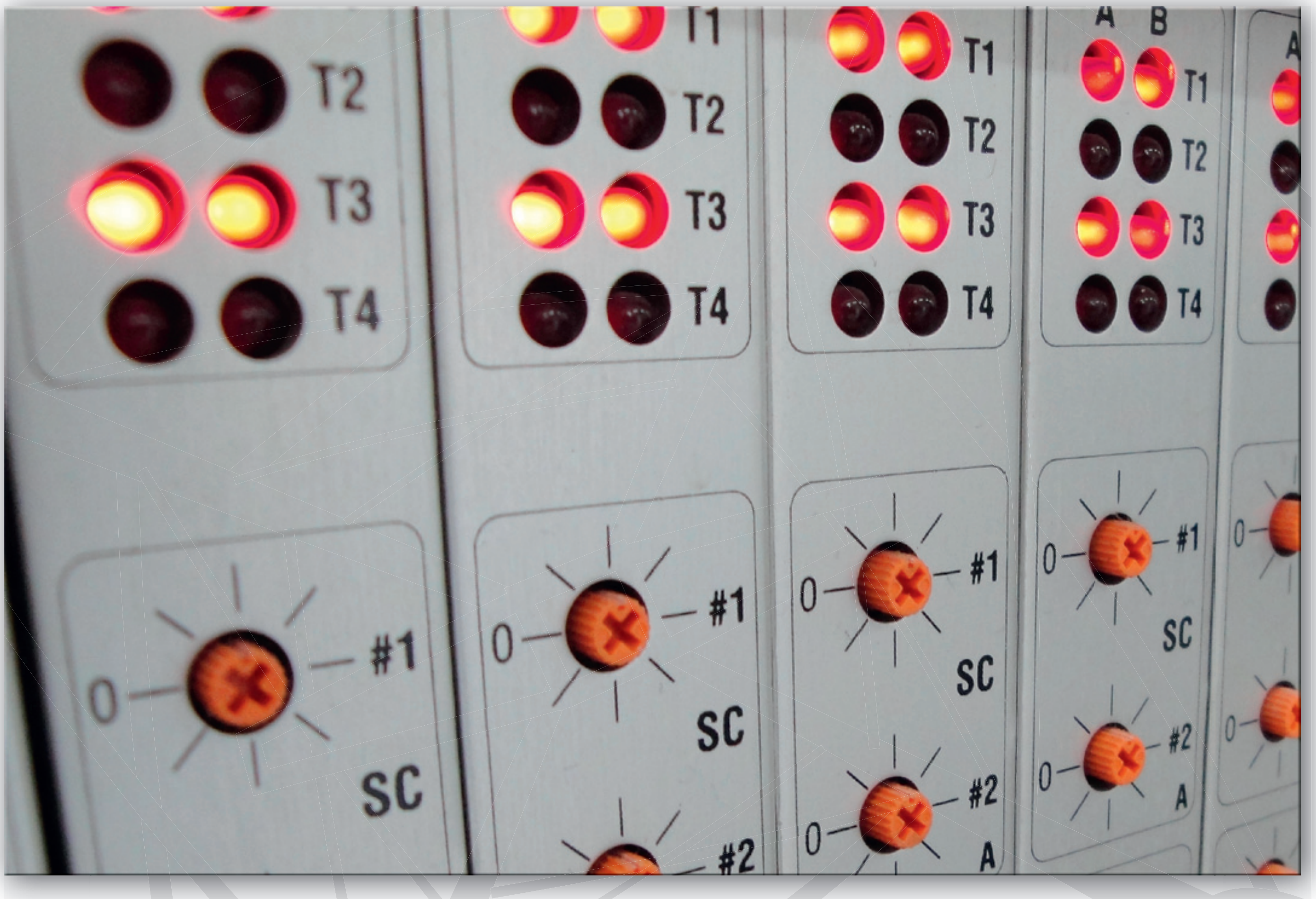
European Distributed Energy
Resources Laboratories

European White Book on Real-Time Powerhardware-in-the-Loop testing



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Abstract:

The European White Book on Real-Time-Powerhardware-in-the-Loop testing is intended to serve as a reference document on the future of testing of electrical power equipment, with specific focus on the emerging hardware-in-the-loop activities and application thereof within testing facilities and procedures. It will provide an outlook of how this powerful tool can be utilised to support the development, testing and validation of specifically DER equipment. It aims to report on international experience gained thus far and provides case studies on developments and specific technical issues, such as the hardware/software interface.

This white book compliments the already existing series of DERlab European white books, covering topics such as grid-inverters and grid-connected storage.

European White Book on Real-Time Power-hardware-in-the-Loop testing

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ABSTRACT

The large-scale integration of distributed energy resources (DER) into public distribution and transmission grids plays a pivotal role in achieving the major European goals on renewable energy, efficiency and CO_2 reduction.

The technical integration, often performed by power electronics, will have an increasingly more profound impact on the grid stability, reliability and availability as the penetration of DER increases.

The role of stringent testing in combination with in-depth simulation will therefore become more prominent to ensure, or even improve, the current level of quality of supply.

However, the testing and validation of individual components will no longer be sufficient on its own. For the purpose of de-risking equipment in complex grids under dynamic situations, the testing should include the entire system. This has a significant impact on the method of testing and the testing facility itself. The combination of simulation together with hardware experimentation will be inevitable to allow the validation of the system at the required complexity including the highly dynamic and transient power system behavior under real-time constraints.

The approach of combining simulation with hardware experimentation is known as hardware-in-the-loop (HIL), and the addition of power components distinguishes power HIL from control HIL. Control HIL encompasses the testing of sub-systems, such as protection relays, power converter controllers and power quality regulators, while power HIL tests complete power devices such as PV-inverters.

Power-hardware-in-the-loop testing allows equipment to be validated in a virtual power system under a wide range of realistic conditions, repeatedly, safely and economically. It combines the power of real-time simulation with the actual response of real power and control hardware components.

The European White Book on Real-Time-Power-Hardware-in-the-Loop testing is intended to serve as a reference document on the future of testing of electrical power equipment, with specific focus on the emerging hardware-in-the-loop activities and application thereof within testing facilities and procedures. It will provide an outlook of how this powerful tool can be utilized to support the development, testing and validation of specifically DER equipment. It aims to report on international experience gained thus far and provide case studies on developments and specific technical issues, such as the hardware-software interface.

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CONTENT

1 INTRODUCTION

1.1 Developments in power technology and regulation

The large-scale integration of distributed energy resources (DER) into public grids plays a pivotal role in achieving the major European goals on renewable energy, efficiency and CO_2 reduction. Due to the impact that can be generated in the quality and in the security of the supply within the hosting networks, the technical issues related to this integration represent a challenge for regulating authorities, network operators, manufacturers and involved research institutions.

Technical requirements are becoming stricter

In order to preserve the security and reliability of the network operation as well as to ensure the fulfillment of the established voltage quality standards (i.e. EN 50160 [1]), while the level of integration keeps growing; the technical requirements for connection and parallel operation of DER have become stricter. This situation has directly impacted the design of the DER units, their power electronic interfaces and the plant components. The increasing demand on capabilities, which mostly depend on the connecting voltage, the MVA capacity and the type of generators, has mainly focused on the aspects related to the operation of the generating plant when connected to the network. Contribution to network support is increasingly in demand. In some grid codes, especially for DER connected to medium voltage networks, merely tolerance requirements (to voltage dips or to frequency deviations for example) have evolved into contributions to the network support, i.e. provision of reactive current during voltage dips or active power during frequency deviations. Control functions for the supply of active power at the point of connection, aiming to avoid imbalances or overloading in the networks (congestion management), have also been imposed. The capability to provide and control the supply of reactive power, in order to contribute to the voltage regulation of the network, is also required, even at the low voltage level as described in the German low voltage technical guideline [2].

Need for efficient testing methods

Manufacturers have had to adapt their products to the increasingly demanding requirements in order to have access to wider markets. At the same time, network operators and regulation authorities of the countries with the most exigent grid codes have had to establish new testing and certification procedures in order to allow quick and well-coordinated demonstration of the adherence to the established requirements.

The verification scheme included in the German guideline for the connection of generating plants to the medium voltage network [3] is an example of the above mentioned procedures. It combines laboratory or field measurements of individual generating units with system level simulations of generation facilities to demonstrate compliance with the established requirements at a specific point of common coupling.

According to [3] each generating unit to be connected to the network requires a so called "type-specific unit certificate". It specifies the electrical properties of the generator. From there proof of conformity with the established requirements can be provided. The test/measuring procedures used to demonstrate the properties of the generating unit are defined in a separate document [4]. This document states that the following properties must be investigated by means of laboratory or field measurements on individual generating units:

- Provision and control of active power output (including active power provision during frequency deviations)
- Provision and control of reactive power exchange
- Network interactions (harmonics, flicker, voltage fluctuations after switching operations)
- Protection settings
- Behavior during network disturbances (low voltage ride through capability and fast acting voltage support during voltage dips)

Changing certification procedures

In order to demonstrate compliance of a generating facility, made up by one or more generation units, at a specific network connection point, a so called "plant certificate" is requested in the procedure from [3]. In this case the verification of the electrical properties can be performed trough load flow calculations, dynamic (Phasor/RMS method) simulations and simple calculations (only for network interactions). The dynamic simulations and the calculations are based on validated models and on measurements of the individual generating units that make up the generating facility. The connection of the facility to the grid is represented by a

Thévenin equivalent with the corresponding short circuit impedance at the point of common coupling. The implementation and validation of the dynamic RMS/Phasor models is performed within the certification process of the individual units (type-specific unit certificate), according to the procedure defined in [5], based on the performed measurements.

1.2 Needs and value

The approach of combining simulation with hardware experimentation is known as hardware-in-the-loop (HIL), and distinguishes control HIL – the testing of protection relays, power converter controllers and power quality regulators – and power HIL – the testing of actual power devices such as PV-inverters.
Power-hardware-in-the-loop testing allows equipment to be validated in a virtual power system under a wide range of realistic conditions, repeatedly, safely and economically [6]. It combines the power of real-time simulation with the actual response of real power and control hardware components

1.3 What is control and power hardware in the loop

Traditionally two possibilities exist for performing system tests with medium to high power ratings:

- performing an experiment on real hardware or
- performing a pure software simulation.

A third possibility is now being developed which is called hardware in the loop testing (HIL). This possibility is a hybrid from of the other two, as is shown in Figure 1.

A straight forward method would be to implement the whole system in real hardware components and run different tests on the real system itself. Concerning the accuracy of the result this is by far the best solution. Other factors, like economical limitations and physical space, are also relevant and thus in a lot of cases render this method useless due to high costs and effort to the implementation as well as the high risk involved during the test itself. Another counter argument is the lack of flexibility a pure hardware experiment offers. It is mostly not possible to change minor or major parts of the system in order to test different approaches. All in all it can be said that in a lot of cases a pure hardware test is not feasible.
The alternative to hardware testing has traditionally always been software simulation. This has very strong advantages over a pure hardware simulation as it is very flexible and has typically only a fraction of the economical costs. Usually one can separate the components of a system in two groups:

- components that are easy to model or of which good and accurate models exist; and
- components that are not easy to model or of which no good and accurate models.

The quality of the simulation results depends greatly on the tester's knowledge of the system and ability to accurately map it on a model. In other words: the better the model is, the better the simulation results will be. If a single component of the whole system is part of the second group or not accurate enough the whole simulation will be inaccurate. In the end the applicability of a pure software simulation largely depends on ones knowledge of the system. It is possible that situations arise where software simulations cannot be used due to lack of system or component knowledge.

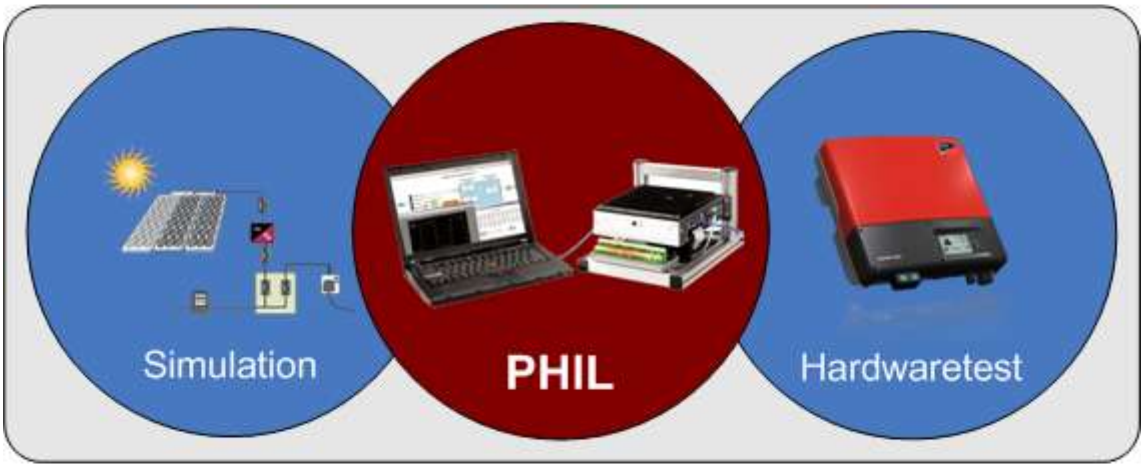

Figure 1 (Power) Hardware-in-the-Loop [7]

1.3.1 Control hardware in the loop

Control hardware in the loop involves the testing of a device on its information ports. Digital – or digitized analogue - signals are exchanged between the device under test and a real-time simulator, see Figure 2. This allows the controller functions of a device to be tested for applications such as:

- The assessment of aerospace industry controllers,
- Automotive industry testing of electronic control units,
- Develop new components and actuators,
- Electrical generators of wind energy conversion systems,
- Power propulsion systems for electric vehicles (EVs) and hybrid electric vehicles [8].

1.3.2 Power hardware in the Loop

Contrary to Control Hardware in the Loop where a controller is tested, Power Hardware in the Loop (PHIL) involves testing of a device which absorbs or generates power (e.g. a photovoltaic inverter or an induction motor). The signals between the Real Time Simulator (RTS) and the Hardware Under Test (HUT) are no longer at low level in which case Analogue to Digital and Digital to Analogue Converters are usually sufficient [9], therefore a special Power Interface is needed (Figure 2).

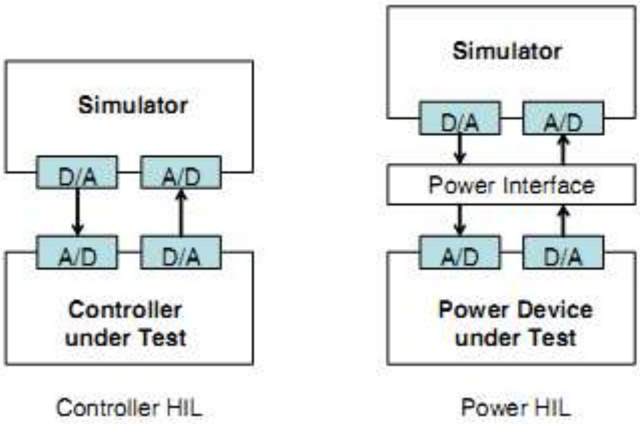

Figure 2 Comparison of CHIL and PHIL simulation approaches [6].

This Power Interface exchanges low level Signals with the Virtually Simulated System (VSS) and real Power with the tested device. The Power Interface consists of a power amplifier which receives a reference value of a variable from the simulation (e.g. Voltage or Torque) and applies it to the HUT, and also a sensor which measures the reaction of the HUT (e.g. Current or rotational speed) and inputs it back into the RTS (Figure 3). This closed loop operation makes possible the interaction of the Virtually Simulated System running in the Real-Time Simulator with a physical power device. As an example a commercial Photovoltaic Inverter can be connected to a simulated Distribution Network via suitable Power Interface and their interaction can be thoroughly studied.

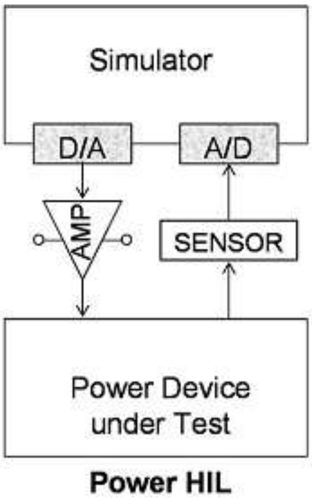

Figure 3 Amplifier and sensor of the Power interface for PHIL simulation [10].

Power Hardware in the loop plays an important role in developing, testing and validating equipment as it combines the benefits of pure simulation and laboratory testing. The real-life system in which the Hardware under Test (HuT) is intended to operate is simulated in the Real-Time Simulator, allowing for testing under more realistic conditions. Simulation offers great flexibility in designing and performing test scenarios. The Virtually Simulated System can be changed easily and quickly without the need for hardware adaptations, (rewiring, etc.) therefore various experiments can be performed repeatedly. Extreme conditions can be studied with minimum cost and risk, while hidden issues of the equipment can be revealed allowing the in depth understanding of the behavior of the tested device [11].

Power Hardware in the Loop (PHIL) simulation provides a novel environment for testing DER devices and networks. Photovoltaic inverters, Wind Energy Systems, whole microgrids or electric vehicles can be tested in various realistic conditions providing useful experience and contributing in studies for achieving higher penetration of DER (e.g. ancillary services, anti-islanding, etc.).

In the next section Power Hardware in the Loop simulation will be addressed in more details.

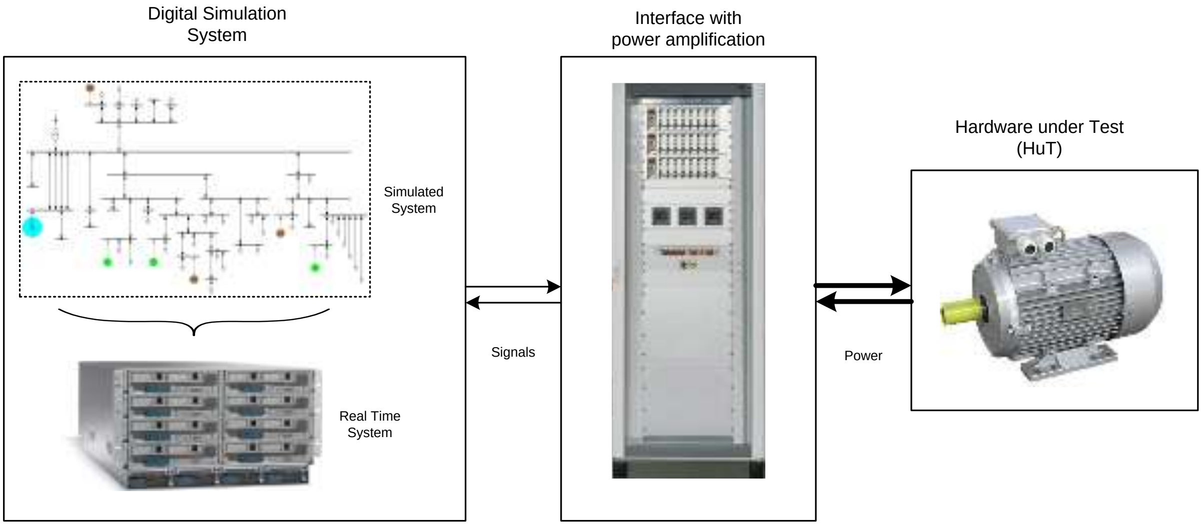

Figure 4 Introduction of a Power Amplifier to HIL - Power HIL [7].

1.4 Scope of white book

This European White Book on Real-Time-Power-Hardware-in-the-Loop testing is intended to serve as a reference document on the future of testing of electrical power equipment, with specific focus on the emerging hardware-in-the-loop activities and application thereof within testing facilities and procedures. It provides an outlook of how this powerful tool can be utilized to support the development, testing and validation of specifically DER equipment. It reports on international experience gained thus far and provides case studies on developments and specific technical issues, such as the hardware/software interface.

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2 STATE-OF-THE-ART OF RT PHIL

In this chapter the state of the art of the basic elements that constitute a state-of-the-art Power Hardware in the Loop environment are presented. Critical issues such as stability and accuracy of PHIL simulation are addressed and representative applications on Distributed Energy Resources are presented.

2.1 Computation power – Real time simulator

The essential part of Hardware in the Loop simulation is the Real Time Simulator (RTS) which computes the simulation model and offers I/O capabilities. As the device under test works in real-time, the simulated system with which it will interact must be computed in real-time. Therefore, the simulation time-step of the Real Time Simulator must be small enough to reproduce the behavior of the simulated system under dynamic conditions.

In principle, a computer with Inputs and Outputs (I/Os) or a controller board can be used as a Real-Time Simulator. However, specially designed sophisticated simulators have been built for simulating large and complex systems in real-time. From an historical point of view, the Real Time Simulators came from the evolution of analogue Transient Network Analyzers and the Electromagnetic Transient Program (EMTP) [11]. The Real Time Digital Simulator - RTDS® was developed in 1993 and has been used for Hardware in the Loop simulations mainly of electrical systems [12]. Different component models of a large electrical system are assigned into different processor cards operating in parallel, allowing for a small simulation time-step to be achieved. OPAL-RT founded in 1997 makes use of multi-core PC processors resulting in small simulation time-step and allowing the realization of Hardware in the Loop simulations not limited to the electrical domain [13]. Other real-time simulation tools are also commercially available. In addition, custom low cost Real-Time Simulators have been developed [14, 15].

Figure 5 The Real-Time Digital Simulator – RTDS [12].

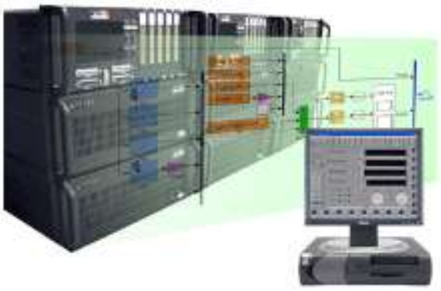


Figure 6 The OPAL-RT eMEGAsim [16].

An example of a state-of-the-art Real Time Simulator that is used to perform PHIL and CHIL simulations is operated in the Center for Advanced Power Systems (CAPS) in Florida, USA. Fourteen racks of the commercial RTDS allow for simulation of large power systems to be performed in real-time (up to 756 electrical nodes), containing machines, transformers, cables etc. with a typical time-step of 50µs. Power electronic subsystems with smaller time-steps of typically 1.5 µs are simulated in a small time step environment. Extensive I/O capability exists to connect hardware to the simulator [6].

2.2 Interfaces issues

In a PHIL simulation particularly for high power applications, the error (i.e. time delay and distortion) introduced by the power interface may cause severe instability issues or unacceptably inaccurate results [17]. The introduction of the power amplifier may cause the system to be unstable, even if the real system would be stable. From a system theoretic view this is the result of introducing an additional closed loop by introducing power amplification. Additionally it can be expected that the introduced power amplification is not ideal thus as a matter of fact errors and delays will be introduced into the system. The consensus that can be found in various papers [17,18][19] is that the interface algorithm between the simulated system and the DuT/HuT has to cope with these issues.

The interface algorithm thereby is defined as the description of the power amplification interface between the simulated system and the DuT/HuT. The choice of the interface algorithm is application specific. A good starting point for choosing the appropriate interface algorithm can be found in [17].

Practical Tests at the AIT showed that also other components, than the interface algorithm, do have a major impact on the stability and accuracy of the PHIL simulation. A very fundamental and crucial part is the Real Time System (RTS) as its sample time has a major impact on the stability behavior of the PHIL simulation. The AD/DA conversion has to be accurate and fast enough to cope with the sample time of the RTS. This may be a very simple specification, but if the AD/DA conversion fails the possible errors could not be estimated or evaluated. This can result in major damage due to the high voltage levels the PHIL deals with. The sensing probes measuring the feedback for the software have to sustain certain accuracy, again for the use of the simulation as well as for safety reasons. [7]

2.2.3 **Power interface**

In PHIL simulation a power interface is needed to allow the interaction of the virtually simulated system with the hardware under test (HuT). The power interface basically consists of a power amplifier and a sensor as shown in Figure 3. Initially, we will consider two different types of PHIL applications:

- Mechanical power hardware in the loop simulation
- Electrical power hardware in the loop simulation

In mechanical PHIL simulation the tested device can be an electric vehicle’s traction system [20], a naval propulsion motor [21], a wind power generation and conversion system [22] etc. The real-time simulator executes a mechanical model, such as a propulsion load model or a turbine model. The tested device can be for example a generator and the power interface can be a motor with corresponding drives which is coupled-to the generator. The real-time simulator provides reference signals (e.g. torque, speed) to the motor-generator set and receives its reaction through feedback signals.

In this document we will however focus on electrical PHIL simulation. Similarly to the mechanical PHIL simulation, in electrical PHIL simulation the HuT is a power device, but the virtually simulated system is electrical. Therefore, the power interface must be electrically coupled to the HuT. The power amplifier matches the power rating of the HuT and accepts reference low level signals from the RTS. High accuracy and small time-delay are very important. As the amplifier can provide or absorb power, 4 quadrant operation is normally required and a power source (e.g. the utility grid) as well as a power sink (e.g. the utility grid or an external load) are needed.

In laboratories around the world different types of power interfaces have been used mainly differentiating on the power amplifier. We will see below some representative examples.

Switchedmode amplifier

Switchedmode amplifiers for PHIL applications consist of power electronic converters. Figure 6 shows a bidirectional 50KVA AC/DC/AC converter used as a voltage amplifier that comprises a front-end rectifier and a back-end inverter [11]. The two sets of three-leg IGBT bridges are composed of a Power Electronic Building Block (PEBB) provided by ABB. The Real Time Simulator sends the reference voltage to the inverter that applies it to the HUT which in this case is an electric motor. The voltage of the DC bus is controlled by the rectifier. A 5 MW (6.25 MVA) variation of this amplifier, that works also as a DC amplifier is analyzed in [23] and another switchedmode amplifier is used and described in [24].

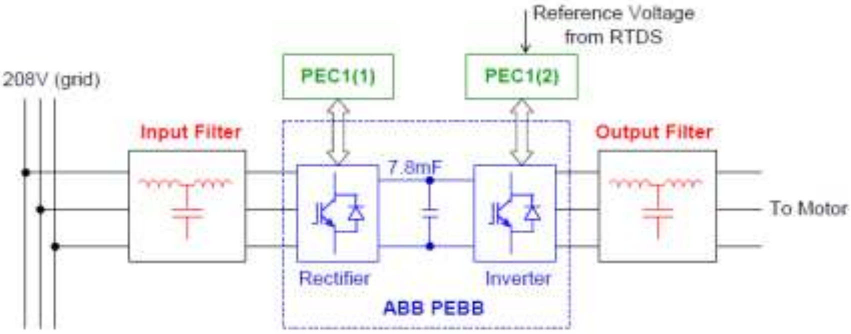


Figure 7   Switch-mode Amplifier for PHIL simulation [11].

<u>Linear amplifier</u>

Linear amplifiers are also used in PHIL simulations. Sophisticated linear amplifiers can function with high accuracy and very small time-delay, which makes them suitable for PHIL applications. A use of such an amplifier is reported in [16] and the topology is shown in Figure 8.

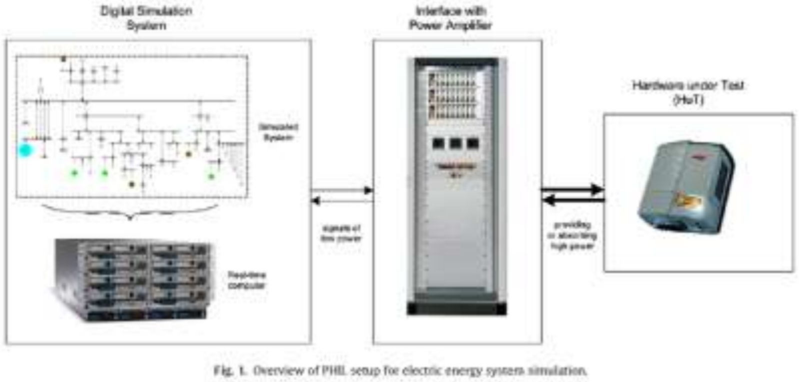


Figure 8   Linear Amplifier for PHIL simulation [16].

<u>Synchronous generator and load bank:</u>

A different approach of interfacing a Real-Time Simulator with physical equipment is shown in Figure 9 [25]. A large synchronous generator is coupled to a motor and the motor-generator set is controlled by a real-time-system controller (labeled “RTS” in Figure 9, which doesn’t refer to the real-time simulator). The RTDS sends the voltage reference VN* to the real-time-system controller and therefore the generator applies the requested voltage VN on the HUT (labeled “laboratory power network” in Figure 9). The current flowing through the HUT is measured and inserted back to the RTDS as in the previous examples. If the HUT generates power a resistive load bank is used to absorb it.

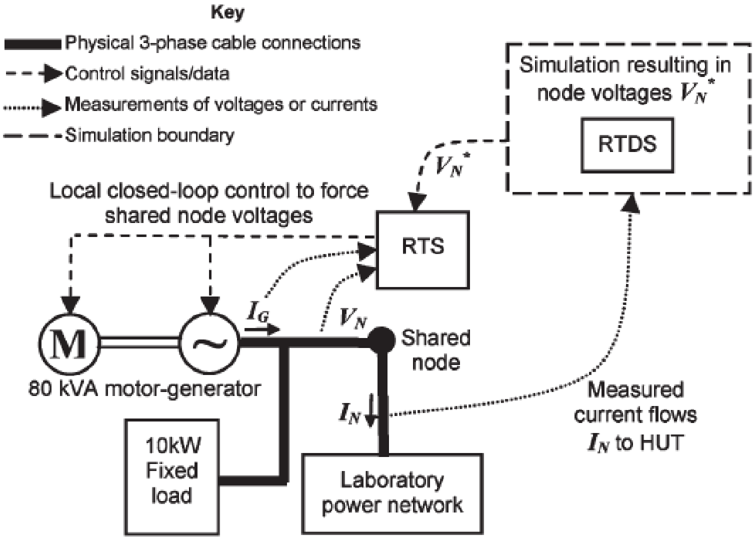


Figure 9 Synchronous Generator and load bank used as Power Interface in PHIL simulation [25].

2.2.4 **Interface Topologies**

The Power Interface plays a critical role in the successful implementation and the validity of PHIL simulation. Ideally, the Power Interface should have unity gain with infinite bandwidth and no time delay, but this is neither achievable nor affordable [11]. In practice, imperfections are present such as the time delay of the amplifier, the low pass filter effect (for a switch mode amplifier), the time delay of the sensor, the sensor's noise etc. The imperfection of the Power Interface can drastically reduce the accuracy of PHIL simulation and even cause instability. This problem is particularly challenging in high-power applications, where high-precision amplifiers are not readily available. In addition, the discrete nature of the real-time simulator adds an additional time-delay to the whole system which affects stability and accuracy.
A lot of research work has been reported on stability of PHIL simulation [9,11,16-18,26,27].

At the current state of PHIL simulation there does not exist any interface which enables "plug & play" PHIL due to the mentioned stability issues. In the following section some interface topologies are described.

2.2.4.1 Ideal Transformer Method (ITM)

The Ideal Transformer Method is a very straight forward method to implement software – hardware coupling for a PHIL simulation. The case shown in Figure 10 is a very good example to describe the difficulties with PHIL simulation as well as discussing the ITM Interface. The assumed model is a voltage divider with one impedance representing the simulated system and one impedance representing the DuT/HuT.

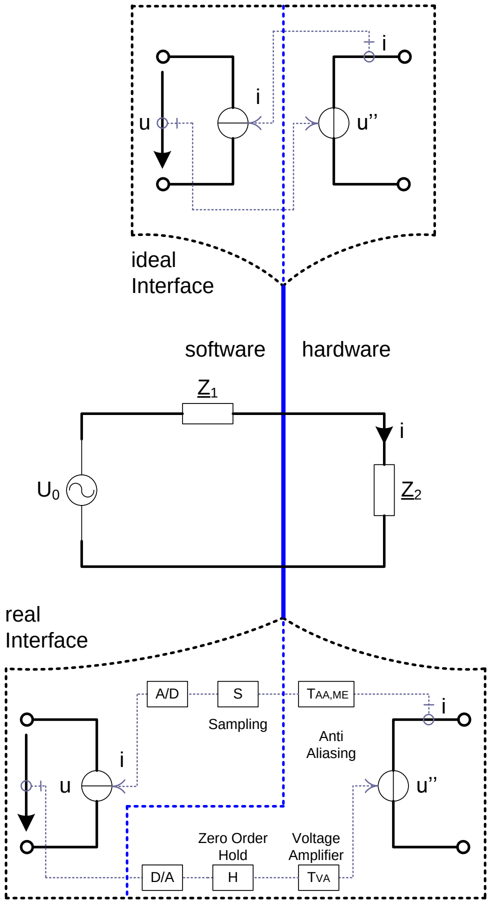


Figure 10 Schematic overview of the ITM interface [28].

U0 and Z1 are being simulated and Z2 is connected as real hardware. U0 and Z1 represent a source and a simulated low-voltage network. For a typical PHIL simulation the simulated network would not only be a single complex impedance but a whole network. Using this simplification does not limit the theoretical considerations and results but simplifies the mathematical complexity.

The ITM interface utilizes the software-hardware coupling using a controlled current source on the software side and a controlled voltage source on the hardware side. Measuring the voltage over the software-sided current source as a set value for the hardware-sided voltage source and vice versa, measuring the hardware-sided current out of the voltage source as a set value for the software-sided current source, creates the coupling (top).

Despite the fact that the theoretic implementation of the ITM interface is very simple, several additional elements have to be taken into account. In the software-to-hardware (the forward) branch a D/A conversion, a Zero Order Hold Filter and a voltage amplifier have to be added. In the hardware-to-software (the feedback) branch an anti-aliasing filter, a sampling and an A/D conversion are introduced (bottom).

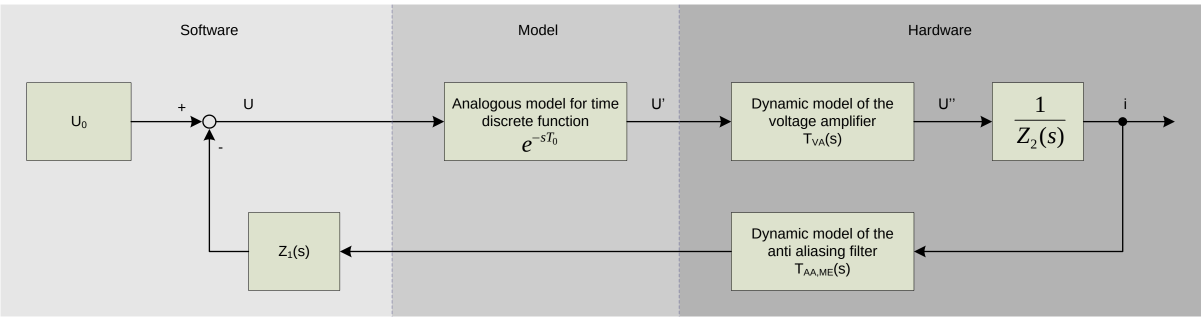


Figure 11 Equivalent circuit diagram of the ITM interface [29].

The resulting equivalent model for the quasi continuous approach is shown in [17, 18, 30]. The corresponding open loop transfer function is

$$-F_O(s) = e^{-sT_D} T_{VA}(s) T_{AA,ME}(s) \frac{Z_1(s)}{Z_2(s)} \cdot$$ **(1)**

with TD the effective delay of the forward and feedback branch together, TVA the transfer function of the voltage amplifier and TAA,ME the transfer function of the transformer and the anti-aliasing filter.

Using the assumption that both the voltage amplifier and the dynamic of the current sensor are ideal, ($T_{VA}(s)=1, T_{AA,ME}(s)=1$) as well as that the time-discrete character of the real-time system can be modeled by using a proper delay element [17,18,31] reduces the open loop transfer function to

$$-F_O(s) = e^{-sT_D} \frac{Z_1(s)}{Z_2(s)} \cdot$$ **(2)**

Using the Nyquist Criterion a statement about stability can be given. In the case of the pure real impedances Z1=R1, Z2=R2 this is especially simple. Stability is always achieved, when R2>R1 [17].

2.2.4.2 Damping Impedance Method

The damping impedance method (DIM) is another approach of realizing the software to hardware coupling. The electric circuit of a DIM for a simple voltage divider is shown in and the associated control loop depicted in Figure 13.

The open loop transfer function is therefore

$$F_O(s) = \frac{Z_1(s)(Z_2(s)-Z^*(s))}{Z_2(s)(Z_1(s)+Z^*(s))} e^{-sT_D} T_{VA}(s) \rightarrow -F_O(s) = \frac{Z_1(s)(Z^*(s)-Z_2(s))}{Z_2(s)(Z_1(s)+Z^*(s))} e^{-sT_D} T_{VA}(s)$$ **(3)**

Z*(s) is the so called damping impedance, a virtual impedance (in software), that is inserted. From (3) it is quite obvious that if the damping impedance equals the impedance of the load, the open loop transfer function reduces to

$$F_O(s) = 0 \,.$$

This result means that stability is guaranteed regardless of Z1(s) and Z2(s) (remembering that Z2(s) is the HUT). The transfer function in this case reduces to

$$T(s) = \frac{u(s)}{U_0(s)} = \frac{Z^*(s)}{Z_1(s)+Z^*(s)} \approx \frac{Z_2(s)}{Z_1(s)+Z_2(s)} .$$ **(4)**

For a typical PHIL application this method has an intrinsic drawback - the fact that the HUT in common is not known. Another counterargument is that if the HUT is known, a model could be built and therefore a pure software simulation would be sufficient.

Therefore this approach could be valuable if the major part of the delay existent in the PHIL simulation can be related to the power amplification and the delay induced by the real-time simulation is negligible.

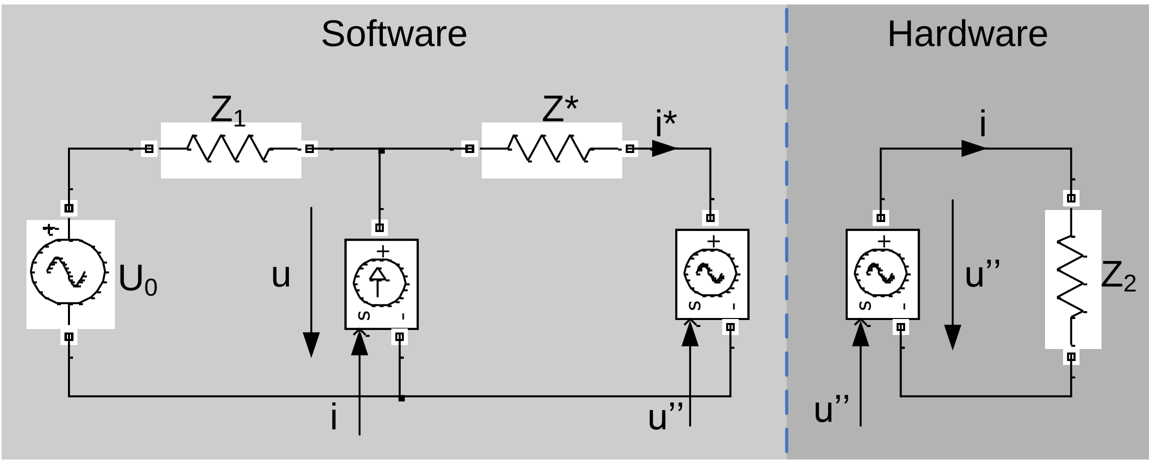


Figure 12 Damping Impedance Method interface algorithm for a simple voltage divider circuit [7].

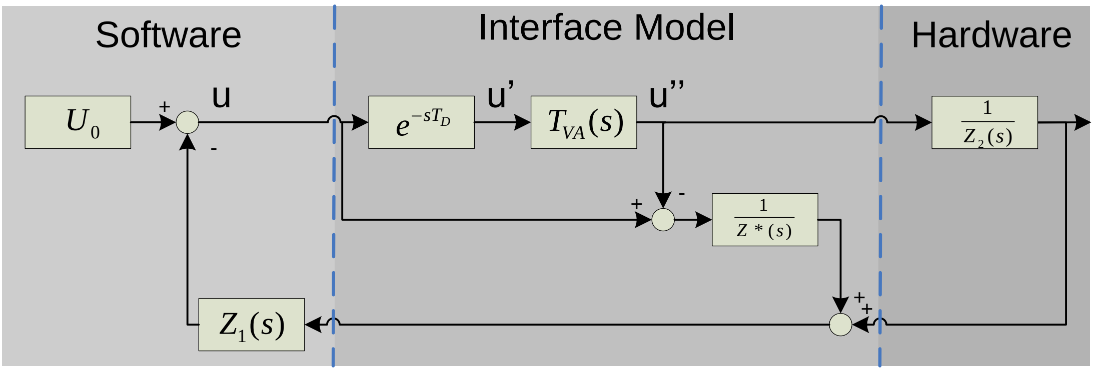


Figure 13 Control loop depiction of PHIL simulation with damping impedance method interface algorithm [7].

2.2.4.3 Interface Compensation

Another approach that is used to improve the stability and/or the accuracy of PHIL simulation is Interface Compensation [9]. In this method the topology doesn't change (i.e. the Interface Algorithm) but additional function blocks are inserted in the simulation to compensate for the time-delay, noise etc. This technique is usually combined with the use of the Ideal Transformer Model Interface Algorithm which is accurate and the most straightforward. The additional controls can be applied to the forward or the feedback path, see Figure 14. On the forward path, a function block (labeled "Lead") can be applied before the amplifier that makes the overall interface frequency response almost ideal [9]. In addition, extrapolation prediction to compensate for time-delays [9], and "phase advance" calibration [25] have been proposed. In the feedback path, a low pass filter has been proposed [10,16] as well as phase shifting of the feedback signal [30]. It is interesting to notice that some of these methods may improve stability but decrease accuracy (e.g. feedback filtering).
Finally, multi-rate Real-Time simulation is proposed as a way to improve the accuracy and stability of PHIL simulation in [16].

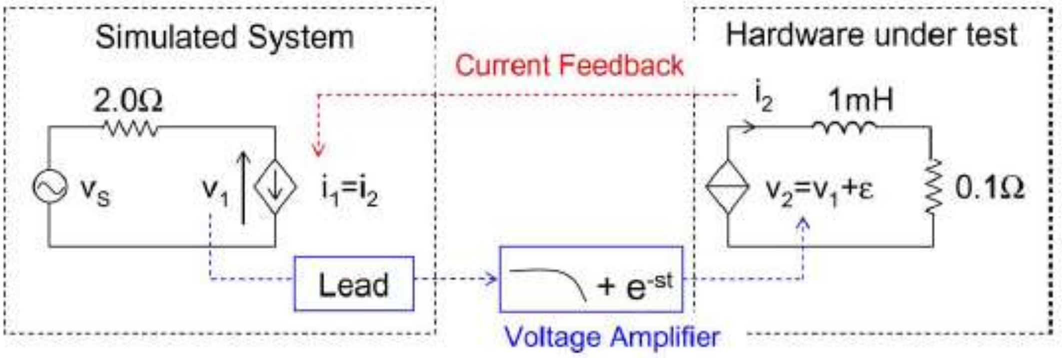


Figure 14 Interface compensation on the forward path [9].

2.3 Reduced and full scale applications

Running a PHIL experiment of high power rating is not a trivial issue. Unexpected behavior can result in seriously damaging expensive equipment. The occurrence of instability can lead to high voltages and/or currents applied on the HUT and Interface. In addition, challenges exist in building high power amplifiers with satisfactory precision [11]. To mitigate risks, it is good practice to initially perform a reduced scale PHIL simulation where the expected operation can be tested and a lot of possible issues can be revealed, resulting in less cost and effort.

In a reduced scale application the simulated system usually has high power rating, but the power of the Interface and Hardware Under Test is reduced. In [8] a reduced scale PHIL simulation is performed with a traction system of an electric vehicle as a HUT, making use of suitable power adaptation to match the different power ratings. In some applications, scaling of the input/output signals of the Real-Time Simulator is enough to couple a simulated system rated at GWs with a HUT in the order of kWs [24]. This demonstrates one of the advantages of PHIL simulation which is the independency of the power rating of the HUT and of the Virtually Simulated System.

The transition from a reduced to a full scale application is shown in [6]. A 50kW power amplifier was operated as a pre-requisite for installing a 5 MW set-up of the same operating principles in order to perform sophisticated PHIL experiments.

3 THE FUTURE OF VALIDATION (VISION)

In this chapter a vision is given about the future of validation, using testing, for Smart Grids. After an introduction in which the changes are introduced that will happen with the coming of the Smart Grids, four directions are investigated in more depth. The four directions are:
- Simulation, gaming and virtual testing
- The interrelations between system studies, consultancy and testing
- Development of in-house testing
- Emerging of distributed testing

3.1 Introduction

The main goal of testing is to de-risk a component, system or technology for its intended purpose in a 'risk-free' environment before connecting / installing it in the real world.

Experience learns the for new low voltage equipment two out of three fails the first time it tested (for certification) and for medium and high voltage equipment the failure rate is roughly one out of two.

With the emerging of Smart Grids there are more and different types of equipment coming on the market. This equipment is produced by known players but also many new entrants. The equipment is more and more equipped with active controllers, this means a controller taking action depending on the actual grid situation and often needs and information / communication connection. Due to the nature of the equipment the susceptibility / immunity requirements related to Power Quality and EMI / EMC of these products are broadened. There is also the need for dynamic interaction verification of the Smart Grid equipment amongst each other and together with the grid. For large-scale systems Smart Grid equipment model validation is part of the product testing and certification. The verified model can be used for system studies by the grid owner /operator. Communication and information interface testing becomes more and more common among Smart Grid equipment. Fact is that more and more the design lives of hardware and software become separated, for example the design life of hardware is 30 years and each 5 years or so new controls have to be "flashed" and software updates come even more and more frequently. And of course the question remains whether or not it is always an improvement, or is it possible that due to a new software release another unexpected problem or interaction of the equipment with the grid can occurs

The testing scope is broadened, not only functionality with respect to power and adequacy, but also protection, communication, and efficiency in general it was sufficient to test for the AC frequency only, but now higher bandwidth testing is required, how does the equipment behave for other frequencies, how much harmonics are generated and how are harmonics influencing the behavior of the equipment, especially for power circuits where control verification has to be done for a correct system integration. Do the controls react correctly in all kind of possible grid situations and interactions, how does the Smart Grid equipment react to disturbances. Even the question what are all possible grid situations and interactions cannot be answered.

The power rating of the equipment is becoming larger, one notices that customer products develop into industrial products, for example PV inverters developed from 1kW range towards 1000kW (and more). Due to the fact that the physical properties of material used in the equipment does not scale linearly (think e.g. of voltage and thermal behavior) unexpected problems often occur with new designs. When equipment becomes bigger (higher power ratings) the testing has to be more rigorous because such equipment can make a significant impact (if malfunctioning) in the power distribution grid.

This trend leads to testing equipment at full power during longer periods minutes and hours instead of (milli)seconds. A consequence of these continuously increasing higher power ratings will be the impossibility of making the test equipment bigger and bigger to test the complete apparatus and a direction towards module testing for power electronics is evident. The question of course will be what will be the module size? Indications are that the individual modules will reach sizes up to 5 (10MW) maximum as can be seen with converters for large wind turbines. It is envisioned that a large number of these modules will make up the modules for the highest voltage and power levels in equipment like HVDC and VSC converters (up to 1000MW/ block size).

Note that this is different compared to classical high voltage or high power testing where the high voltage is applied only to test the integrity (dielectric strength) of the design or at short circuit testing when only for a very brief period of time the short circuit power needs to be available to demonstrate the ability of the equipment to withstand.

More and more there will be interaction between the grid and the object under test and the behavior of the equipment under test will be more and more dependent on the actual grid condition and situation this calls for a adjustable or programmable grid to test the interface, operation and protection strategy under different conditions, fault ride through capabilities to ensure grid support at times when it is needed and immunity / susceptibility testing including harmonic emission.

Equipment is becoming smarter, intelligence is built in to create a new functionality or new combinations of equipment are used e.g. when connecting a large number of small generating units (spatial at different locations) together through ICT and operate them as one single unit one can create virtual devices like virtual power plants, virtual loads etc. with user defined prescribed values and unprecedented possible effects on the grid. Imagine for example the possibilities of creation of a virtual load in a residential area by hooking up a large number of electric heaters. Now it becomes possible to control all those individual heaters if it was one unit. It can be used advantageous in active demand to balance load and generation but it also can be used in a malicious way when switching on many of them simultaneously and creating a local black out. Note that this type of behavior was previously not possible because of the random nature of the human operator. The possibilities have a potential huge impact for the availability and reliability of the system, not to mention the danger due to cyber security.

Local interaction with the grid at the point of common coupling is not enough. The Smart grid equipment uses information from the (wider) grid and other smart equipment for correct functioning this means that an isolated test without a proper grid connection (hardware and software) is not possible anymore.

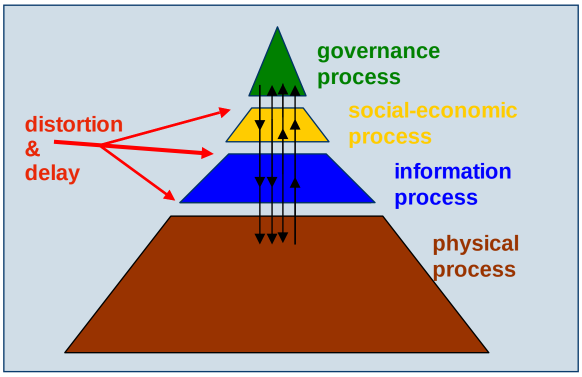
Equipment vendors start promoting Smart Grid equipment solutions that need system level integration testing of these components. In order to be able to achieve this power hardware-in-the-loop (PHIL) functionality has to be introduced. With PHIL physical equipment under test is interfaced to a wider electrical network model being executed on a real time digital simulator. When PHIL is implemented it will be able not only to examine how primary system components respond to different grid imposed conditions but also demonstrate how the smart component will affect the wider electrical network to which it is connected.

The growing importance of information technology in Smart Grid equipment has consequences for the skills people need to test, operate and maintain them. Knowledge of the primary equipment like transformers and switchgear is not enough anymore. Knowledge in needed for new equipment like inverters and storage systems but increasingly software skills are needed to solve faults occurring in the equipment or grid due to the automation level. This development can be compared with what happened for example in the car industry maintenance & testing becomes: connect to the diagnose computer and tune some chips. Grid equipment asset management will also change similar as what can be observed in consumer electronics, simply replace (an electronic board) instead of repairing. And of course security of equipment, people and operation of the Smart Grid is a very important issue that has to be guaranteed and assessed with the testing.

3.2 Simulation, gaming and virtual testing

One of the directions of future validation will be the use of simulation, gaming and virtual testing. When using simulation as a tool to get insight in certain phenomena one needs to have a validated model (or models) of the physical world but increasingly also the human behavior has to be incorporated through gaming because this cannot be modeled yet. For an integrated approach, apart from the physical system, market information, social-economic and governance processes are needed. The development of such tools is termed "serious gaming" and is becoming an increasingly important topic in academia and industry.

For the development of testing requirements for (future) equipment in Smart Grids simulation and gaming tools could be very valuable. Imagine that it is possible to model the Smart grid power system with all its



physical, information and societal interactions. Then it would be possible to "test" the effect of a new piece of equipment, how it behaves in the grid, what effect it has on the availability, investment but also things like energy saving etc. It would also be possible to see in which way actors use it in the grid, how regulation or incentives are influencing the introduction and roll out, and how it creates value to the society. For this to be measured the human behavior has to be implemented or accounted for. Based on several e.g. development or energy scenarios requirements for the testing of equipment could be derived.

One way to incorporate behavior of people in such systems is through the use of artificial intelligence. Although, in the (computer) gaming industry the level of artificial intelligence in e.g. NPC's (non playable characters) can be quite good, people prefer to interact with the less predictable human players. This is the key of the success of the MMORPG's (Massive Multiplayer Online Role Playing Games) like World of Warcraft.

Computer simulations and games are powerful tools that can be used to study scenario's and the effect of planning decisions. There are many energy (and carbon footprint impact) games available at the web but very few very focus on the Smart Grid and its aspects / constraints and development. An example is Simcity Societies (a building sim) where it is possible to develop a community with a certain energy scenario, e.g. based on renewables or fossil fuel and study the effects on reliability and carbon emission. Included are features like storage systems and smart substations. Such a game could be developed into an online multiplayer game with human interaction. Requirements are that the model contains a physical model of the energy system that is accessible at micro level (cable, component), meso level (neighborhood, city) as well as macro level (regulation, incentives, and interconnections). The model possesses a relational database with information of the infrastructure components, energy use, economic model etc. The model also has a memory function in order to be able to perform analysis afterwards.

Several aspects of Smart Grid development can be studied like economic efficiency, capacity use and development, availability and stability, integration of renewable energy sources but also the use of new type of equipment, their interaction with the grid and based on that even requirements for testing such devices, based on observations, can be made.

Whereas modeling, simulation and gaming is a direction which can deliver (additional) requirements for new equipment, the concept of virtual testing is another method of de-risking or assuring the quality of Smart Grid equipment.

Power output from renewable resources is inconsistent, storing energy here makes them more efficient.

Virtual testing is a concept of quality assurance by which not a physical apparatus is tested, but a model of it. The advantage is that the number of actual testing can be reduced or in some cases even completely eliminated.

Given the availability of cheap massive computing power and commercially available software packages for the simulation of relevant physical processes, it is tempting to explore the possibilities of virtual testing for Smart grid equipment.

KEMA started pioneering in this field with a consortium of companies more than 10 years ago. In a EU supported project a system of “digital testing” was developed that claims to predict the fault current interruption capability of a high-voltage circuit breaker in various fault conditions, other than actually tested. For this approach, special measurement technology was needed in order to provide input data for the interruption model that was developed. This technology was (and still is) transferred to a number of manufacturers all over the world that use it to speed up development of switching equipment. It has not been brought to the level yet that designs could be digitally tested.

In CIGRE context it was tried to stretch the idea of virtual testing even further. Is it possible to predict performance of equipment based on design only? In CIGRE Working group A3.22 this idea was worked out, and tested. A challenging exercise was carried out, in comparing prediction of dielectric performance of a (digital) design by seven major manufacturers with actual laboratory measurements of the performance in a realization of this model. The result of this (and similar studies) was that stresses (mechanical, electrical, thermal) can be modeled adequately, but that prediction of withstand or yield to such stresses cannot yet be predicted reliably. Therefore, wide acceptance of the users of apparatus of "virtual testing" might not be expected regarding withstand capability tests.

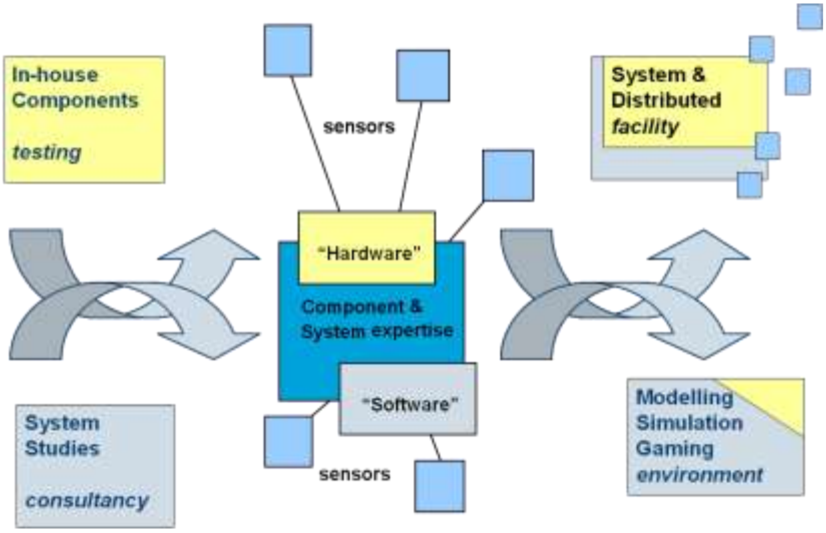
The conclusion with respect to virtual testing might be that in the future increasingly a number of tests can be replaced by virtual testing, analyzing digital designs. And perhaps some of the tests could be done by using validated models in a simulation and gaming environment to investigate possible interactions, but still some tests will have to be performed for real to demonstrate the adequacy of the design. Just as in the airline industry many things are tested on the design table but the proof of the pudding is the actual flight of the new aircraft.

3.3 System studies, consultancy and testing

Although power system studies, consultancy and testing are often viewed as separate businesses there is a trend that the activities move closer to each-other. Power systems become more and more integrated in consultancy business, as one of the tools and in the testing business the trend is to incorporate and use more system aspects. It started with the integration of hardware with embedded control and information systems in new components. Furthermore in the consultancy business, not only computer simulations are done but also to incorporate some form of hardware connected service (e.g. including sensors and /or real time digital simulations).

In the picture below this development of merging of in-house component testing with system studies towards an integrated system & distributed facility, combined with a modeling, simulation and gaming environment is depicted.

The system & distributed facility consists of an interface with the object to be tested with the power grid



through sensors and information & control links. It is completed with a fully local grid interface (converter) and augmented with the wider grid through a PHIL concept.

New system tools and interfaces for power flow control, state estimation, and protection and control will become available in the future.

3.4 In-house testing and history of testing of PV inverters

A future in-house component test facility will in the future do fewer tests, some of them will be virtual or done in the modeling, simulation & gaming environment but two types of test will still be needed. First the integrity testing of the design, can it fly and what are the characteristics. This is needed to obtain a validated model. Second the interaction / integration test with the system in order to validate the correct functioning of the information and thermal interfaces, controls and protection.

Future test facilities can also "play back" recorded disturbances occurred in the grid and effects can be analyzed in a safe environment. Also real grid measurements of load and generation in a time varying manner can be transferred to the test facility and converted to real "power and load and study its effects and interactions with test objects. Even signals from individual energy customers can be fed into the laboratory and thus study actual human behavior effects on the grid. A future test facility will look less of a classical electrical equipment test facility but more like a modern computer controlled "test environment" where the needed parts are linked together by computers and the test (partially) will run automatically.

What is challenging and different of future in house testing is the ability to not only “test” the integrity of the electrical and mechanical properties, its performance but also the control and communication layer of the equipment as part of the grid, including its interaction, and the possibility too perform and witness tests from everywhere in the world.

The history of testing according to safety, EMC, performance related standards especially for grid connected distribution units such as PV inverters or wind energy plants is characterized and formed according to economic demands, technical and technological development and heavily affected by transmission and distribution network operator respectively.

The simulated area of generation power plants as a proper in-house testing area has developed dramatically in the past alongside novel technologies in the fields of power electronics, computing power and measurement equipment as well as a better understanding of their signal/power interconnections.

Driven by countries like Japan, the US and nowadays Germany many standards were established, modified and updated in last decades resulting in many different approaches in different countries to meet the requirements for stand-alone and grid-connected electrical generation systems.

The following list of shows both obsolete and effective standards for functional safety for PV inverters up in the following:

- VDE 0126-1-1:1999/2006; FGW TR3/4; BDEW RL EA am MS-Netz; ect. (Germany)
- CEI 0/21, CEI 11-20, V2; ENEL Guida Connessioni Ed I 1 (Italy)
- IEEE 1547.1/UL1741 (USA)
- ER G83/1-1 (UK)
- IEEE 929-2000 (China)
- UL1471 (US, Canada)
- IEC 62116, et al.

An important part within these standards and guidelines is represented by the behavior to the equipment under test on various grid-interconnection scenarios such as voltage dips/fault ride-through, flicker/harmonics, grid voltage/frequency variations or active/reactive power tests. Knowing the requirements for the above mentioned tests including their specific test procedures for test laboratories it is possible to automate certain test sequences with the help of PHIL testing. This can be seen either as an accelerating method for pre-compliance testing or even as a fully valid test method for accredited tests in parallel to conventional hardware testing. Looking at modeling and validation of simulations (FGW TR4) there is concrete field of application for PHIL testing regarding the simulation of the inverter model in software/hardware combined.

In terms of performance testing PHIL simulations can feature certain predefined or free programmable scenarios both on AC grid (simulated conditions at virtual PCC) side as well as on the DC side (e.g.: partially shaded conditions or efficiency measurement according to EN50530:2010) [32,33].

PHIL simulations can and will become part of the standard testing procedures in the near future. Areas for suitable PHIL applications in testing will be established in the next years and parts of the acquired research topics could go straight over into normative testing.

It is very important to mention that the above listed possible fields of application involve the quality of the used equipment and adequate requirements for the key components used for a PHIL test. These can be described as measurement equipment (current/voltage probes), peripheral equipment (DA/AD interface) and the used power amplification stage(s).

Not going into detail about the relevant characteristics of used amplification topologies, their dynamics represent a hard limiting criterion for every PHIL simulation besides the achievable step-time. For any statement related to investigations on harmonics or flicker scenarios it is necessary having an adequate bandwidth of the PHIL simulation in hand which is heavily impacted by characteristics of the AC/DC amplifier. This can hardly be achieved with switched-mode amplifiers, which often have a limited bandwidth around 1kHz or less depending on the applied power ratings (kW or MW range). The time lag, which is very relevant for PHIL tests, is in the range of some hundreds of µs and typical slew rates are in the range of some ms (see Figure 15). Their compact design is often used for so-called 50Hz simulations, which means that only the fundamental wave is simulated in an adequate way.

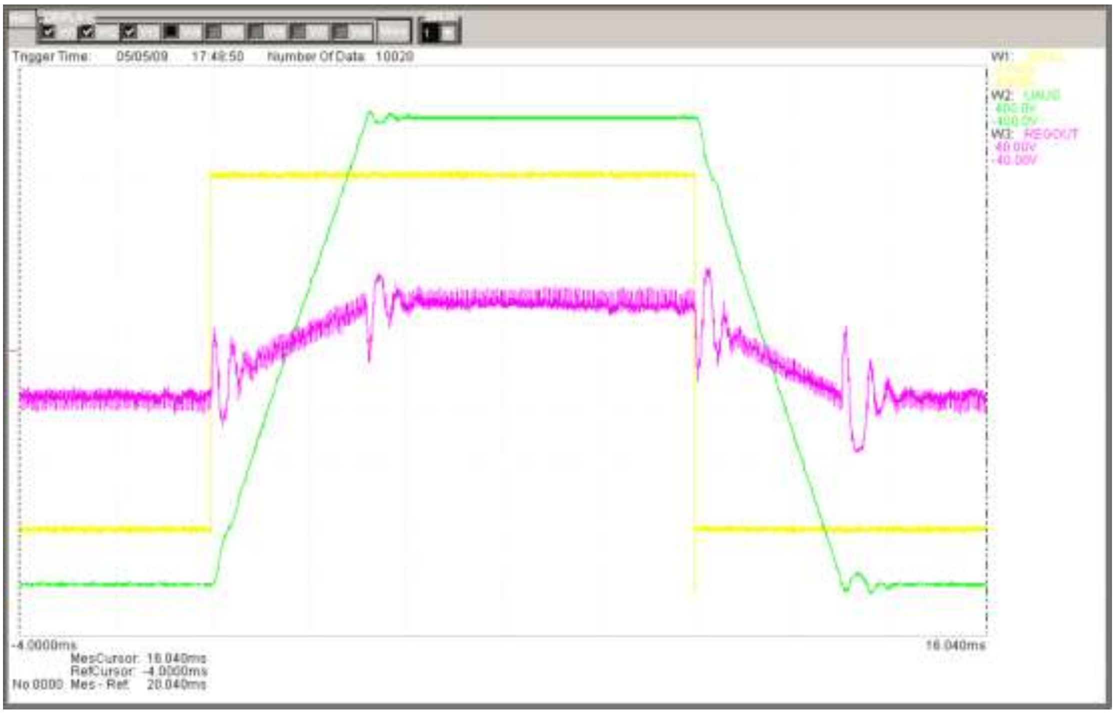


Figure 15 Typical step-response of a switched mode amplifier with partial load (yellow: setpoint input voltage signal, green: output voltage signal, red: output control signal) [[].

The dynamic characteristics of linear stages are superior to those ones of SM amplifiers having both time lags and slew rates in the range of some µs, which enables a reachable simulation step size of 20-100 µs. This entails many advantages in terms of combined stability and accuracy and a considerable bandwidth of the whole simulation system can be reached for selected applications. Obvious drawbacks such as high costs or major constructions restrain linear amplification stages in terms of power rating, therefore the simulation bandwidth of the PHIL simulation for very powerful equipment under test is simply not manageable.

3.4.4.1 Project specific test standardization

Distributed testing

One of the future directions is distributed testing, because more and more equipment will become interconnected and controlled by information technology e.g. many small PV power plants operating together in a VPP, the charging of a fleet of EV, active demand control of many electric heaters / coolers.

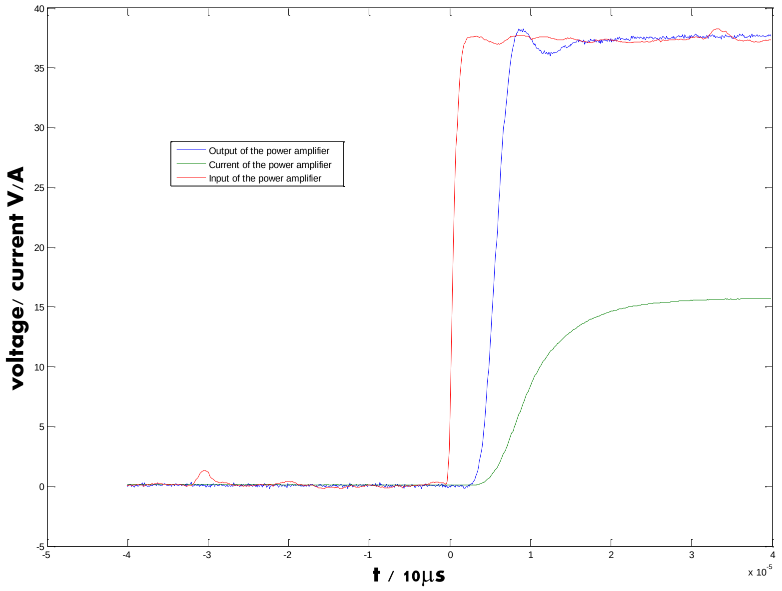
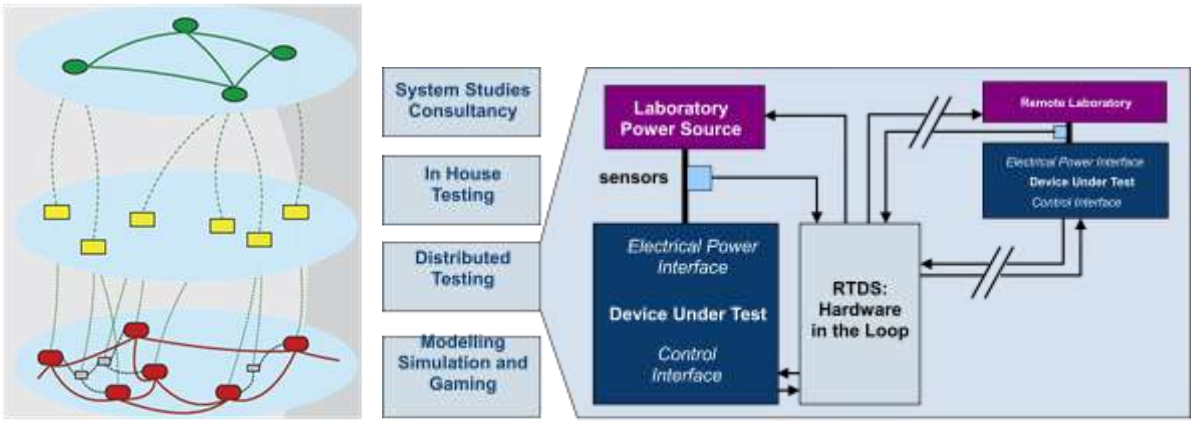


Figure 16 Typical step-response of a linear amplification unit with partial load (red: setpoint input voltage signal, blue: output voltage signal, green: output current signal).

When enabling distributed testing the development and advancement of test techniques and best practices improves, because universities, research institutions, industry and consultants can more easily work together and share knowledge and information in a pre-competitive way to advance the testing business.

The European distributed test infrastructure is capable to investigate uncertain Smart Grid developments in an integral sense covering the multi-level, multi-actor approach for actual network situations with various timescales (long term stability - control actions – transients).

For this reason the distributed infrastructure consists of a number of laboratories, as a whole covering all the test layers ranging from systems of big DER equipment to VPP / AD controllable loads and microgrids. The contributing facilities are equipped with power “hardware” testing equipment, a real time - real power simulator, sensors and communication connections to the real power system and relevant layers to allow interaction and have dynamic hybrid (real and virtual) modeling. The individual laboratories are equipped with



“cockpits” that allow users and participants transparent high speed data access from various places in Europe and is connected with existing research infrastructures.

4 OUTLOOK

4.1 A common procedure for performing PHIL tests

As a first step towards the large-scale acceptance and standardization of PHIL testing as part of conformity assessment for example, it is imperative to derive a common procedure for performing PHIL tests. This will increase the repeatability of PHIL testing and reduce the dependence of results on location or testing body.

Based on the experience gained within the DERlab Network of Excellence with regard to PHIL testing, a general procedure is proposed and discussed herein.

The procedure is organized in the following seven main steps:
a) Development of a possible PHIL use case or experiment
b) Generation of a system theoretic model of the use case
c) Stability evaluation
d) Generation of the real-time capable model
e) Preparation of the laboratory equipment
f) Execution of the PHIL experiment
g) Analysis of the PHIL experiment

The specific steps in the above procedure are presented in more detail here:
a) Development of a possible PHIL use case or experiment

PHIL is at the current state of its development, a very application specific simulation topology due to the fact that a lot of use case specific engineering effort has to be taken into account. Thus the use case development is a very fundamental element of the total testing procedure.
The use case development is driven by the following factors:

- Costumer need(s) and wishes
- Brain storming sessions
- System control research

The use case development is strongly limited to the available testing equipment which is suitable to carry out PHIL tests, due to the fact that PHIL simulations need very specific equipment.
b) Generation of a system theoretic model of the use case

Due to the stability issues with PHIL simulations the first thing that has to be done after developing a use case is to do a system theoretical stability evaluation. More details about analyzing the stability issues when dealing with PHIL experiments are described in [28]. This can be done in the following way:

1. Derive the transform functions of every individually simulated component, or define one comprehensive transform function for the total system, if possible.
2. Derive the transfer function of the power amplification stage.
3. Develop the transform functions of the Hardware/Device under Test (HuT/DuT) or approximate as good as possible. This might in some cases be a very hard task as the HuT will not always be known to the level of detail often required from a stability point-of-view.

c) Stability evaluation

The system's theoretical stability has to be evaluated depending on the PHIL interface algorithm being used – a good list of possible interface algorithms can be found in [17]. It is important to take into account the discrete time behavior of the real time simulation system (i.e. the delay due to the real time simulator).
The stability evaluation is done using the Nyquist stability criterion [34]. Based on the results of the stability evaluations, the PHIL experiment can be carried out, or further stabilization measures have to be taken.
Note: *It is strongly recommended not to carry out an unstable PHIL simulation as the test set-up can be exposed to severe power fluctuations and depending on the power amplification used: extreme voltages or currents.*

d) Generation of the real-time capable model

After having evaluated the system theoretical stability one can design the models for the real time simulation environment.
The environment differs per real-time simulator vendor:

- the Opal RT real time simulation system [13] uses the real time environment provided by MatLab/Simulink and its toolboxes (e.g. SimPowerSystems);
- the RTDS real time simulation system [12] uses the real time environment provided in RS-CAD.

It is recommended to do an offline simulation before connecting any hardware as assumptions, simplifications or even errors in the preliminary modeling can result in instability when modeled for the real time system.

e) Preparation of the laboratory equipment

The laboratory equipment has to be set up and prepared for the PHIL experiment. This task includes checking the safety of integrated components (e.g. power amplification, HuT, power connections, etc.), validation of the used setup and equipment and its P/U/I ranges (e.g. measuring equipment, AC/DC Sources, etc.) and the check of the mechanical contacts. This task is very user specific; the generic approach will depend strongly on the specific laboratory equipment being used.

f) Execution of the PHIL experiment

The most exciting task might be carrying out the PHIL experiment itself. During this task the test engineer has to be aware of the simplifications that have been done during the modeling phase. The most crucial part might be that the HuT is only roughly known and thus it was only briefly modeled during the stability evaluations.

g) Analysis of the PHIL experiment

The analysis of the PHIL experiment is very use case specific and thus cannot be described in a generic manner.

4.2 Case studies

To illustrate the wide range of possibilities offered by PHIL, three case studies are presented. Each case study builds on its predecessor in complexity. The case studies are intended as general example of the application possibilities of PHIL, its complexities and the added value gained by implementing this technique.

4.2.1 Case: Getting started

The first case study describes a voltage divider as shown in Figure 17. It is a fairly simple experiment with a low number of components and is intended to provide basic insight into the described procedure and the practical issues associated with running PHIL experiments. It clearly shows the system theoretical pitfalls that come along with PHIL simulation. The example continues from Section 2.2.4 on page 11.

Voltage divider

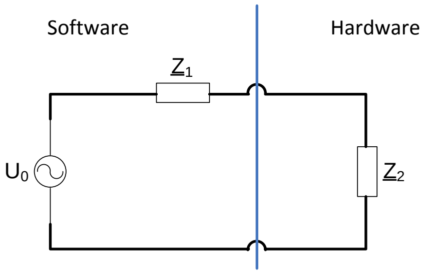


Figure 17 Depiction of the Voltage Divider used to describe the best practice for PHIL experiments

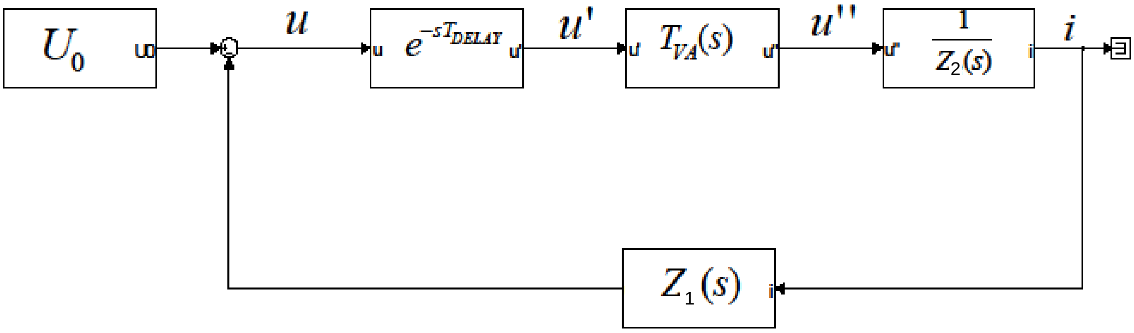


Figure 18 Control Loop depiction of a simple PHIL example using the ITM interface algorithm.

The interface algorithm used is the Ideal Transformer Model (ITM) interface algorithm as described in [17]. From Figure 18 the open loop transfer function can be derived as

$$-F_O(s) = e^{-sT_D} T_{VA}(s) \frac{Z_1(s)}{Z_2(s)} \tag{5}$$

For further explanation of the best practice the power interface is assumed to be ideal and thus the open loop transfer function can be simplified to

$$-F_O(s) = e^{-sT_D} \frac{Z_1(s)}{Z_2(s)} \tag{6}$$

It can be seen that the stability of the system depends on the ratio of Z1/Z2. For further detail on that issue please refer to [17,28,29]. The example Nyquist plots in Figure 19 shows the Nyquist curves for an unstable (left diagram of Figure 19) and a stable (right diagram of Figure 19) case of the voltage divider example.

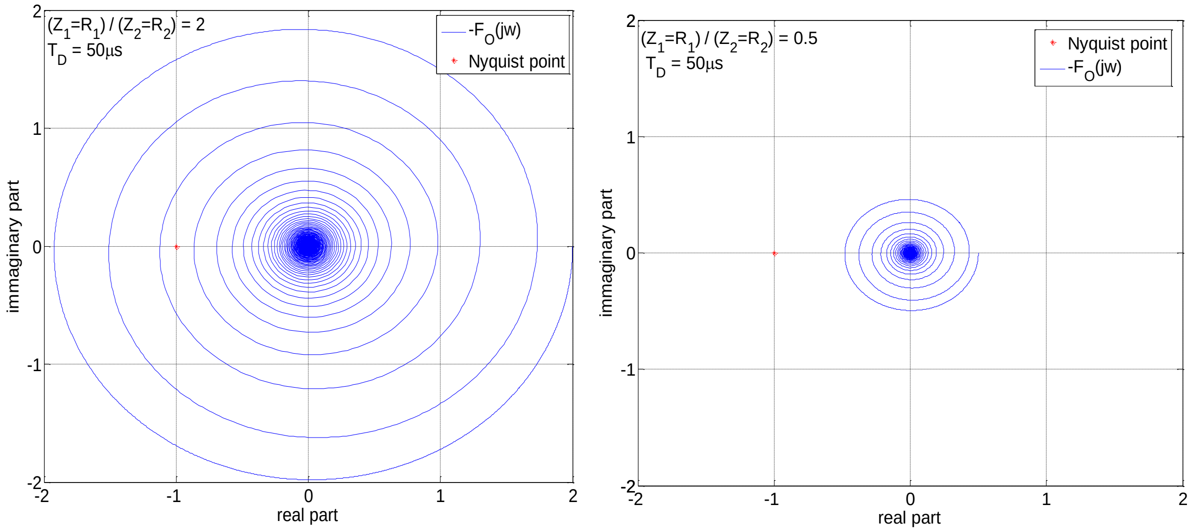


Figure 19 Example of Nyquist plot of two Methods (unstable: left; stable: right)

Figure 20 shows the modeling of the presented voltage divider example using the ITM interface algorithm using the MatLab SimPowerSystems toolbox and the conversion from that Simulink Model into a Model for the Opal RT real time simulation environment.

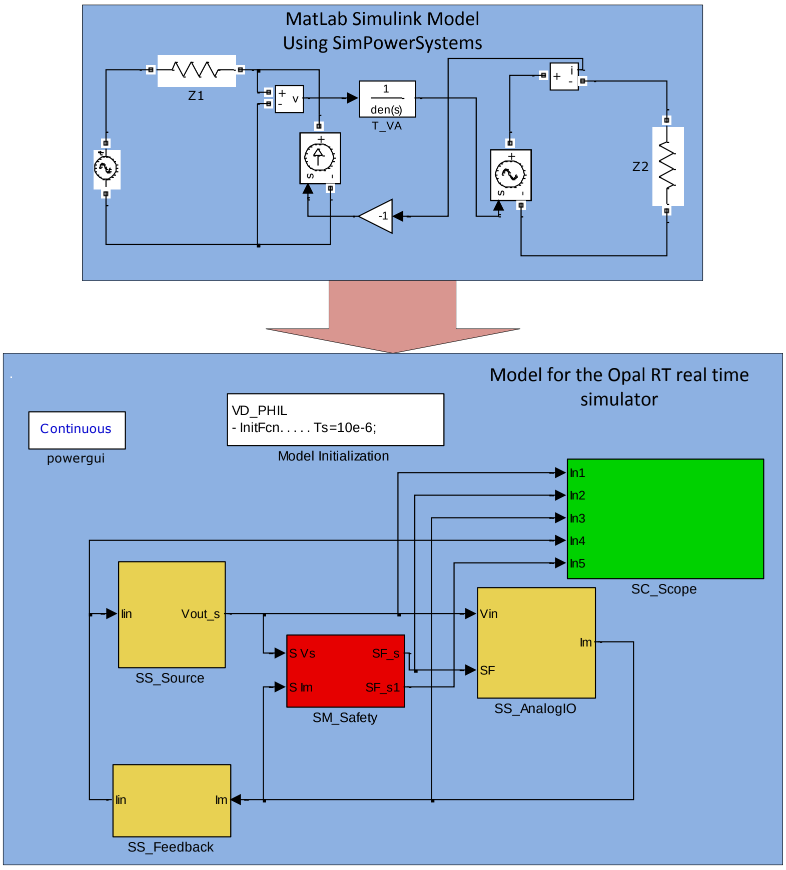


Figure 20 Conversion from a MatLab/Simulink Model to a model for the Opal RT real time environment

4.2.2 Case: 'Slow'

Diesel generator set

This case study consists of a low voltage 3-phase micro grid network containing a range of sources (synchronous, induction and inverter connected) and loads (rotating and static). The micro grid network can be de-coupled from the local public network through the use of an 80kVA motor-generator (M-G) set; this is the power interface of this facility. The voltage and frequency of the output terminals of the M-G set can be controlled using the outputs from a power system simulation, a simulation of a different type of generator, or using a playback of a pre-recorded/ calculated event.

Within this facility there are two platforms for providing the model to control the output of the power interface, an RTDS Simulator provided by RTDS Inc. [12], and an rtX platform running the ADvantage software provided by Applied Dynamics International (ADI) [35]. Each one is used for a different type of simulation. The RTDS system with RSCAD modeling software has been developed to perform real-time simulations of power systems and their control systems only. The rtX platform and the Advantage software have been developed as a general real-time simulation/ analysis platform. The models for the rtX system are developed in the MATLAB Simulink© package and compiled into real-time C code using the inbuilt Real-Time Workshop. The rtX platform is therefore particularly suited to the testing of single component models, e.g. a diesel engine, rather than power system models.

Laboratory set-up

The laboratory has two set-ups depending on which real-time platform is providing the information for driving the network. The set-up for running a simulation from the rtX box is shown in Figure 21. In this set-up the computation of the output of the M-G set is calculated by the real-time simulator/ controller.

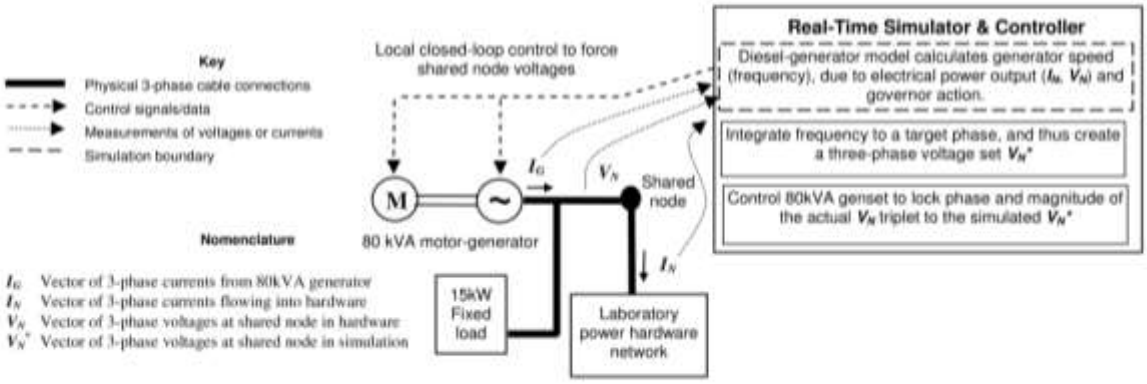


Figure 21 Power hardware-in-the-loop (PHIL) environment for the diesel generator model. Using an RTS as the real-time model simulator.

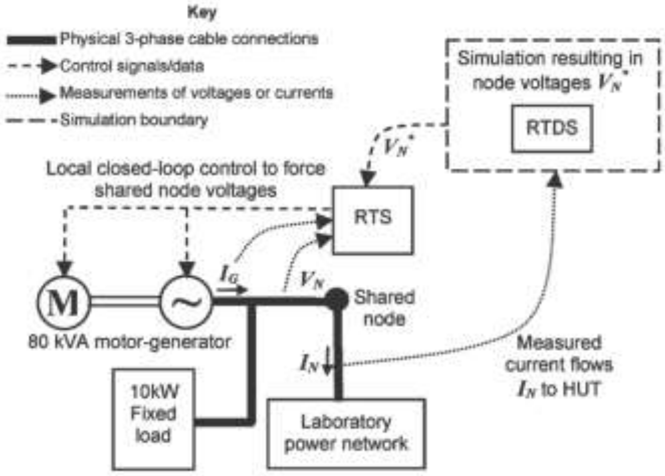


Figure 22 PHIL-environment for M-G set driven by power system simulation running on RTDS.

Scenarios

In this chapter a number of example scenarios will be presented. This will include the set-up, tests performed, results and analysis, and challenges using RT-PHIL.

Including a power system simulation in the loop

With the increasing complexity of the power distribution network a method of system verification is to couple entire electrical networks in hardware to digital models of other electrical networks running in real time. The hardware network might contain many generators, loads, cables, transmission lines, and transformers. The simulated network might be even more complex or might be a very simple network such as an infinite bus or a large single generator. The construction of such a system allows sections of power systems to be constructed in hardware and coupled to simulations of larger power networks which cannot be implemented in hardware due to constraints of time, cost, and space. The results from experiments performed on such a system have high credibility due to the use of actual hardware and control systems wherever possible. For example if the systems described in [36, 37, 38] were installed in a multi-kilowatt scale laboratory and coupled to a simulation of the distribution grid at a point of common coupling it would be possible to provide further verification and even validation of their systems. The hardware network can then be subjected to simulations of grid perturbations, faults, etc., and the desired response is verified. Such a step represents a sensible final test of a prototype power system component before deployment in the real world.
The network simulation is carried out on an RTDS simulator [12], which operates with a 50µs frame time. This uses the RSCAD [39] simulation environment. This simulation resource is two floors distant from the laboratory hardware and the machine controls. The laboratory hardware, including the machine controls for the 80kVA motor generator set, is controlled using an RTS real time-system controller [40], which is a multiprocessor VME-based system [41], operating at a 2000µs fundamental frame time with ADC sampling and

digital pre filtering at 666.66μs. The RTS controller can be programmed via MATLAB Simulink (using the Real Time Workshop extension) which makes it suitable for rapid prototyping and implementation of novel power system control and protection schemes [42]. The RTS controller is situated locally to the laboratory hardware, since it has many hard wired instrumentation connections to the hardware. This hybrid use of the RTDS simulator and the RTS controller results in some communication overhead, but allows the different strengths of each of these two devices to be best used.

Instrumentation and communication

Measurement of VN, the voltage at the shared node, is done by using a 3 phase voltage transformer (VT). Measurement of the currents IN and IG is done using current transformers (CTs) burdened with suitable resistances. In all cases, shielded treble twisted pair cable sets are used to bring the signals to the RTS controller (VN and IG) and RTDS simulator (IN), via suitable scaling, isolation and anti-aliasing filtering. The measurement IG is not directly required for the hardware in the loop system, but is used for the feed forward control of the 80kVA drive, described in section V. At the RTS controller and RTDS simulator, signals are sampled using ADCs. A non-trivial stage is the passing of data from the RTDS simulator to the RTS controller. This data consists of the 3 phase voltage set VN* which the RTDS simulation wishes to force at the shared node. This passing of data is required because the simulation and control functions have been split between the RTDS simulator and RTS controller.

It was considered to implement this control digitally via an optical link, and this may eventually prove to be a better system due to lower calibration and noise errors. In the present implementation, however, the simulated 3-phase voltage set VN* at the shared node in the simulation is simply passed using analogue voltages. The signals pass from 3 digital to analog converters (DACs) at the RTDS simulator via a shielded treble twisted pair cable set to the RTS controller where they are re sampled on 3 unfiltered ADCs.

Comprehensive data logging is carried out using the RTS controller infrastructure. The results of the simulation on the RTDS can also be captured. Matching the two sets of data together after test runs presently requires some degree of manual intervention since there is currently no synchronized clock information between the RTS and RTDS datasets.

Control of the generator voltage and phase/ frequency

A critical capability, handled by the RTS controller, is the ability to match the actual voltages VN to the simulated voltages VN* in real time, both in amplitude and phase. The active control of the phase of a synchronous generator is unconventional and is achieved here by using fast-acting controls for the armature current of the motor which drives the 80 kVA generator. To create the phase-locking control system, an existing application which implemented a droop less frequency and voltage control via proportional–integral–differential (PID) control loops has been modified and augmented. The generator frequency/phase is manipulated with the throttle control, while the voltage magnitude is manipulated with the field control. Figure 23 shows a simplified diagram of the control scheme. The error signal for the field PID controller is simply the difference between the positive sequence magnitudes of VN* and VN.

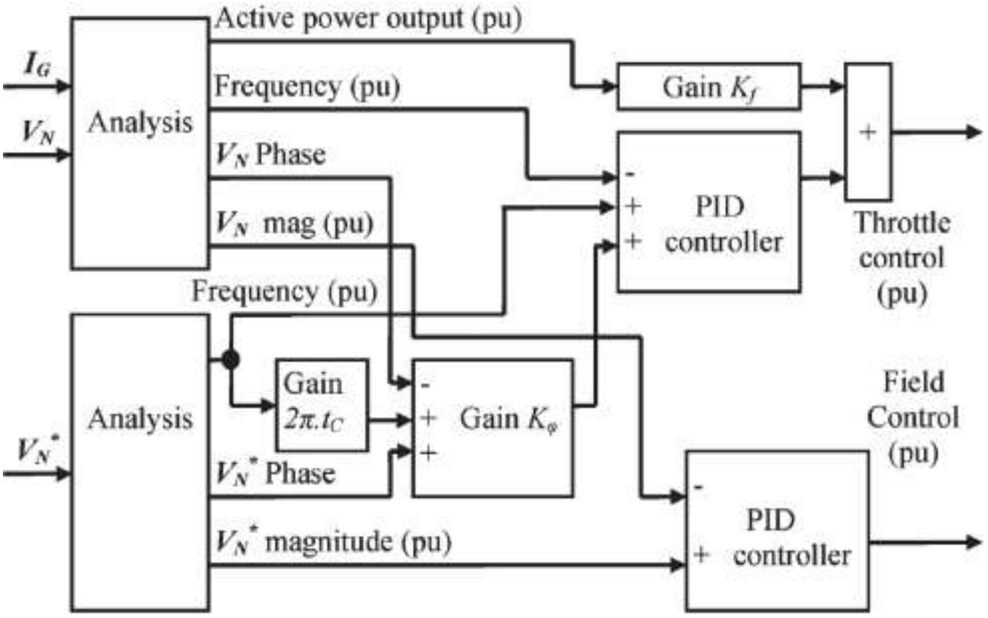


Figure 23 80kVA generator and field controls.

The error signal to the throttle PID controller is more complex, consisting of two main terms. The first is the difference between the frequencies of VN* and VN , which tends to bring the frequency of the generator toward that of the simulation. The second error term consists of a gain KΦ times the difference between the phases of VN* and VN. This error term tends to bring the generator terminal voltages into phase lock with the desired simulation voltages VN*. The value of KΦ has been set by empirical tuning to 0.2/π, equating to a maximum 5 Hz offset for a 90° phase-lock error. The use of a throttle feed forward control term Kf(= 1) significantly improves the phase/frequency response of the generator when subjected to step changes in load. The improvement occurs because a change in power flow can be measured within 1 ½ – 2 cycles, whereas any resulting change in frequency occurs more slowly, as an integral response to power imbalance, inversely proportional to the inertia of the generator and HUT.

Subtle extra features of the control are an additional small frequency offset added during the lock acquisition and a code for the detection of successful lock acquisition/hold. When a lock is not yet acquired or has been lost, the gain KΦ is set to zero.

The PID controls contain some non-standard code which limits the differential control contributions to fixed proportions of the error signal magnitudes. This allows differential controls to be used (to minimize the generator response time) without adding noisy differential control outputs when they are not required. A further additional feature is that the field control voltage is allowed to become negative at certain times. This can be used to forcibly collapse the field current as fast as possible to introduce voltage dips into the hardware.

Example scenarios including a power system in the loop

Results from two scenarios are shown below. These scenarios are deliberately designed to show the limits of performance of the PHIL system as implemented.

Scenario A: Direct on line start in simulation

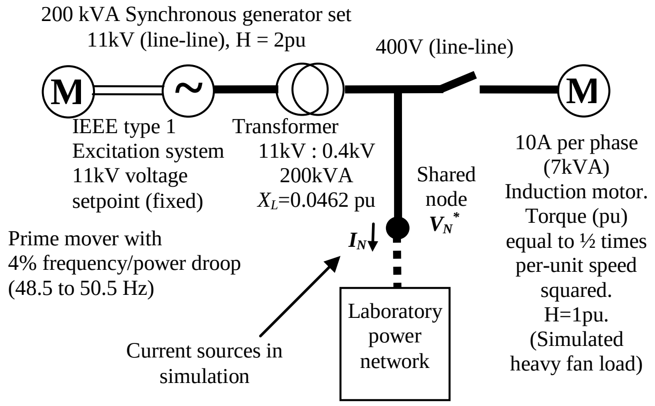


Figure 24 Example of a simple simulation on the RTDS

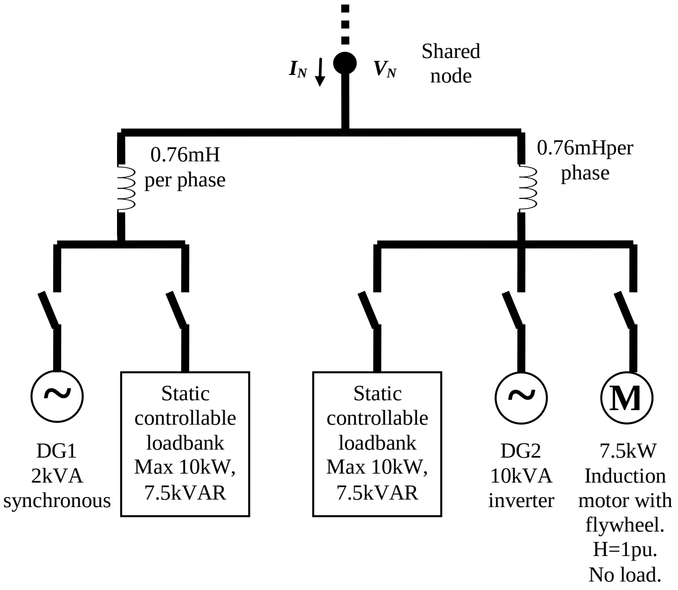


Figure 25 Example of a laboratory network Hardware Under Test (HUT)

In the first scenario, an induction machine is started direct on line (DOL) in simulation (Figure 24), and then disconnected. This causes a transient in frequency and voltage which the laboratory network reacts to. In this scenario, DG1 and DG2 generators are both on line, working at setpoints of 1500W, 0 VAR and 8000W, 0 VAR respectively, both with frequency droops of 5% and voltage droops of 10%. The constant impedance loadbank local to DG1 is set to 9.5kW at unity power factor (PF). The constant impedance loadbank local to DG2 is set to 9.5kW at PF=0.95 (3.3kVAR). The induction machine local to DG2 is running unloaded, consuming 1.4kW and 5.2kVAR.

Figure 26 shows that the tracking of frequency between the HUT and the simulation is suitably maintained.

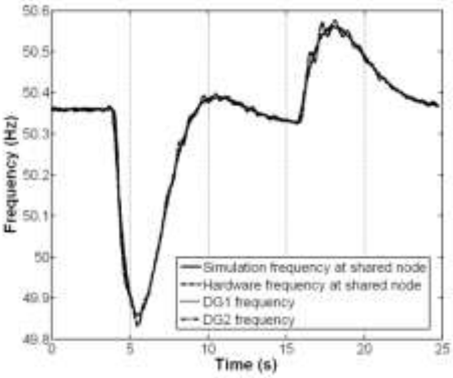


Figure 26 Scenario A: Frequency tracking between hardware and simulation.

Phase tracking (Figure 27) is generally within 1°, apart from a brief excursion to 7° during the DOL at t=4s when ROCOF suddenly exceeds 0.5 Hz/s. Accurate phase tracking recovers quickly following the initial transient.

Voltage tracking is shown in Figure 28 and Figure 29. Generally, performance is satisfactory, although there is a finite reaction time in the hardware, as the 80 kVA generator field current is adjusted to hit the target set by VN*. The generator has been shown capable of achieving average 200 V/s (line to line RMS) slew rates over 1 second, but for sudden changes over smaller timeframes the 200 V/s figure is not achievable. Over the initial 200ms of a transient, the achievable slew rate is approximately 30 V/s. Thus, although VN* only drops at 70 V/s in Figure 28, a lag in the actual performance of VN in hardware is still noticeable. The peak voltage tracking error is 5V at t=4s.

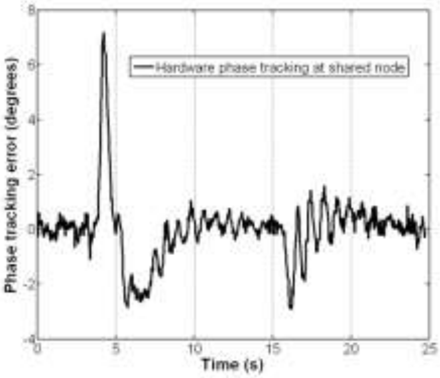


Figure 27 Scenario A: Phase tracking (angle by which VN leads VN*).

The active power flows in the hardware are shown in Figure 30. Clearly, the hardware loads, especially the loads local to DG2 including the induction motor, consume less power during the start-up transient around t=4 to t=7s, due to the drop in frequency and voltage. In addition the active power output from DG2 rises due to its 4% droop slope. DG1 is not shown as its power output is much lower, rising from 1300W to 1500W during the event.

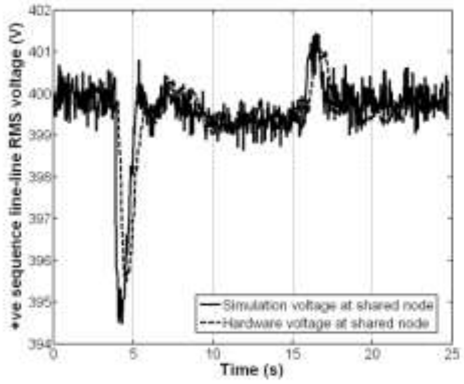


Figure 28 Scenario A: Voltage tracking between hardware and simulation.

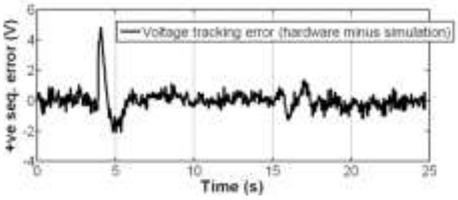


Figure 29 Scenario A: Voltage tracking error.

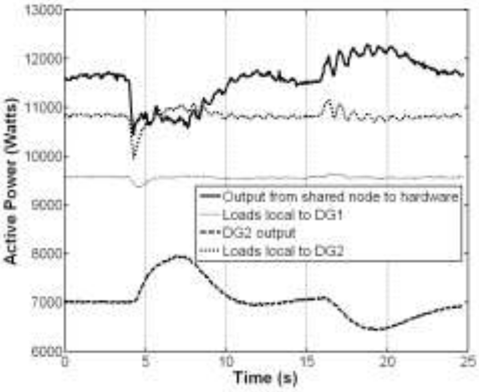


Figure 30 Scenario A: Active power flows (DG1 not shown for clarity).

To achieve adequate tracking, the recommendation for the present system is therefore to limit ROCOF within the simulation to less than 0.25 Hz/s, and to limit the voltage slew rate within the simulation to 30V/s (0.075pu/s). This should ensure peak transient phase tracking errors within 5°, and peak transient voltage tracking errors less than 4V (1%).

Scenario B: Direct on-line start in hardware

In the second scenario, a sequence of loads are added and then removed in hardware. The generators DG1 and DG2 are disconnected during this experiment. First, a constant impedance 9.5kW load at PF=0.95 (3.3kVAR) is added local to DG1 (t=6s). Then, a constant impedance 9.5kW load at PF=0.95 is added local to DG2 (t=17s). Finally an induction machine is started direct on line (DOL) in hardware (t=29s). These steps are then reversed to disconnect the apparatus.

Frequency tracking is generally satisfactory (Figure 31) apart from some transient deviations immediately following the DOL start. This also shows up as some large (up to 40°) but brief phase tracking errors (Figure 32). The tracking of frequency and phase performs much better (less than 5° peak error) during the addition and removal of the static loads, and during the removal of the induction machine load.

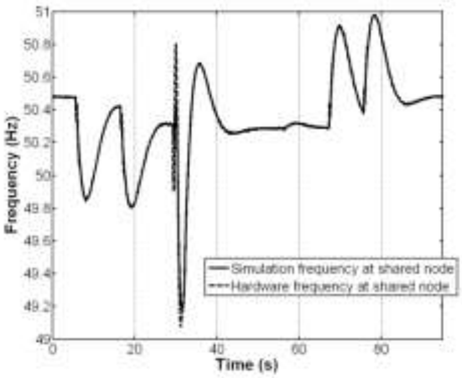


Figure 31 Scenario B: Frequency tracking between hardware and simulation.

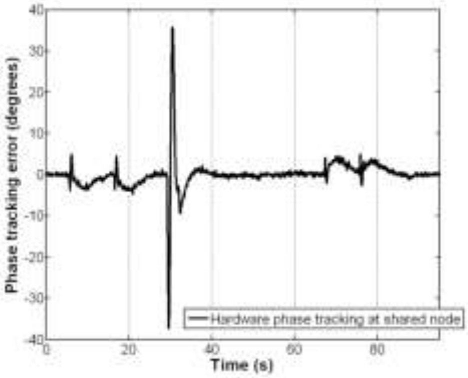


Figure 32 Scenario B: Phase tracking (angle by which VN leads VN*).

The voltage tracking is shown in Figure 33 and Figure 34. In this case, a major deviation is visible during the DOL start when the hardware voltage drops by more than 100V (0.25pu) for just over 2 seconds, while the simulation voltage oscillates around 400V. During the DOL start, the active power reaches 35kW and reactive power reaches 45kVAR, a total of 57kVA, 71% of the rating of the 80kVA generator. Smaller unwanted hardware voltage drops (and rises) of 10V (0.025pu) can be seen during the static load additions and removals (about 10kVA each, 12% of the rating of the 80kVA generator).

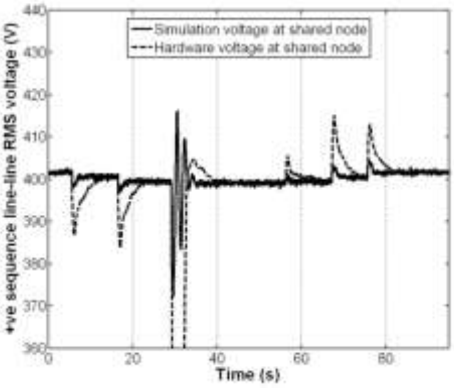


Figure 33 Scenario B: Voltage tracking between hardware and simulation.

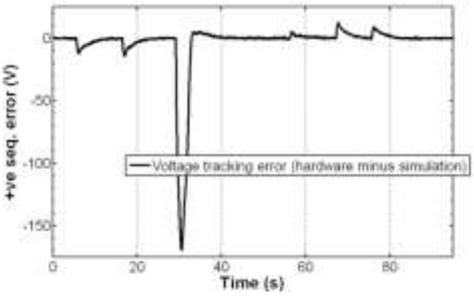


Figure 34 Scenario B: Voltage tracking error

To achieve adequate tracking, the recommendation for the present system is therefore to limit sudden load steps in the hardware to less than 8kVA, i.e. less than 10% of the rating of the generator. This should ensure peak transient phase tracking errors within 5°, and peak transient voltage tracking errors within about 10V (2.5%).

Emulating a diesel generator in hardware

The simulation model used includes a governor controller, the coupling dynamics of the engine to the generator shaft, and also the inertia of, and torque applied to, the generator. The simulation model does not include magnetic phenomena or the electrical behavior of the generator; the electrical behavior is determined by the physical synchronous generator.

The diesel model was originally developed in the “continuous” mode, and so this was converted for use with discrete simulations (and HIL applications) by replacing all filters, differentials and integrals with digital equivalents. A time step of 2ms is used, since it matches that used in the HIL application.

Implementation in of diesel engine model in power hardware in the loop scenario

The engine model can be placed within a HIL environment Figure 21. In this case, the aim is to control a real 80kVA synchronous motor-generator so that it behaves with the same speed/torque and inertial response as the model of the diesel engine and coupled generator. This allows an entire laboratory network of loads, interconnectors, breakers, and smaller generators to be connected. The power hardware network is thus virtually driven by the model of the diesel/generator, and the model of the diesel/generator becomes loaded by the network. The closure of this feedback loop creates a HIL environment.

The 80kVA motor-generator is driven by a fast responding DC motor coupled to a thyristor drive. In this case the simulation of the diesel engine can be executed on the same computer as the HIL control (the simulator and controller in Figure 21). Also, the diesel engine model returns a speed output as a response to a torque input, and this speed output must be integrated to provide the phase of VN*. This integration includes an arbitrary (constant) phase offset value which is essentially a free variable. For these two reasons, so long as the sampled values of VN, IN are measured carefully with matched anti-aliasing filters and made coherently (or processed to be coherent as in [25]), then there is essentially zero loop delay. This significantly simplifies the implementation compared to previous work in [25].

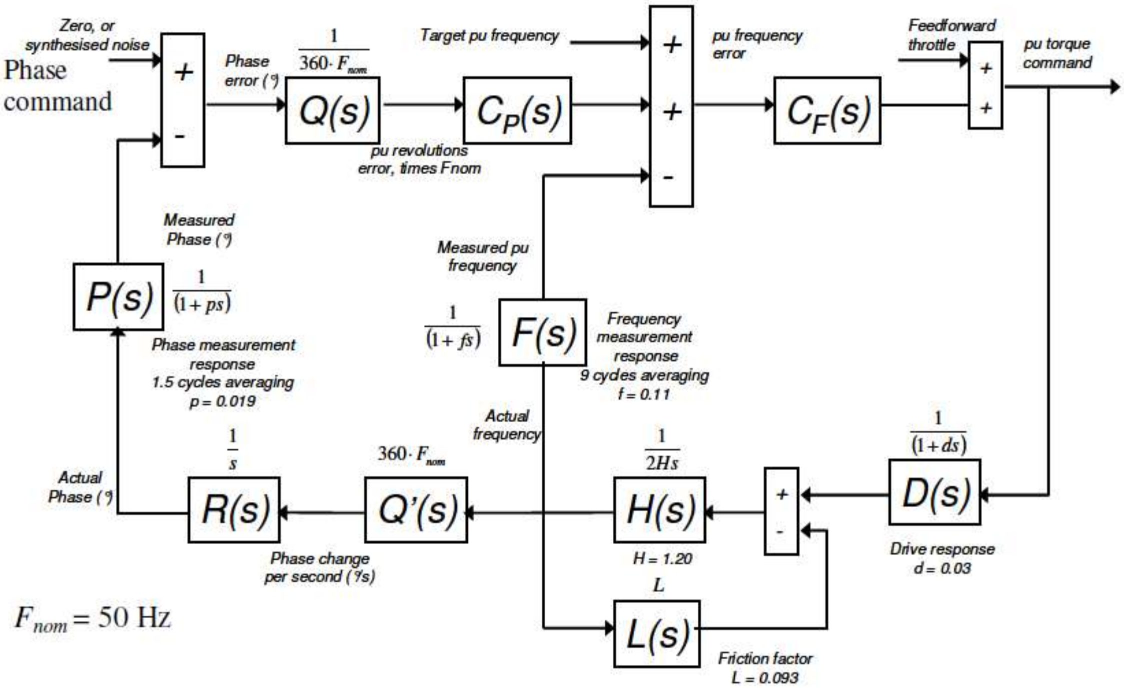


Figure 35 Throttle control system

Control of the generator voltage and phase/ frequency

The physical generator is controlled by a modified governor and AVR (Automatic Voltage Regulator). The AVR controller is a simple PID (proportional-integral-derivative) controller, but the throttle control (for frequency and phase tracking) has been improved. To enable this, the parameters for the generator and measurements were measured through a series of tests, such as spin-down tests (to measure inertia and friction), and step-changes in command torque (to measure drive response). Knowledge of these parameters, combined with knowledge of the measurement algorithms, allows the system to be modeled to the required level of accuracy. The model structure is shown in Figure 23.

The right-hand loop of Figure 23 is a conventional loop for controlling frequency to a given target. The left-hand loop augments the control system with the unconventional (but required) control of generator phase to achieve a given target. In the model, this input can be regarded as a zero input for OLTF (open-loop transfer function) stability analysis, or can be used to simulate the effects of measurement noise at different frequencies in a CLTF (closed-loop transfer function) analysis. To simplify the control system, the right-hand frequency control loop could be opened during phase control, leaving only the left-hand loop active. However, this means that both the integration (1/s) stages H(s) – the generator inertia, and R(s) – the frequency-to-phase transformation, would be present in the OLTF. This means that the phase lag of the OLTF would be 180° even at DC, becoming even more lagged at higher frequencies due to the action of low-pass filters and measurement times. Stabilizing such a loop presents a significant problem requiring large amounts of differential gain.

Thus, the control is easier to stabilize if both the control loops are cascaded, since the effect of the inertial lag can be reduced by closing the frequency-control loop.

Targets were set for the desired CLTF responses of the frequency control loop, and then the phase control loop. The targets are defined such that the frequency and phase response should ideally behave as a first-order low-pass filter response to a command signal. Firstly, the CLTF for the frequency-control loop:

$$\frac{C_f \cdot D \cdot \frac{H}{(1+HL)}}{1 + C_f \cdot D \cdot \frac{H}{(1+HL)} \cdot F} = \frac{1}{(1+as)} \qquad \textbf{(7)}$$

where a is the target first-order response time.

Secondly, the CLTF for the phase-control loop:

$$\frac{Q \cdot C_P \left[\dfrac{C_f \cdot D \cdot \dfrac{H}{(1+HL)}}{1 + C_f \cdot D \cdot \dfrac{H}{(1+HL)} \cdot F} \right] \cdot Q' \cdot R}{1 + Q \cdot C_P \left[\dfrac{C_f \cdot D \cdot \dfrac{H}{(1+HL)}}{1 + C_f \cdot D \cdot \dfrac{H}{(1+HL)} \cdot F} \right] \cdot Q' \cdot R \cdot P} = \frac{1}{(1+bs)} \tag{8}$$

where b is the target first-order response time.
Assuming that (3) can be satisfied, then (4) can be simplified to

$$\frac{\left(C_P \left[\frac{1}{1+as} \right] \cdot R \right)}{\left(1 + C_P \left[\frac{1}{1+as} \right] \cdot R \cdot P \right)} = \frac{1}{1+bs} \tag{9}$$

(3) and (5) can then be solved, yielding:

$$C_P = \frac{\left[L \cdot \frac{1}{s} + \big(2H + L(f+d)\big) + \big(2H(f+d) + Lfd\big) \cdot s + 2Hfd \cdot s^2 \right]}{(f+a)\left(1 + \frac{fa}{(f+a)} \cdot s\right)} \tag{10}$$

And

$$C_P = \frac{\left[0 \cdot \frac{1}{s} + 1 + (a+p) \cdot s + ap \cdot s^2 \right]}{(p+b)\left(1 + \frac{pb}{(p+b)} \cdot s\right)} \tag{11}$$

Equations (6) and (7) define the parameters for the two controllers CF and CP. Notably these controllers are unconventional PIDA (proportional-integral-derivative-acceleration) controllers, combined with low-pass filter elements. The acceleration terms (in s2) dramatically aid the stability, since they counter the phase lags. However, the risk in a practical system is that the (and indeed even the differential controls) introduce large amounts of noise due to the differentiation stages.

Setting the actual controls in practice involved the following steps, recognizing that Figure 35 is only an estimation of the actual system, and that the simple targets (1) and (2) do not fully define the response required in all scenarios:

- Choosing response times a and b, evaluating (6), (7) and then examining OLTF (stability) and CLTF (response) bode plots using MATLAB®.
- Trials of the chosen settings in the hardware implementation, making small changes to the settings of a and b
- Reductions in the actual proportions of acceleration (s2) controls used, from those suggested in (6) and (7), to limit the response to measurement noise, as shown in Table 1.
- Increasing the amount of integral gain in CF to improve the initial settling to a new frequency, as shown in Table 1.
- Repetition of trials of steps 2-4, in a range of scenarios, until the best behavior is achieved.

The control parameters used in the experiments described in this section are shown below in Table 1. The hardware and measurement responses are shown in Figure 36.

Table 1 Control parameters for real 80kVA generator controller.

Description	*Parameter*	*Adjustments to (4) &(5)*	*Final Value*
Target frequency CLTF response time	a		0.15 sec
Target phase CLTF response time	b		0.02 sec
Frequency loop C_F	K_i	Boosted by 10x	3.434
“	K_p		8.935
“	K_d		1.352
“	K_a	Reduced to ¼ x	0.008589
Frequency loop C_F low-pass filter cut-off	$\frac{fa}{f+a}$		64.70 ms 2.46 Hz
Phase loop C_P	K_i		0
“	K_p		22.29
“	K_d		3.898
“	K_a	Reduced to ¼ x	0.02078
Phase loop C_P low-pass filter cut-off	$\frac{pb}{p+b}$		9.734 ms 16.35 Hz

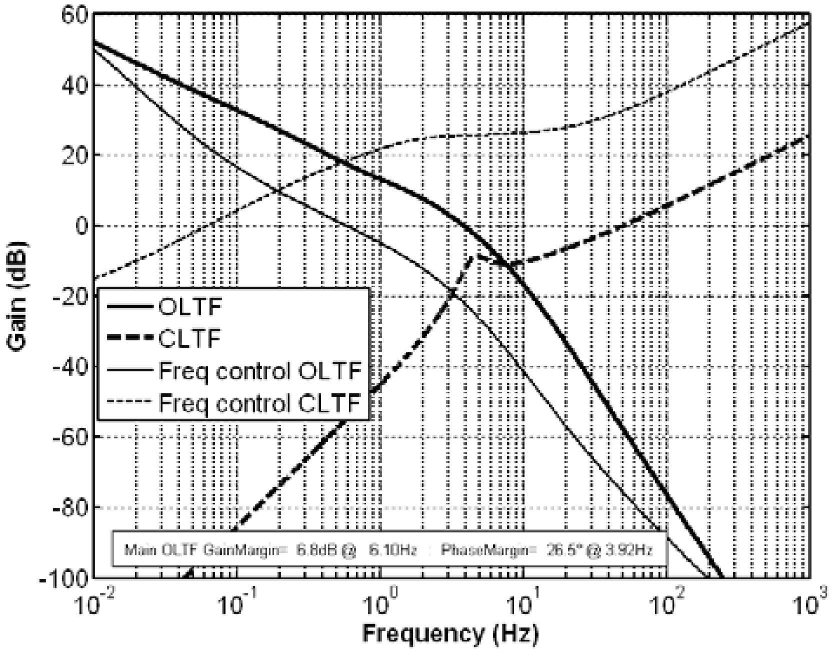


Figure 36 OLTF and CLTF Bode plots (gain).

The bode plots of the OLTFs and CLTFs are shown in Figure 36 and Figure 39, which show OLTFs for both the overall phase-control system, and also the inner frequency-control loop. The gain margin and phase margin are forecast at 6.8dB and 26.5° respectively, and, indeed, the hardware system is fast responding and on the limit of stability with this configuration. It is certainly found that if the Ka acceleration terms (in s2) are set to zero, the hardware is unstable. Conversely, if the Ka terms are increased to their theoretical values, noise (from phase/frequency measurements) becomes significant at the throttle output. In fact, the non-zero Ka terms are only acceptable due to the presence of the single pole low-pass filters within CF and CP (Table 1), and the careful design of the phase and frequency measurements [37], which reduce instrumentation noise as much as possible. Figure 36 shows that at high noise frequencies, the CLTF gain is high (and increasing with frequency) due to the effect of the Ka terms.

Diesel-generator PHIL results

The power demand is shown in Figure 37. The “Pure Simulation” demand is a step to 0.5pu, but the HIL demand does not exactly track this. The reason is shown in Figure 38, which shows the 3 phase-phase voltages. In simulation, the voltage is fixed at 1pu, 400V. In HIL, the voltage dips when the load is suddenly applied. Further analysis shows that the field drive hardware did not possess enough voltage range or dynamic response to slew the synchronous generator field current fast enough to maintain 400V, 1pu. The driver is capable of achieving 1pu voltage in steady state, as shown at t=18s on Figure 38, but is unable to mirror the most dynamic scenarios of demand and frequency variation.

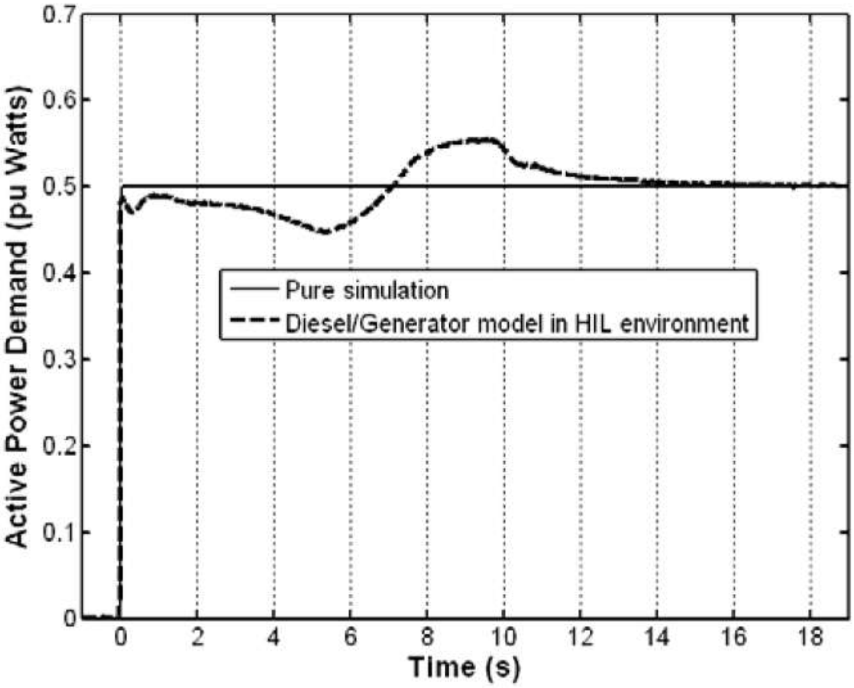


Figure 37 Power Demand of Diesel Generator

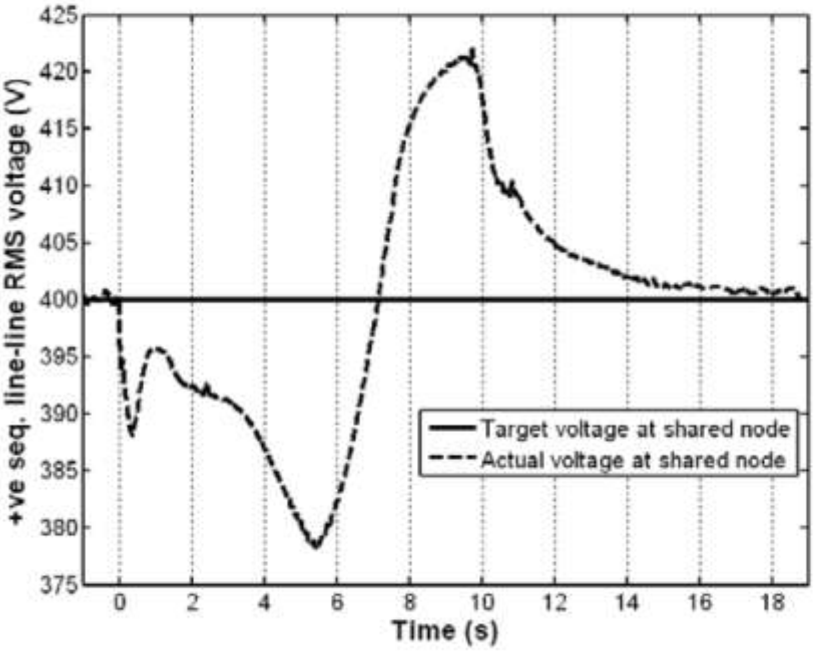


Figure 38 Voltage tracking of hardware against simulation target.

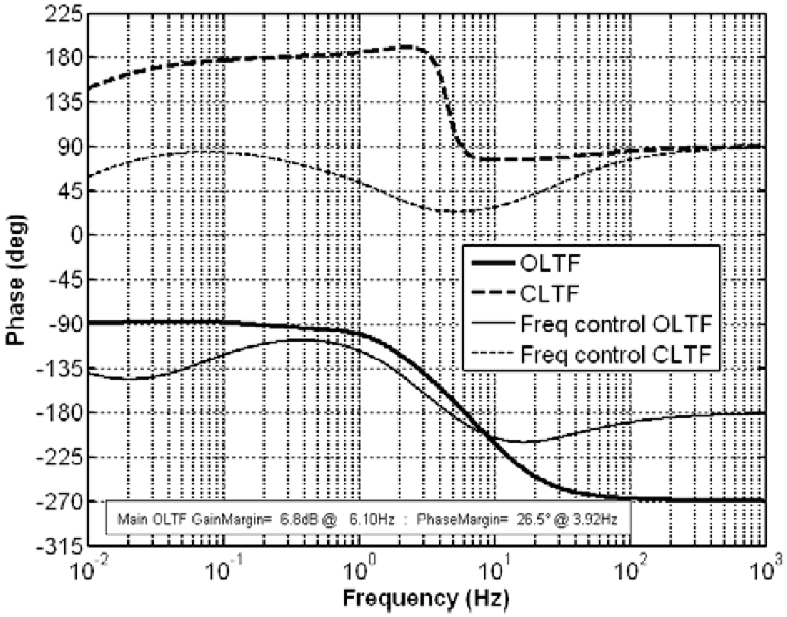


Figure 39 OLTF and CLTF bode plots (phase).

Because the voltage in the HIL case varies from the scenario 400V (1pu) target, the power demand, and hence generator torque (Figure 40), varies between the simulation and HIL cases. In consequence, the resulting frequency profiles differ (Figure 41). However, on Figure 41, it can be seen that within the HIL case, the frequency of the diesel model and the frequency of the actual hardware generator track very well, despite a ROCOF (rate of change of frequency) of up to 5Hz/s during the scenario. This is a consequence of the tight control. The tracking of phase is shown in Figure 42. The peak tracking error is 10-15° which appears at the onset of the 5Hz/s dynamic changes.

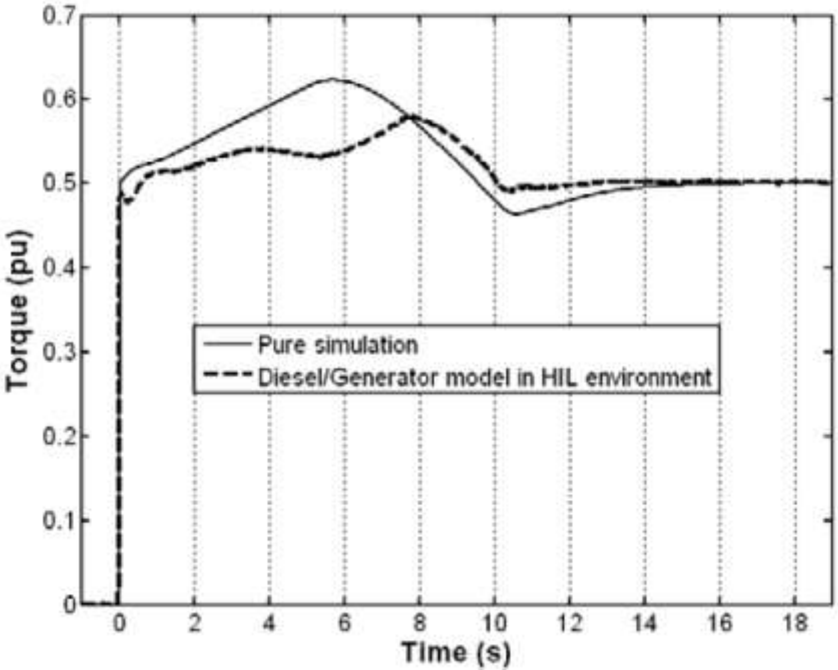


Figure 40 Generator torque.

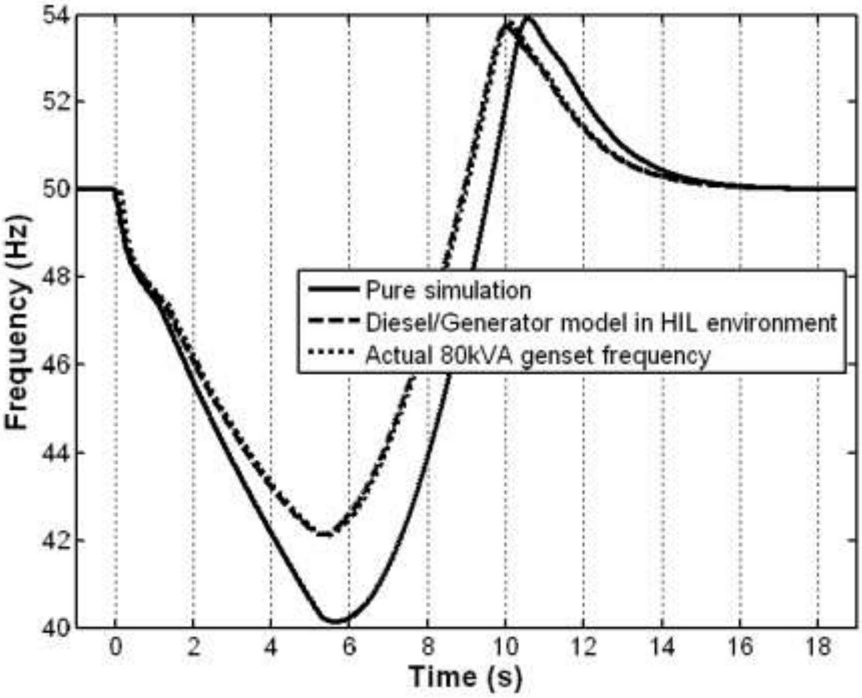


Figure 41 Network frequency.

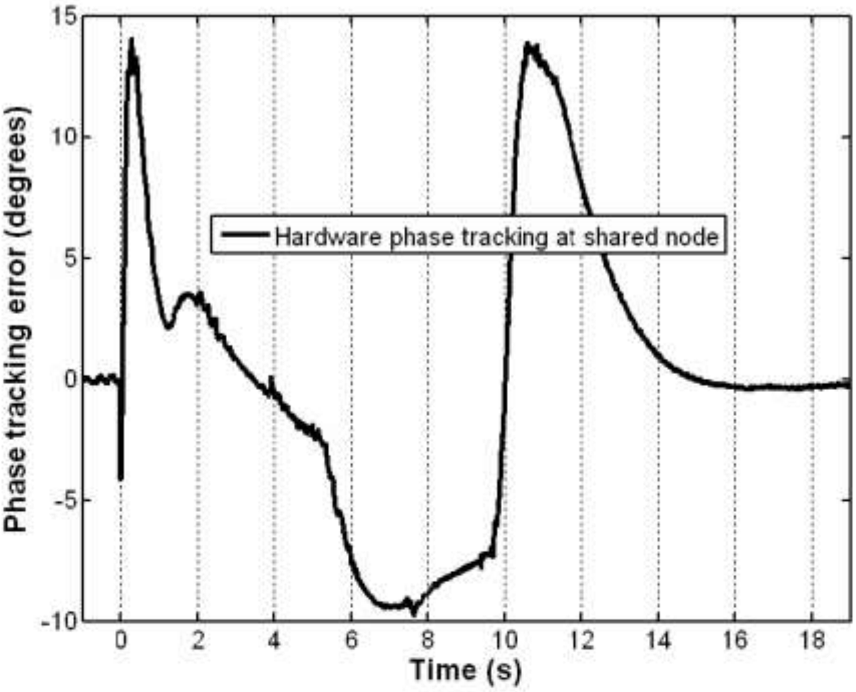


Figure 42 Generator phase tracking.

Of note in this scenario is the large frequency dip. This is due to the behavior of the turbo-charger which takes time to “spin up”, especially when engine speed drops in response to the load step. The turbo pressure (in gauge bar) can be extracted from the HIL model in real time, and is shown in Figure 43. Scenarios with large constant-power demand steps are more serious than those with constant-torque demand steps, due to the increased drop in engine speed and resulting torque increases.

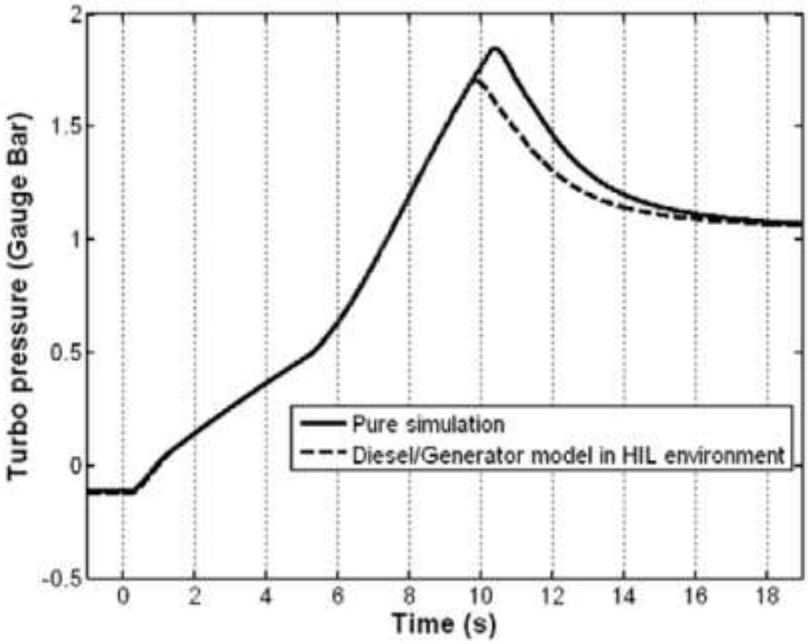


Figure 43 Turbo pressure.

Notes on experience

Issues with integrating a power system simulation into a microgrid

Using a synchronous generator as the interface between hardware and simulation has the constraint that neither harmonics nor unbalance can be deliberately injected into the hardware. There are also limits to the ROCOF and rate of change of voltage in simulation which can be tracked accurately. Using the described setup, tracking with peak errors of 5◦ (phase) and 1% (amplitude) can be achieved for simulation slew rates of 0.25 Hz/s and 30 V/s for fast transient events. Hardware transients of up to 10% of the synchronous generator rating can also be accommodated with 5◦ (phase) and 2.5% (amplitude) tracking errors. However, the use of a synchronous generator may allow brief hard faults to be placed in the hardware, with resulting currents much larger than 1 p.u. In contrast, an inverter would have to be significantly over designed with corresponding expense to allow such large currents to be accommodated without requiring a trip of the inverter itself.

Improvements to diesel model integration

Improved performance of the diesel engine-generator model requires that the field drive hardware for the synchronous generator is increased in size and bandwidth. In the experiments considered, the physical generator was not able to accurately track the desired voltage during the step change in demand. This led to differences between the simulated and HIL cases. A higher (bidirectional) voltage output, using purely solid-state amplifiers, would allow the generator field current to be slewed much more quickly. This would not only allow the presented scenario to be modeled more accurately, but would also allow scenarios such as sharp voltage dips to be modeled.

4.2.3 **Case: 'Fast'**

PV

The micro grid used in this set-up comprises two PV generators, a small wind turbine, battery energy storage, controllable loads and a controlled interconnection to the local LV grid. The battery unit, the PV generators and the wind turbine are connected to the AC grid via fast-acting DC/AC power converters. The converters are suitably controlled to permit the operation of the system either interconnected to the LV network (grid-tied), or in stand-alone (island) mode, with a seamless transfer from the one mode to the other. The central component of the micro grid system is the battery inverter, which regulates the voltage and frequency when the system operates in island mode, taking over the control of active and reactive power.

A schematic diagram of the micro grid system is depicted in Figure 44.

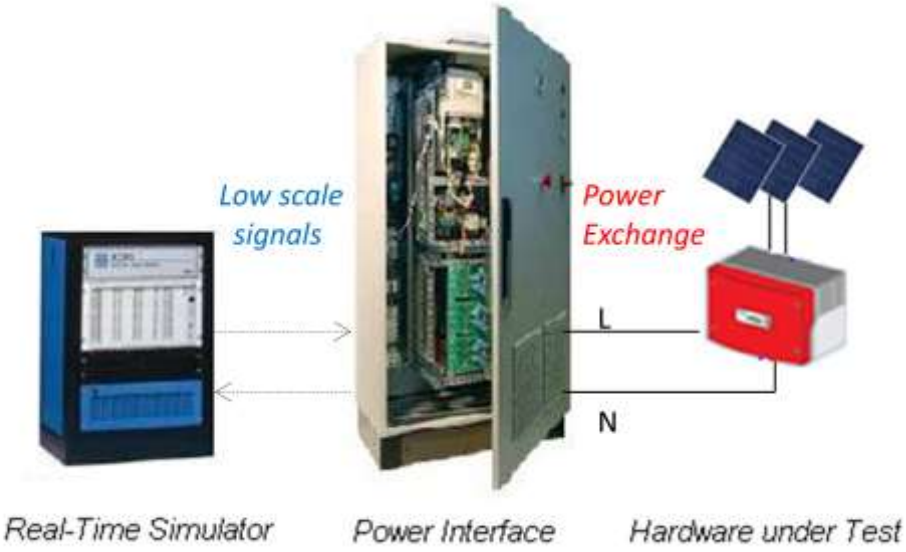


Figure 44 PV-Inverter connected to a low voltage grid simulated in a Real-Time Simulator [28]

A PHIL experiment is presented here, where the real PV panels and the PV inverter are the Hardware Under Test. The single phase PV inverter consists of a DC/DC converter to perform the Maximum Power Point Tracking (MPPT) and a DC/AC inverter. If there is sufficient solar irradiation, (i.e. sufficient DC voltage) the PV inverter is capable of providing power. When a grid of suitable voltage and frequency is applied to its AC terminals synchronization occurs and the inverter starts supplying current. The same operation is performed in this application with the difference that instead of the utility grid, the PV inverter is connected to the controllable AC grid produced by the power amplifier.

In the software of real-time simulator a low voltage distribution grid is modeled (e.g. a very simple version is shown in Figure 45a). The voltage of the common node of the simulated network and HUT (N1 in Figure 45) is calculated. Suitable signal attenuation is performed and the D/A converter of the simulator are used to send the low level reference voltage to the amplifier. The A/D converter of the amplifier samples the signal which gets amplified and the control-unit sends the firing pulses to the converter that produces the requested voltage. This variable AC grid is applied to the common AC bus of the micro grid. The PV inverter synchronizes with the AC grid and starts supplying current/power according to the available irradiation. Subsequently, the injected current of the PV inverter is measured by the Power Interface, gets attenuated, passes through its D/A converter and is sent back to the real-time simulator. The A/D converter of the simulator samples the feedback signal, amplified and a current source is added in the simulated network representing the current provided by the PV inverter (Figure 45b). This process is demonstrated in Figure 46. It is noted that the power produced by the PV inverter is injected into the utility grid via the power amplifier.

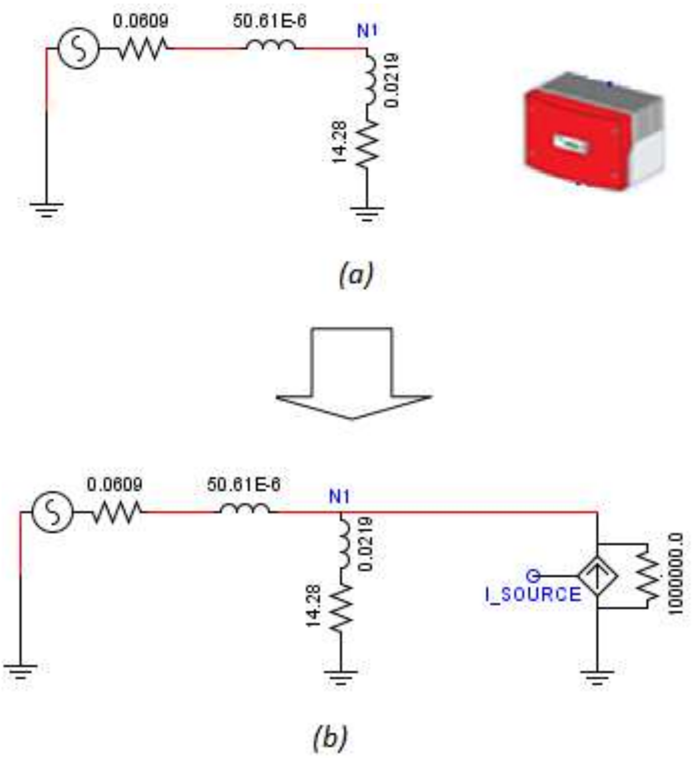


Figure 45 Virtually simulated system (a) and HUT modeled as a current source (b).

The interface algorithm used is based on the Ideal Transformer Model (see Chapter 1.4.4) because of its simple implementation and high accuracy. However, the relatively small impedance of the PV inverter could lead to instability, therefore a low pass filter is inserted on the feedback current, as proposed in [16] for a very similar application. This feedback filter reduces the accuracy of the PHIL simulation. Ensuring stable operation without reducing the accuracy is a real challenge taking into account that the HUT is not known in detail and that the time-delay introduced by the Power Interface is not negligible (due to the switch-mode amplifier).

With the development of this topology the PV inverter can be tested in an environment, that conventional testing can't offer. The independence of power ratings of the simulated network and the PV inverter by suitable scaling (Figure 46) can "transform" a 1.1kW PV inverter into a large PV system which interacts within a large power network.

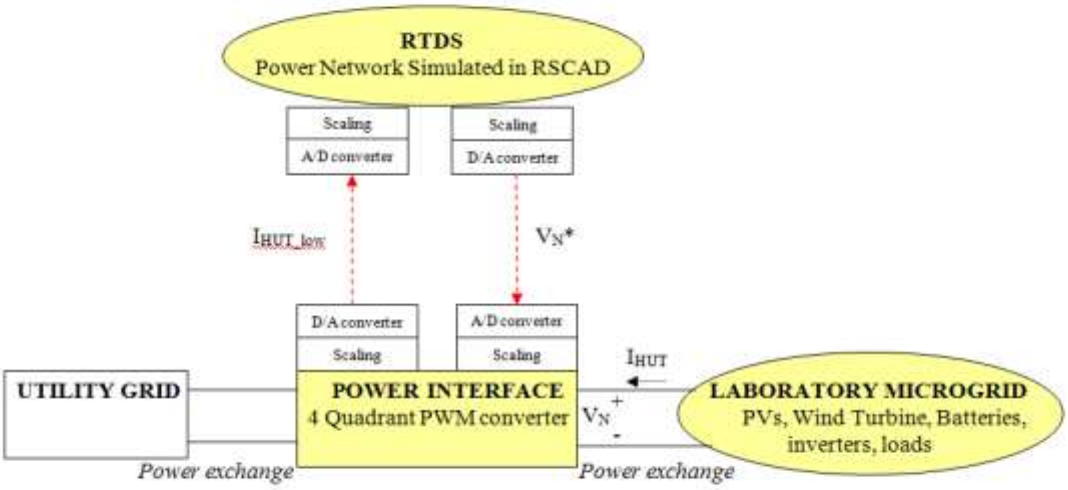


Figure 46 Low level signals (VN*,IHUT_low) and power exchange (VN, IHUT) in the PHIL simulation

5 GENERAL CONCLUSIONS

This white book gives an introduction to real-time power hardware in the loop (RT-PHIL) testing and its role in achieving the major European goals on renewable energy, efficiency and CO_2 reduction: technical requirements are becoming stricter, leading to a need for efficient testing methods to satisfy changing certification procedures.

RT-PHIL testing is a hybrid form of the existing hardware and software testing methods, combining their benefits in terms of accuracy, costs, duration and safety. Using basic example test configurations the various interface aspects of RT-PHIL testing are covered such as different power interfaces and interface topologies. These issues are often first addressed using a scaled-down version of the set-up before full power RT-PHIL testing.

A vision is given on the necessary developments in testing to de-risk components, systems and technology prior to installation in the 'real world'. The place of RT-PHIL is given in the range of possibilities such as simulation and gaming, virtual testing, system studies, in-house testing and distributed testing.

RT-PHIL experiences that have already been obtained are reported using some case studies. These case studies explain in depth how complexities encountered in actual RT-PHIL experiments were addressed. Also an outlook is given of which are the next steps in the development of RT-PHIL.

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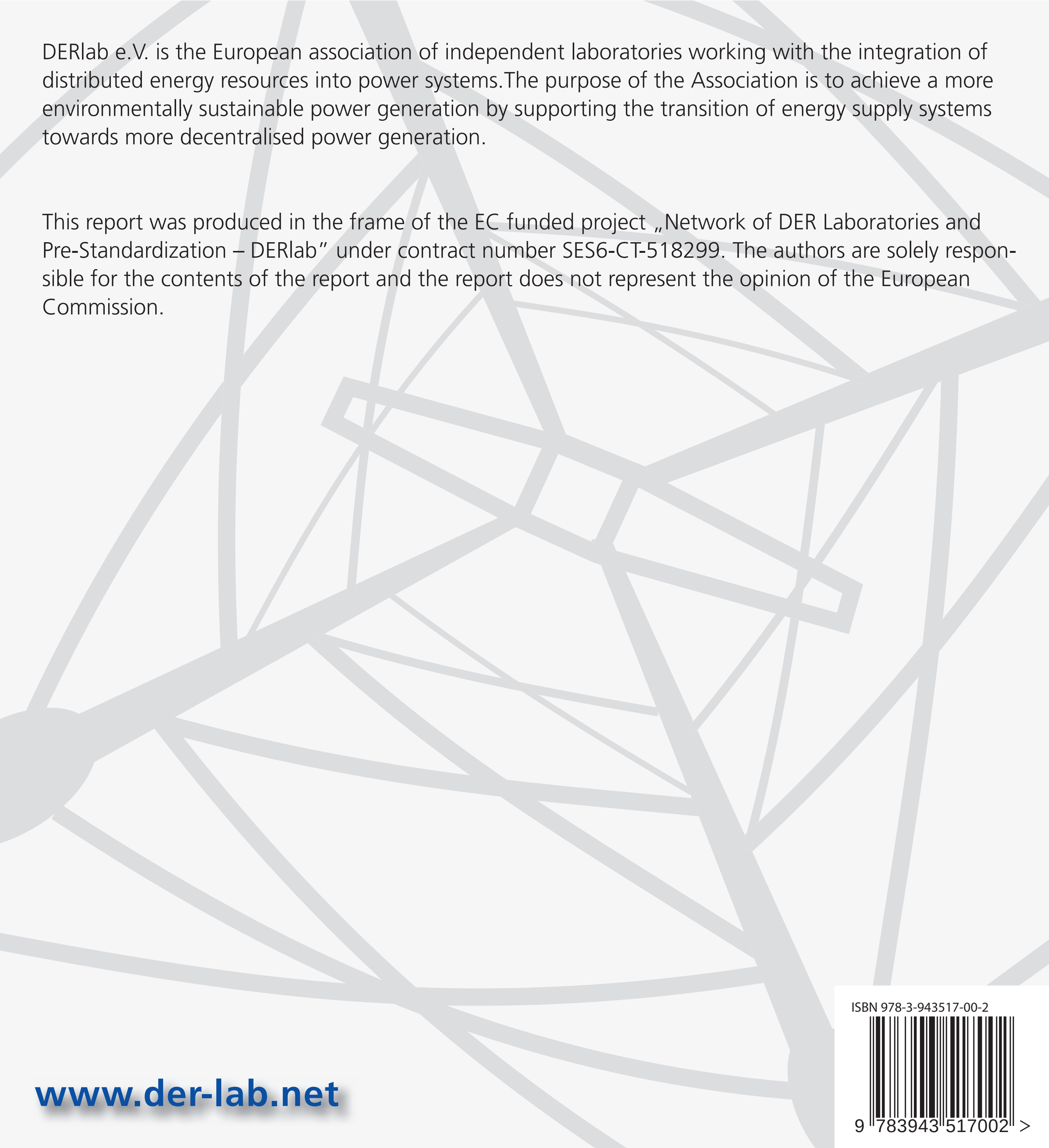

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