become increasingly popular to test and validate equipment and algorithms in a controlled and realistic environment. The synchronization between simulation time steps and the elapsed real-time allows the exchange of physical inputs and outputs between the real-time simulator and connected devices, since a simulated second corresponds to a second of elapsed time. There are several examples of the use of real-time simulation in power systems: the development and testing of protection and control systems, distributed generation units[9][10] -especially with renewable energy resource integration and microgrid control [8]- and of energy storage solutions[11][12]. The development of real-time simulation and HIL testing solutions for modern energy stems can be broken down into several subtasks such as: development of solvers for different time steps, interconnection of laboratories over a communication network, configuration of hardware in the loop experiments, integration of system wide testing. An overview of different approaches, technologies, and products as well as their performance is provided in [13]. In the following we are mainly discussing latest developments related to small time step solver, laboratory remote connections, and slow dynamics solvers of real-time simulation

### 1. Small time step solver

Historically one of the main interests for real-time simulation in the electrical engineering field was the testing of relays for terrestrial power system as, for example, in [14]. In [15] a real-time, resistive companion type of solver is presented; in [16], applying the Multiarea Thevenin

Equivalent (MATE) [17] concept, a 78-nodes power system is executed in real-time on a PC Cluster. Starting in the same years, but with a significant growth of interest in recent years, real-time simulation and hardware in the loop methods also for power electronic systems have attract the interest of both academia and industry.

With the rise of increasingly larger and more complex energy conversion systems with ever faster dynamics -e.g. power electronics converter based on wide band gap power devices- the need for real-time simulators capable of simulating such systems and their fast transients has grown. In this paper we refer to simulator/methods able to accurately simulate those system as small time step solvers (time step smaller than 500ns). The strong nonlinear behavior of the system and the small time step size required by the high switching frequencies are between the main challenges of real-time simulation of power electronics converters. In the last few years, to face these challenges, there has been a change also in the type of processors used: mixed solution based on DSPs/CPU and FPGA are more and more common. FPGAs are used both as interface and also for computation. While CPUs have in general higher computation capabilities that FPGAs the latencies associated with access to memory and communication busses limit the algorithms parallelizability and make the use of high speed input-out interface difficult is not impossible. In general it is hard to imagine the use of CPUs for real-time simulation with time step smaller than 1us. In recent years, the use of Field Programmable Gate Array (FPGA) devices has so been the center point of new work in academia and industry to perform real-time simulation of energy systems with fast dynamics.

Large number of works have been published in recent years that focus on defining simulation methods fitted for the real-time simulation of power electronics systems using FPGAs: in

[18][19][20] an AC machine, a power converter and a nonlinear power transformer are directly simulated on an FPGA. In [21] an MMC converter is simulated using an FPGA in combination with a CPU. For solutions fully based on FPGA execution, time steps as small as 40 ns [22] have been achieved. A common trend in recently published approaches on real-time simulation is the focus on non-linear behaviors. [22]-[25] focus on defining modeling approaches that allow creating models that – while representing with good accuracy the non-linear characteristic of power electronics converters – can be executed in real-time with very small-time steps. Several papers [26]-[30] have been published that focus on the modeling of device level behaviors. Even if look-up tables and pre-computed behavior are used, this level of detail was for sure hardly imaginable – for real-time simulation – until a few years ago. In [31] and [32] authors focus on the molding of the non-linear behavior of electrical machines.

A common problem in the use of FPGA for real-time simulation is the steep learning curve necessary for the programming of those devices. Recently developed High Level Synthesis (HLS) tools are simplifying this process. Several of the papers recently published and previously mentioned use those type of tools, [33] provides an overview of the use of HLS tools for real-time simulation programming. Another interesting approach for real-time simulation on FPGA devices have been proposed in [34] and [35] where the FPGA has been used as solver engine.

While FPGA based solvers can achieve very fast execution with a quite constant time step at the growing of the size of the system simulated, their main limitation is the resource usage, [22] and [25]. Numerical methods and interface solutions for multi-FPGA execution are proposed in [36] and [37].

## 2. Laboratory remote connection

Modern energy systems are often characterized by a wide adoption of power electronics interfaced generation and loads especially at low voltage and medium voltage distribution level. This leads to an increase of modelling complexity often reaching the scalability limit of digital real-time simulators [38][39], leading to the situation where the local available Digital Real-Time Simulators (DRTS) might not be adequate for a desired scenario. Furthermore, devices to be tested and simulators are often geographically distributed. Those scenarios can be seen as drivers for distributed simulation and laboratory interconnection. An often-overlooked aspect for distributed real-time simulation lies in the inherent data confidentiality. Each laboratory/participant can simulate its own part locally while solely exchanging interface variables with the interconnected systems as depicted in Figure 1.

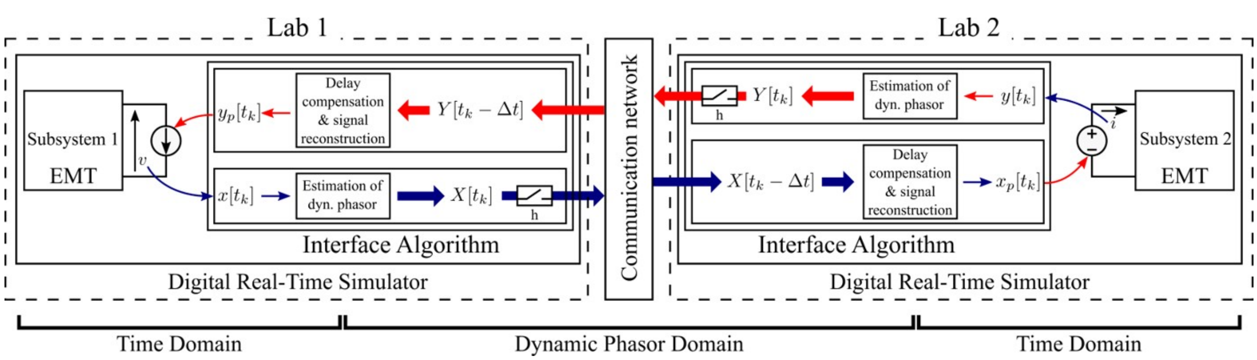



*Figure 1: Laboratory - distributed co-simulation [30].*

This resembles the logic of the power grid where regional and national power grids are interconnected through tie-lines. The communication delay caused by the coupling of different simulators over the internet may be of orders of magnitude larger than the simulation step of commercial DRTS, which would make the data exchange at every time step not possible. For such cases a compensation of the delay would be required which follows the same logic of the Interface Algorithm (IA) used in Power Hardware-in-the-Loop (PHIL) experiments[40].

## 3. Slow dynamics solver

A common approach to partition power systems for parallelization is the use of the travelling wave transmission line model [41], which travels about 15km in 50μs and is a typical time step in real-time power system simulation. The expected delay in internet enabled simulation is tens of milliseconds, therefore the communication delay will cause instability. This can be explained by the sampling theorem in which the required sampling frequency is at least twice the maximum frequency expected in the systems. A possible solution is the usage of static phasors, which implicitly include the system frequency although it is fixed and therefore do not support variable frequency. An extension to the static phasors are the dynamic phasors. Dynamic phasors were initially developed for power electronics analysis [42] to increase the accuracy of state-space averaging method. Later, the concept was extended to cover power systems analysis [43] representing a compromise between steady state solutions and classical electromagnetic transient analysis.

Dynamic Phasors are a very efficient method to study signals that have a frequency spectrum in a limited band. This is the typical case of power systems where all the quantities have typically a frequency content that is in a reasonably small neighborhood of 50 Hz (60 in US and Japan). By means of a shift in the frequency domain, the signal can be seen as characterized by a frequency spectrum limited around the 0 Hz. As result, longer time steps are possible allowing a faster and more efficient simulation operation.

In the post-processing stage, the simulation results are shifted back in the right frequency range.

All in all, the process can be interpreted as performing the simulation to calculate the envelope of an oscillatory signal instead of calculating the signal itself. As result, very large systems can be calculated in a very efficient way performing real-time dynamic simulation of complex power systems by using also off-the-shelf hardware. The application of dynamic phasors for multi-source and multi frequency systems including time-varying frequencies was shown in [44].

## B. Control Hardware-in-the-Loop

Controller Hardware-in-the-Loop (CHIL) is a methodology which combines numerical simulations with hardware testing. Instead of connecting the controller hardware to the power unit, it is interfaced with a DRTS. The input signal for example voltage and current measurements and output signals for power system control are exchanged in real-time as depicted in Figure 2. CHIL testing has become a wide adopted methodology since it bridges the gap between simulation and power experiments. It offers the engineer low cost and low risk combined with high flexibility and fast realization, which can shorten the development cycle [45].

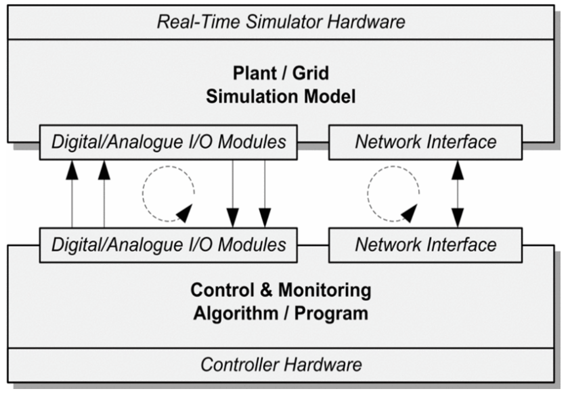



*Figure 2: CHIL validation approach [46].*

## 1. Laboratory-based testing of energy infrastructure

The focus on the CHIL and PHIL is often part of prototyping chain that bridges the gap between simulation and real implementation. Often the focus lies here on the single component and its interactions with an emulated environment. It enhances the testing quality of the implemented algorithms and allows the verification of the desired system behavior at normal and abnormal operating conditions while relying on measured values.

Laboratory-based testing of the energy infrastructure extends the focus from CHIL and PHIL towards the on the system integration as shown in Figure 3. When looking at the figure it becomes obvious that modern energy systems are interconnected systems, which are more complex to design, develop and validate. They are now a multi-domain system of systems. In this context functionality, integration, and performance assessment have to be verified while also ensuring interoperability and interchangeability of the designed solutions. This system integration testing needs to bridge the gap between simulations and field trials and is done in a laboratory. In this context, the concept of digital twin already used in factory automation domain [46] needs to be applied. The reason for this is that due to the amount of possibilities a field test to assess the performance every solution and device would not be possible or at least very time consuming and expensive. Furthermore, in the area of power systems the system operator is less eager to perform certain test which may result in disconnected customers.

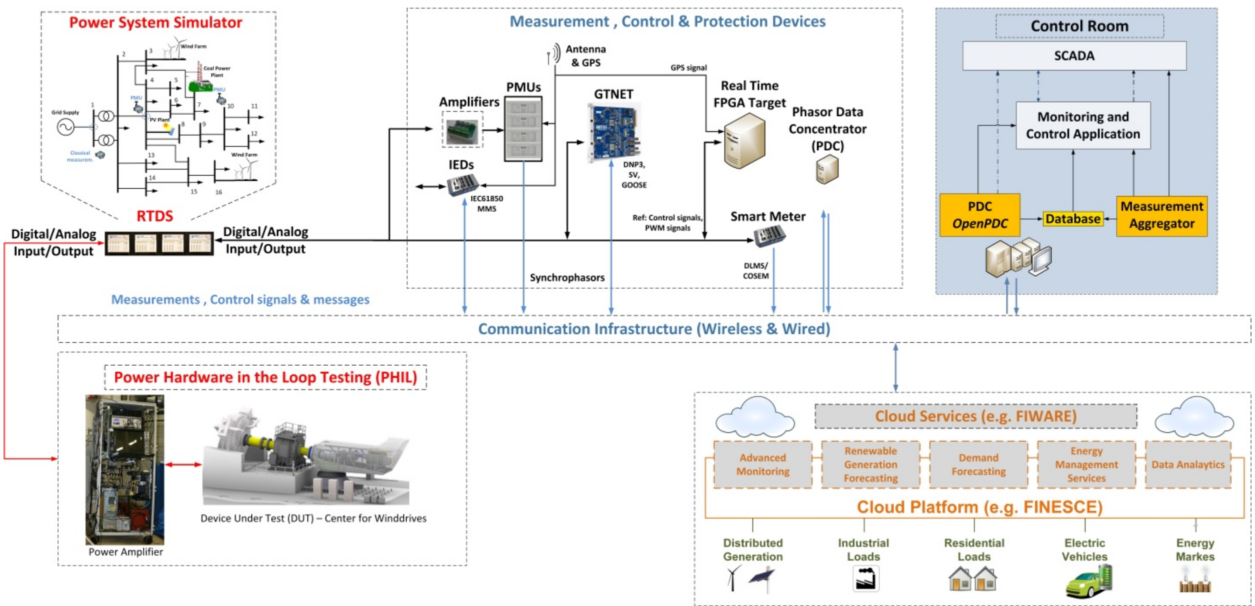



*Figure 3: Testing environment from concept to demonstrations.*

## 2. CHIL applications and examples

CHIL has been applied in different fields such as the vehicles, aerospace, power electronics converter design, renewable energy sources [47] and microgrids [48]-[51]. Real-time testing for microgrid controllers has become mandatory for validation and compliance testing and therefore recommending CHIL testing for evaluating controller performance [52].

It can be concluded that HIL simulations became an advanced means for investigative experimentation, model validation, and testing before implementation of electrical subsystems in actual processes [53]. This is reflected in the ongoing standardization efforts [46].

## C. Power Hardware-In-the-Loop

The validation of hardware performance is a fundamental step before the commercialization. During this phase, the hardware shall prove to achieve the results planned in the analysis. The validation is initially left to simulations. However, the accuracy of the results depends strongly on the modeling adopted, and complex modeling, despite accurate, may require an unacceptable simulation time for industrial practice [54]. The current practice for hardware validation, e.g., power electronics converters for distributed generation applications, is to recreate in the laboratory equivalent grids using voltage sources and real impedances, with the goal to reproduce the grid behavior at the point of connection. However, this approach has two main drawbacks: it does need physical changes if new grid conditions are to be tested (e.g., grids with different impedance); and only the hardware performance in a specific point of the grid can be proved, without being able to verify the performance on the overall grid.

To overcome this limitation, the PHIL concept has been introduced [55]-[57]. It combines the advantages of testing real hardware in realistic grid conditions, without being limited by the need to build up large grids in the laboratory context.

The PHIL operations involve three main actors: the Hardware-under-Test (HuT), which is the hardware that we want to test the performance; the DRTS, where the test grid is simulated in real-time; the power amplifier, with the goal to replicate the simulated grid conditions at hardware level; and the measurement system, which allows to read physical variables and send them to the DRTS as shown in Figure 4.

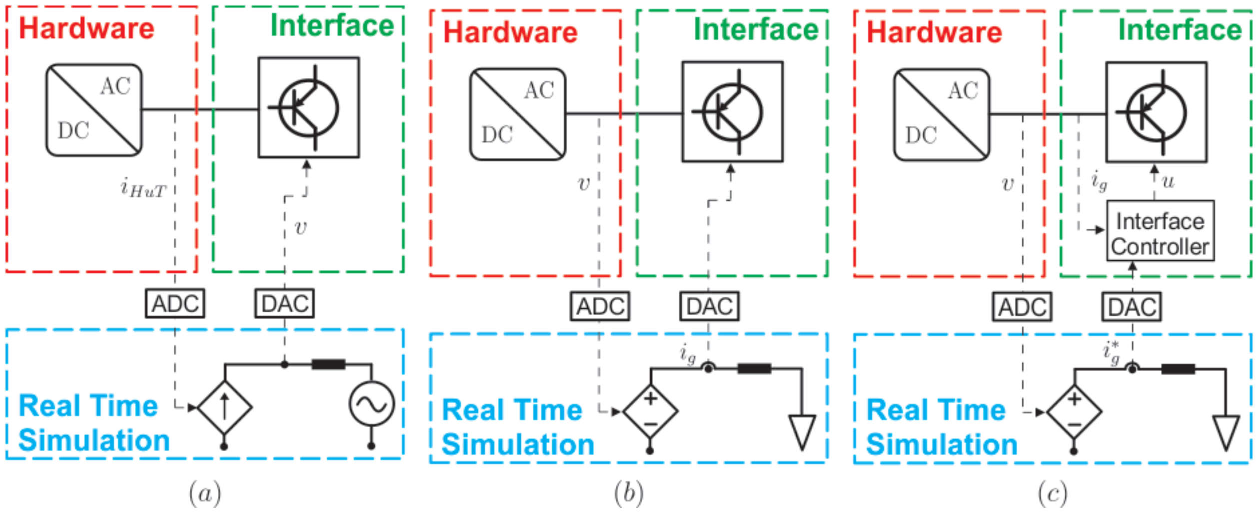



*Figure 4: PHIL possibilities: (a) voltage-type, (b) ideal current-type, (c) modified current-type PHIL*

## 1. Power amplifiers and interface algorithms

In PHIL applications, how to interface the HuT with the simulated grid has always arisen interest in the engineering community. In literature, two typologies of PHIL evaluation currently exists; voltage-type and current-type PHIL. The first one (Figure 4a), largely discussed in literature, is the most adopted PHIL interface, that is used to validate customer-level appliances, such as drives [58], on board systems [59], renewables or battery plants [56], [60]. The power amplifier replicates in hardware the voltage waveform in the point where the HuT shall be tested, while the HuT output current is measured in hardware and reproduced in the software by means of a current source.

In the last years, grid-forming converters have attracted high interest in the scientific and industrial community. These converters principal feature is to synthesize the voltage waveform in the fed grid, despite the lack of a synchronous connection with the mains. Due to this feature, using a voltage-type PHIL evaluation can be tricky in terms of stability. Two voltage-source converters, both controlled in voltage (and presumably with comparable control bandwidth), that are connected in series, can create possible loop unstable conditions. For this reason, current-type PHIL evaluation is carried out for testing grid-forming converters, such as HVDC terminals or smart transformers [61]. An ideal current-type PHIL evaluation is shown in Figure 4. The power amplifier is a current source converter that, connected to the grid-forming converter under test, reproduces in hardware the current demand of the simulated grid. The voltage waveform, synthesized by the converter, is then measured and replicated in software by means of a controlled voltage source at the point of common coupling with the fed grid.

However, an ideal current-type is difficult to realize due to the lack of current source converter-based power amplifier. For this reason, a modified current-type PHIL interface is proposed in [61], [62]. As can be seen from Figure 4c, the power amplifier is still a voltage source converter, but controlled in current, by means of a high bandwidth current controlled implemented either in the DRTS, or in customized micro-controller. The main advantage of this approach is the use for current-type PHIL evaluation of voltage source converters, widely available in the market. As drawback, the capacity of the power amplifier to reproduce accurately in hardware what occurs in the simulated grid is strongly dependent on the interface current controller bandwidth. The need for reproducing accurately the software currents in hardware calls for increasing the current controller bandwidth. On the other side, an aggressive current controller can destabilize the stability of the loop. As concluded in [62], a tradeoff between accuracy and stability of the system must be found, in order to represent accurately in hardware higher frequency current content, without making the system unstable.

When designing a PHIL experiment is important to take in consideration some practical aspects that may significantly impact the accuracy of the performed test. PHIL interfaces add nonidealities in the loop, thus affecting the accuracy of the evaluation. To address properly the accuracy of the PHIL evaluation, three main factors have to be considered:

1. *Communication between DRTS and the power interface*: all the PHIL components work with a specific time-step, depending on the computational capabilities of their respective controllers. As can be seen from Fig. 4, Digital/Analog (DAC) and Analog/Digital Conversion (ADC) stages are interposed between the real and the simulated system. This implies that analog measurements have to be discretized within the sampling frequency of the DRTS (typically 20kHz), and the HuT (typically in the range [5-20]kHz). As consequence, further delay is introduced in the loop that can affect the accuracy and stability of the system.
2. *Software interface*: the stability and accuracy of the PHIL evaluation are affected by the strategy to interface the software and hardware sides. Several algorithms have been developed and their characteristics investigated in literature [56][57]: Ideal Transformer Method (ITM), Transient First-order Approximation (TFA), Transmission Line Approximation (TLA), Partial Circuit Duplication (PCD), and Damped Impedance Method (DIM). Each of these methods have advantages and disadvantages related to the simplicity of the implementation, accuracy, stability, need for external interface impedance. Being this topic widely described in the literature, it is not deeply treated here, but the reader can refer well-known literature in this regard for a detailed explanation [55][56][57].

| **Software Interface** | **Advantages** | **Disadvantages** |
|---|---|---|
| Ideal Transformer Method (ITM) | • Based on transferring voltage and current measurements between | • Stability and accuracy are dependent on software/hardware impedance ratio |

| | | |
|---|---|---|
| | hardware and software.<br>• Simplicity in the implementation<br>• High accuracy | • Noise rejection not possible due to the lack of controlling loops.<br>• Need for numerical filtering to increase the system stability, sacrificing the loop accuracy at higher frequencies. |
| Transient First-order Approximation (TFA) | • Modelling of the HuT as first order transfer function<br>• Prediction method | • Not suitable for complex HuT, such as voltage source converter, due to the first-order approximation<br>• Instable behavior caused by wrong modeling of the system<br>• Accuracy strongly dependent on measurement noise |
| Transmission Line Approximation (TLA) | • Based on long-line decoupling method that is well-known approach for decoupling large systems<br>• Numerically stable due to the trapezoidal implementation | • Need for a physical resistor, that leads to high losses in large power applications<br>• The resistor value needs to be updated any time the simulated system changes, leading to low flexibility<br>• On-line topology changes of the simulated system are not possible due to the fixed resistor value in each experiment |
| Partial Circuit Duplication (PCD) | • Based on software relaxation technique, allowing to split the loop in two subsystems.<br>• Higher stability than ITM algorithm, due to the possibility to change the linking impedance and to keep the hardware/software ration below unity. | • Need for a physical impedance<br>• To reduce the error in each iteration the linking inductance shall be larger that the HuT and simulated grid ones, leading to high power losses.<br>• Low accuracy resulting from the difficulty to realize large linking inductance. |
| Damped Impedance Method (DIM) | • Method mixing PCD and ITM, inserting a damping impedance.<br>• If the HuT equivalent impedance is accurately estimated, the loop error tends to zero.<br>• Lower power losses than PCD method | • Estimation of HuT equivalent impedance not easily to acquire, thus the loop error depends on the HuT modeling error.<br>• HuT equivalent impedance is influenced by the HuT controller, thus different controllers may affect strongly the loop accuracy. |

3. *Power interface dynamic and rating*: representing accurately the simulated variables in hardware is fundamental for a correct representation of the simulated phenomena. However, this representation depends on the capability of the power interface to follow

dynamically the reference signal coming from the DRTS. Currently, two power interface technologies are available on the market: switching element-based power interface, and linear power amplifiers. In the first category, all the semiconductor-based technologies are included. The advantages of switching element-based power interface lie in the high power ratings [55][56][57] and in the power bi-directionality, that allows to send the current back in the grid, without the need of burning it in external resistors. The drawback in this technology is the limited bandwidth of the converters (up to few kHz) and the input/output delay (in the order of few hundreds of microseconds). The linear power amplifiers instead are based on linear operational-amplifiers, that allows high bandwidth (up to 180kHz). However, the linear power amplifiers are still largely limited in power ratings (up to few hundreds of kW) and do not allow bi-directional operations. If a four quadrant mode (positive/negative current/voltage) is requested, this technology requires to integrate external resistors to burn the reverse power. Another limitation of this devices is the linear dependence of the power injection on the voltage level. Being linear operational-amplifier devices employed, the rated power is possible only under nominal voltage conditions. A lower voltage limits linearly the power that can be injected by the amplifier. A third possibility exists on the market, despite it is not used for distribution grid-level tests: synchronous generators are exploit for balanced grids testing, with clear constraints in the bandwidth and accuracy in representing current and voltage.

| **Power Interface** | **Advantages** | **Disadvantages** |
|---|---|---|
| Synchronous Generator | • Low-cost solution<br>• High power / high voltage | • Low dynamics<br>• Only balanced simulations are |

| | | |
|---|---|---|
| | capability | possible |
| Switching elements-based | • High power capability (up to several MVA)<br>• 4-quadrant application | • Bandwidth limited to few kHz<br>• Introduced delay in the order of several hundreds of microseconds. |
| Linear Power Amplifier | • Medium power capability (up to hundreds kW)<br>• High bandwidth (up to 180kHz)<br>• Low introduced delay in the PHIL loop (few microseconds) | • Power reverse is not possible, thus the system needs resistors to burn the power send back to the power amplifier. This feature is usually limited to 1/3 of the power amplifier rated power.<br>• Power capability is directly dependent on the voltage. |

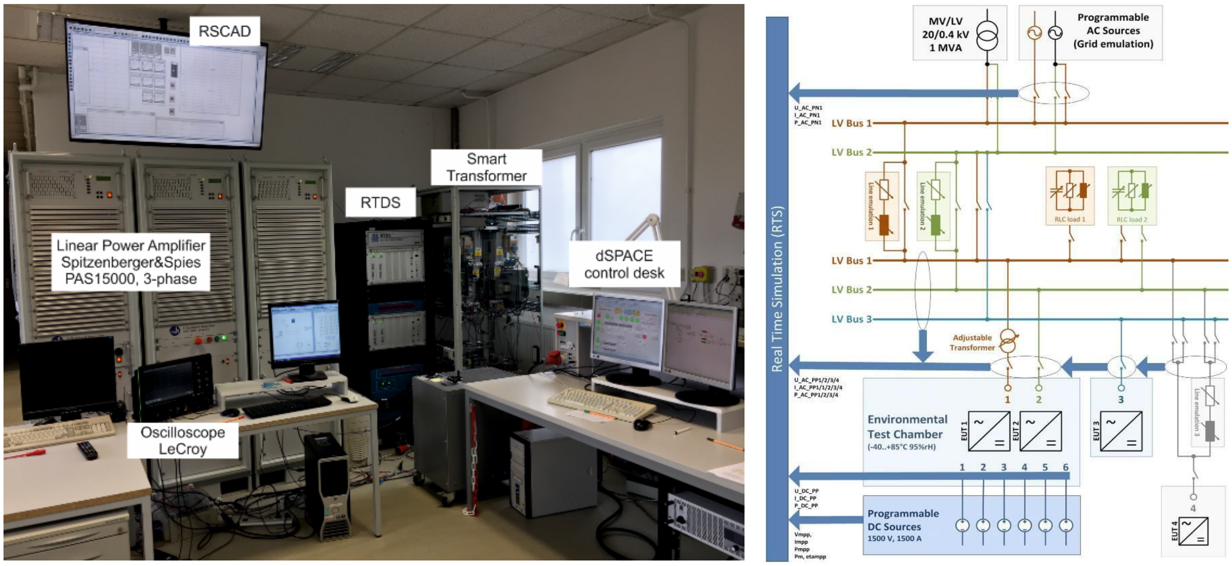
## 2. PHIL applications, examples, and existing facilities

PHIL has been chosen as validation tool in a large number of academic and industrial applications. As an example, voltage-type PHIL is commonly adopted for validation of renewable energy sources. Several examples are present in literature. Microgrids facilities, composed of batteries, diesel generators, electronics loads and renewables, are interfaced with PHIL setups, to validate grid integration tests with fast (e.g., drop in the irradiation in photovoltaic plants) [63] and slow dynamics (e.g., power dispatch of renewables) [21].

High power facilities, in the range of MVA, are beginning to be developed in university and industrial facilities. The "Energy Lab 2.0", developed in the Karlsruhe Institute of Technology (Germany) [64], has a 1 MVA PHIL facility that can be interfaced with a 1 MW photovoltaic power plant, 50 kW flywheels, and large battery storage systems. Wind turbine generators can be tested in the range of 10 MVA at Fraunhofer IWES (Germany) [65]. This setup is mainly used for wind turbine validation and certification purposes, with the possibility to reproduce a large variety of grid conditions in cheaper way than an only hardware-based test bench. Electric drives are tested at Florida State University, where a PHIL-setup in the order of 5 MW and 4.16 kV has been realized [58].

Although, the main PHIL application regards the scientific and industrial aspect, the education one shall be considered too. As described in [63], basic power systems operations, such as the effect of increased integration of distribution generation or the power sharing between generators, can be effectively taught to classrooms by means of PHIL. The students are able to directly witness real practical problems, like the impact of line impedance ratio on the voltage control, and adopt remedial control actions in first person.

In Kiel University, a 45 kW modified current-type PHIL facility has been built for validating grid-forming converters, such as Smart Transformers (ST) or grid-forming converters [61]. This setup allows to explore new control features for asynchronously-connected grids, such as voltage control and fault current limitation. Another interesting PHIL-setup using a voltage-type approach is provided by the AIT Austrian Institute of Technology which allows to test up to 1 MW inverter-based distributed energy resources and storage devices as well as active distribution grids with corresponding control strategies. Therefore, the AIT lab provides a configurable low-voltage distribution grid with test places for distributed energy resources and storage devices which can be connected via switched-mode (up to about 800 kW power range) or linear amplifiers (up to about 30 kW power range) with a commercial DRTS in order to characterize and test the aforementioned components but also to evaluate the impact of them onto the grid (e.g., power quality studies, unintentional islanding testing, fault ride-through testing, electric vehicle and energy storage systems charging behavior, control and automation system validation) as described in [67].




(a) (b)

*Figure 5: PHIL facilities: (a) modified current-type PHIL developed in Kiel University [22], (b) voltage-type PHIL developed at AIT Austrian Institute of Technology[67].*

In addition to the above provided examples the authors in [8] provide a comprehensive overview of real-time simulation and PHIL-related applications covering functional applications (designing, rapid prototyping, testing, teaching and training), field-specific applications (power system, distributed energy resources/power electronics, control systems) and simulation fidelity-based applications (EMT, phasor and hybrid simulation) of smart energy systems

## IV. Future Research

Modern energy systems tend to be more complex as traditional approaches due to their cyber-physical and multi-domain/modal nature. Especially, the planning, design, and implementation phases (incl. validation and testing) as well as the operation need suitable concepts, methods, and corresponding tools. This paper summaries real-time simulation/HIL based validation and testing approaches which tend to be more suitable in order to comply with future needs. Those approaches have been further developed over the last couple of years and they are used nowadays on a broad scale. However, the cyber-physical nature of modern energy system requires a further development and harmonization/standardization (like the IEEE P2004 for real-time system/HIL recommended practices) of the tools. The implementation of DRTS-based application is still time-consuming and highly linked with the provided tools from the corresponding manufacturers. Model-exchange and coupling of different DRTS from different vendors need to be improved in order to allow a multi-domain/modal analysis of modern energy systems. There is still enough room and needs for future research and technology developments.

# 1. References


[1] E. A. Martinez Cesena, N. Good, M. Panteli, J. Mutale and P. Mancarella "Flexibility in Sustainable Electricity Systems: Multivector and Multisector Nexus Perspectives" IEEE Electrification Magazine, vol. 7, no. 2, pp. 12-21, June 2019.

[2] V. C. Gungor, D. Sahin, T. Kocak, S. Ergüt, C. Buccella, C. Cecati and G. P. Hancke "Smart Grid Technologies: Communication Technologies and Standards" IEEE Transactions on Industrial Informatics, vol. 7, no. 4, pp. 529-539, Nov. 2011.

[3] X. Yu and Y. Xue, "Smart Grids: A Cyber–Physical Systems Perspective," Proceedings of the IEEE, vol. 104, no. 5, pp. 1058-1070, May 2016.

[4] T Strasser, F. P. Andren, G. Lauss, R. Brundlinger, H. Brunner, C. Moyo, C. Seitl, S. Rohjans, S. Lehnhoff, P. Palensky, P. Kotsampopoulos, N. Hatziargyriou, G. Arnold, W. Heckmann, E. Jong, M. Verga, G. Franchioni, L. Martini, A. Kosek, O. Gehrke, H. Bindner, F. Coffele, G. Burt, M. Calin and E. Rodriguez-Seco "Towards holistic power distribution system validation and testing-an overview and discussion of different possibilities," e & i Elektrotechnik und Informationstechnik, vol. 134, no. 1, pp. 71-77, Feb. 2017.

[5] M. Uslar, S. Rohjans, C. Neureiter, F. P. Andrén, J. Velasquez, C. Steinbrink, V. Efthymiou, G. Migliavacca, S. Horsmanheimo, H. Brunner and T. Strasser "Applying the Smart Grid Architecture Model for Designing and Validating System-of-Systems in the Power and Energy Domain: A European Perspective," Energies, vol. 12, no. 1, pp. 258 – 297, Jan. 2019.

[6] K. Heussen, C. Steinbrink, I. F. Abdulhadi, V. H. Nguyen, M. Z. Degefa, J. Merino, T. V. Jensen, H. Guo, O. Gehrke, D. E. M. Bondy, D. Babazadeh, F. P. Andrén and T. Strasser "ERIGrid Holistic Test Description for Validating Cyber-Physical Energy Systems" Energies, vol. 12, no. 14, pp. 2722-2753, July 2019.

[7] I. Papaioannou, S. Tarantola, A. Rocha Pinto Lucas, E. Kotsakis, A. Marinopoulos, M. Ginocchi, M. Masera and M. Olariaga-Guardiola "Smart grid interoperability testing methodology" Tech. Rep., Joint Research Center (JRC) of the European Commission (EC), 2018.

[8] X. Guillaud, M. Omar Faruque, A. Teninge, A. H. Hariri, L. Vanfretti, M. Paolone, V. Dinavahi, P. Mitra, G. Lauss, C. Dufour, P. Forsyth, A. K. Srivastava, K. Strunz, T. Strasser and A. Davoudi "Applications of real-time simulation technologies in power and energy systems" IEEE Power and Energy Technology Systems Journal, vol. 2, no. 3, pp. 103-115,2015.

[9] X. H. Mai, S. Kwak, J. Jung and K. A. Kim "Comprehensive Electric-Thermal Photovoltaic Modeling for Power-Hardware-in-the-Loop Simulation (PHILS) Applications" IEEE Transactions on Industrial Electronics, vol. 64, no. 8, pp. 6255-6264, Aug. 2017

[10] O. Nzimako and R. Wierckx "Modeling and Simulation of a Grid-Integrated Photovoltaic System Using a Real-Time Digital Simulator" IEEE Transactions on Industry Applications, vol. 53, no. 2, pp. 1326-1336, March-April 2017

[11] Y. Kim and J. Wang "Power Hardware-in-the-Loop Simulation Study on Frequency Regulation Through Direct Load Control of Thermal and Electrical Energy Storage Resources" IEEE Transactions on Smart Grid, vol. 9, no. 4, pp. 2786-2796, July 2018

[12] Z. R. Ivanović, E. M. Adžić, M. S. Vekić, S. U. Grabić, N. L. Čelanović and V. A. Katić "HIL Evaluation of Power Flow Control Strategies for Energy Storage Connected to Smart Grid Under Unbalanced Conditions" IEEE Transactions on Power Electronics, vol. 27, no. 11, pp. 4699-4710, Nov. 2012.

[13] M. O. Faruque, T. Strasser, G. Lauss, V. Jalili- Marandi, P. Forsyth, C. Dufour, V. Dinavahi, A. Monti, P. Kotsampopoulos, J. A. Martinez, K. Strunz, M. Saeedifard, X.Wang, D. Shearer, M. Paolone, R. Brandl, M. Matar, A. Davoudi and R. Iravani "Real-Time Simulation Technologies for Power Systems Design, Testing, and Analysis" in IEEE Power and Energy Technology Systems Journal, vol. 2, no. 2, pp. 63-73, June 2015.

[14] P. McLaren, R. Kuffel, R.P. Wierckx, J. Giesbrecht and L.H. Arendt; "A real time digital simulator for testing relays" IEEE Transactions on Power Delivery, vol. 7, pp. 207-213, January 1992.

[15] J.R. Marti and L.R. Linares; "Real-time EMTP-based transients simulation" IEEE Transactions on Power Systems, vol. 9, pp. 1309-1317, March 1994.

[16] J.R. Marti, J.A. Hollman; "Real time network simulation with PC-cluster" IEEE Transactions on Power Systems, vol. 18, pp. 563-569, February 2003.

[17] M. Armstrong, J.R.Marti, L.R. Linares, P. Kundur; "Multilevel MATE for efficient simultaneous solution of control systems and nonlinearities in the OVNI simulator" IEEE Transactions on Power Systems, vol. 21, pp. 1250-1259, February 2006.

[18] M. Matar and R. R. Iravani; “FPGA Implementation of the Power Electronic Converter Model for Real-Time Simulation of Electromagnetic Transients” IEEE Transactions on Power Delivery, vol. 25, Page(s): 852-860, February 2010.

[19] M. Matar and R. R. Iravani “Massively Parallel Implementation of AC Machine Models for FPGA-Based Real-Time Simulation of Electromagnetic Transients” IEEE Transactions on Power Delivery, vol. 26, pp. 830-840, February 2011.

[20] J. Liu, V. Dinavahi “A Real-Time Nonlinear Hysteretic Power Transformer Transient Model on FPGA” IEEE Transactions on Industrial Electronics, vol. 61, pp. 1254-1260, July 2014.

[21] H. Saad, T. Ould-Bachir, J. Mahseredjian, C. Dufour, S. Dennetiere, S. Nguefeu “Real-Time Simulation of MMCs Using CPU and FPGA” IEEE Transactions on Power Electronics, vol. 30, no. 1, pp. 259-267, Jan. 2015

[22] M. Milton, A. Benigni “Latency Insertion Method Based Real-Time Simulation of Power Electronic Systems” IEEE Transactions on Power Electronics, vol. 33, pp.7166-7177, August 2018.

[23] K. Wang, J. Xu, G. Li, N. Tai, A. Tong and J. Hou, "A Generalized Associated Discrete Circuit Model of Power Converters in Real-Time Simulation," in IEEE Transactions on Power Electronics, vol. 34, no. 3, pp. 2220-2233, March 2019.

[24] Z. Huang and V. Dinavahi, "A Fast and Stable Method for Modeling Generalized Nonlinearities in Power Electronic Circuit Simulation and Its Real-Time Implementation," in IEEE Transactions on Power Electronics, vol. 34, no. 4, pp. 3124-3138, April 2019.

[25] M. Milton, A. Benigni, J. Bakos "System-Level, FPGA-Based, Real-Time Simulation of Ship Power Systems" IEEE Transactions on Energy Conversion, vol. 32, pp. 737-747, April 2017.

[26] H. Bai, H. Luo, C. Liu, D. Paire and F. Gao, "A Device-Level Transient Modeling Approach for the FPGA-based Real-Time Simulation of Power Converters," in IEEE Transactions on Power Electronics.

[27] C. Liu, R. Ma, H. Bai, Z. Li, F. Gechter and F. Gao, "FPGA-Based Real-Time Simulation of High-Power Electronic System With Nonlinear IGBT Characteristics," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 7, no. 1, pp. 41-51, March 2019.

[28] H. Bai, C. Liu, S. Zhuo, R. Ma, D. Paire and F. Gao, "FPGA-Based Device-Level Electro-Thermal Modeling of Floating Interleaved Boost Converter for Fuel Cell Hardware-in-the-Loop Applications," in IEEE Transactions on Industry Applications.

[29] N. Lin and V. Dinavahi, "Detailed Device-Level Electrothermal Modeling of the Proactive Hybrid HVDC Breaker for Real-Time Hardware-in-the-Loop Simulation of DC Grids," in IEEE Transactions on Power Electronics, vol. 33, no. 2, pp. 1118-1134, Feb. 2018

[30] H. Bai, C. Liu, A. K. Rathore, D. Paire and F. Gao, "An FPGA-Based IGBT Behavioral Model With High Transient Resolution for Real-Time Simulation of Power Electronic Circuits," in IEEE Transactions on Industrial Electronics, vol. 66, no. 8, pp. 6581-6591, Aug. 2019.

[31] B. Jandaghi and V. Dinavahi, "Real-Time HIL Emulation of Faulted Electric Machines Based on Nonlinear MEC Model," in IEEE Transactions on Energy Conversion.

[32] B. Jandaghi and V. Dinavahi, "Real-Time FEM Computation of Nonlinear Magnetodynamics of Moving Structures on FPGA for HIL Emulation," in IEEE Transactions on Industrial Electronics, vol. 65, no. 10, pp. 7709-7718, Oct. 2018

[33] F. Montano, T. Ould-Bachir and J. P. David, "An Evaluation of a High-Level Synthesis Approach to the FPGA-Based Submicrosecond Real-Time Simulation of Power Converters," in IEEE Transactions on Industrial Electronics, vol. 65, no. 1, pp. 636-644, Jan. 2018.

[34] A. Hadizadeh, M. Hashemi, M. Labbaf and M. Parniani, "A Matrix-Inversion Technique for FPGA-Based Real-Time EMT Simulation of Power Converters," in IEEE Transactions on Industrial Electronics, vol. 66, no. 2, pp. 1224-1234, Feb. 2019.

[35] Z. Wang, F. Zeng, P. Li, C. Wang, X. Fu and J. Wu, "Kernel Solver Design of FPGA-Based Real-Time Simulator for Active Distribution Networks," in IEEE Access, vol. 6, pp. 29146-29157, 2018.

[36] M. Milton, A. Benigni and A. Monti "Real-Time Multi-FPGA Simulation of Energy Conversion Systems" IEEE Transactions on Energy Conversion.

[37] P. Li, Z. Wang, C. Wang, X. Fu, H. Yu and L. Wang "Synchronisation mechanism and interfaces design of multi-FPGA-based real-time simulator for microgrids" IET Generation, Transmission & Distribution, vol. 11, no. 12, pp. 3088-3096, 24 8 2017.

[38] M. Mirz, S. Vogel and A. Monti "RESERVE D4.4 v1.0 First Interconnection test of the nodes in pan-European simulation platform"

[39] A. Monti, M. Stevic, S. Vogel, Rik W. De Doncker, E. Bompard, A. Estebsari, F. Profumo, R. Hovsapian, M. Mohanpurkar, J. D. Flicker, V. Gevorgian, S. Suryanarayanan, A. K. Srivastava and A. Benigni "A Global Real-Time Superlab: Enabling High Penetration of Power Electronics in the Electric Grid" IEEE Power Electronics Magazine, vol. 5, No. 3, pp. 35-44, 2018

[40] S. Marija, A. Estebsari, S. Vogel, E. Pons, E. Bompard, M. Masera and A. Monti "Multi-site European framework for real-time co-simulation of power systems" IET Generation, Transmission & Distribution 11, no. 17 (2017): 4126-4135.

[41] P.B. Johns, M.O'Brien "Use of the transmission line modeling (t.l.m) method to solve nonlinear networks" The Radio and Electronic Engineer, 1980, Volume: 50, Issue: 1/2, Page(s) 59 – 70.

[42] S.R. Sanders, J.M. Noworolski, X.Z. Liu and G.C. Verghese "Generalized averaging method for power conversion circuits" IEEE Transactions on Power Electronics, vol. 6, no. 2, pp. 251–259, 1991.

[43] T. Demiray, G. Andersson and L. Busarello, "Evaluation study for the simulation of power system transients using dynamic phasor models" in Transmission and Distribution Conference and Exposition: Latin America, 2008 IEEE/PES. IEEE, 2008, pp. 1–6.

[44] T. Yang, S. Bozhko, J.-M. Le-Peuvedic, G. Asher, C. Ian Hill "Dynamic phasor modeling of multigenerator variable frequency electrical power systems" IEEE Transactions on Power Systems, vol. 31, no. 1, pp. 563–571, 2016.

[45] J. Burbank, W. Kasch, J. Ward "Hardware-in-the-Loop simulations" An Introduction to Network Modeling and Simulation for the Practicing Engineer, Wiley-IEEE Press, pp. 114-142, 2011.

[46] G. Lauss, F. P. Andren, F. Leimgruber and T. I. Strasser "Analyzing standardization needs for CHIL-based testing of power systems and components" 2018 IEEE International Conference on Industrial Electronics for Sustainable Energy Systems (IESES), Hamilton, 2018, pp. 523-528.

[47] F. Tao, H. Zhang, A. Liu and A. Y. C. Nee, "Digital Twin in Industry: State-of-the-Art," IEEE Transactions on Industrial Informatics, vol. 15, no. 4, pp. 2405-2415, April 2019.

[48] M. Pokharel, A. Ghosh and C. N. M. Ho, "Small-Signal Modelling and Design Validation of PV-Controllers With INC-MPPT Using CHIL," IEEE Transactions on Energy Conversion, vol. 34, no. 1, pp. 361-371, March 2019.

[49] C. Sun, J. N. Paquin, F. Al Jajeh, G. Joos and F. Bouffard, "Implementation and CHIL Testing of a Microgrid Control System," 2018 IEEE Energy Conversion Congress and Exposition (ECCE), Portland, OR, 2018, pp. 2073-2080.

[50] J. Wang, Y. Song, W. Li, J. Guo, A. Monti, "Development of a Universal Platform for Hardware In-the-Loop Testing of Microgrids" IEEE Transactions on Industrial Informatics, vol. 10, no. 4, pp. 2154-2165, Nov. 2014.

[51] M. Cupelli, M. de Paz Carro and A. Monti, "Hardware in the Loop implementation of a disturbance based control in MVDC grids" 2015 IEEE Power & Energy Society General Meeting, Denver, CO, 2015, pp. 1-5.

[52] M. Cupelli, M. de Paz Carro and A. Monti, "Hardware in the loop implementation of linearizing state feedback on MVDC ship systems and the significance of longitudinal parameters," 2015 International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles (ESARS), Aachen, 2015, pp. 1-6.

[53] IEEE P2030.8/DI2", IEEE Draft Standard for the Testing of Microgrid control systems, pp. 1-43, March 2018

[54] G. De Carne, M. Langwasser, M. Ndreko, R. Bachmann, R. W. De Doncker, R. Dimitrovski, B. J. Mortimer, A. Neufeld, F. Rojas, M. Liserre "Which Deepness Class Is Suited for Modeling Power Electronics?: A Guide for Choosing the Right Model for Grid-Integration Studies" IEEE Industrial Electronics Magazine, vol. 13, no. 2, pp. 41-55, June 2019.

[55] W. Ren, M. Steurer and T. L. Baldwin "Improve the Stability and the Accuracy of Power Hardware-in-the-Loop Simulation by Selecting Appropriate Interface Algorithms" IEEE Transactions on Industry Applications, vol. 44, no. 4, pp. 1286-1294, July-Aug. 2008.

[56] G. F. Lauss, M. O. Faruque, K. Schoder, C. Dufour, A. Viehweider and J. Langston, "Characteristics and Design of Power Hardware-in-the-Loop Simulations for Electrical Power Systems" IEEE Transactions on Industrial Electronics, vol. 63, no. 1, pp. 406-417, Jan. 2016.

[57] C. S. Edrington, M. Steurer, J. Langston, T. El-Mezyani and K. Schoder "Role of Power Hardware in the Loop in Modeling and Simulation for Experimentation in Power and Energy Systems" Proceedings of the IEEE, vol. 103, no. 12, pp. 2401-2409, Dec. 2015.

[58] M. Steurer, C. S. Edrington, M. Sloderbeck, W. Ren and J. Langston "A Megawatt-Scale Power Hardware-in-the-Loop Simulation Setup for Motor Drives" IEEE Transactions on Industrial Electronics, vol. 57, no. 4, pp. 1254-1260, April 2010.

[59] T. Roinila, T. Messo, R. Luhtala, R. Scharrenberg, E. C. W. de Jong, A. Fabian, Y. Sun "Hardware-in-the-Loop Methods for Real-Time Frequency-Response Measurements of on-Board Power Distribution Systems" IEEE Transactions on Industrial Electronics, vol. 66, no. 7, pp. 5769-5777, July 2019.

[60] F. Huerta, J. K. Gruber, M. Prodanovic and P. Matatagui, "Power-hardware-in-the-loop test beds: evaluation tools for grid integration of distributed energy resources," in IEEE Industry Applications Magazine, vol. 22, no. 2, pp. 18-26, March-April 2016.

[61] G. De Carne, M. Langwasser, X. Gao, G. Buticchi and M. Liserre, "Power-Hardware-In-Loop Setup for Power Electronics Tests" PCIM Europe 2017; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, Nuremberg, Germany, 2017, pp. 1-7.

[62] G. De Carne, G. Buticchi and M. Liserre, "Current-type Power Hardware in the Loop (PHIL) evaluation for smart transformer application," 2018 IEEE International Conference on Industrial Electronics for Sustainable Energy Systems (IESES), Hamilton, 2018, pp. 529-533.

[63] P. Kotsampopoulos, A. Kapetanaki, G. Messinis, V. Kleftakis, N. Hatziargyriou, "A Power-Hardware-In-The Loop facility for microgrids" International Journal Distributed Energy Resources Technology, vol. 9, no. 1, pp. 89-104, Jan. 2013.

[64] V. Hagenmeyer, H. Kemal Çakmak, C. Düpmeier, T. Faulwasser, J. Isele, H. B. Keller, P. Kohlhepp, U. Kühnapfel, U. Stucky, S. Waczowicz, R. Mikut "Information and Communication Technology in Energy Lab 2.0: Smart Energies System Simulation and Control Center with an Open-Street-Map-Based Power Flow Simulation Example" Energy Technology, 4: 145-162. doi:10.1002/ente.201500304.

[65] https://www.nrel.gov/grid/assets/pdfs/20170425-mehler-overview-iwes-grid.pdf

[66] P. C. Kotsampopoulos, V. A. Kleftakis and N. D. Hatziargyriou "Laboratory Education of Modern Power Systems Using PHIL Simulation," in IEEE Transactions on Power Systems, vol. 32, no. 5, pp. 3992-4001, Sept. 2017.

[67] G. Lauss, F. Andrén, M. Stifter, R. Bründlinger, T. Strasser, K. Knöbl and H. Fechner "Smart Grid Research Infrastructures in Austria - Examples of available laboratories and their possibilities," 13th IEEE International Conference on Industrial Informatics (INDIN 2015), Cambridge, UK, 2015.