Power Hardware In the Loop laboratory testing capability for energy technologies

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***Abstract*—The development of new energy technologies plays an important role in achieving a fast and orderly energy transition. However, validating the performance of such technologies is not trivial. Despite extensive laboratory evaluation, the performance of the technology while integrated in the electrical grid can vary depending on several electrical factors, e.g. grid impedance. For this reason, the early testing of such technologies in realistic grid conditions play an important role. This paper provides a description of the Power Hardware In the Loop laboratory at the Karlsruhe Institute of Technology, and shows its capability in realistic testing energy technologies.**

***Index Terms*—Power Hardware In the Loop, real time simulation, Real lab.**

I. Introduction

In the recent years, new energy technologies have been developed to increase the electrical grid hosting capability for renewable energy sources: energy storage systems, power electronics actuators, DC grids, etc.. While for largely implemented resources in the grid, such as battery energy storage system, there is a large set of available field data, it is difficult to prove the performance of novel energy technologies (e.g. flywheels [1], [2], supercaps [3], solid state transformers [4]) in offering grid services.

Simulation studies can offer a good overview of these technologies' capabilities. Through studied models of the technology and its connected grid, it is possible to assess their impact on the electrical grid in a large set of scenarios. However, this comes under the assumption that the technology model is accurate and sufficiently detailed to ensure meaningful results. In case of missing data or inaccurate models, misleading results may occur.

On the other side, the development of an initial prototype and its implementation in a field test guarantees a highly accurate assessment of the technology performance. However, this comes to high costs, lengthy installation times, and not repeatability of the results.

For the aforementioned reasons, the concept of Power Hardware In the Loop (PHIL) [5]–[8] has been developed in the last years. The PHIL allows to interface the real hardware under testing (e.g., an initial prototype) with a digital real time-simulated electrical grid by means of power amplifiers. This setup enables to test the hardware, that will go in the future in the market, under a large set of scenarios (simulated in real time), allowing repeatability of the results.

In this work, the testing capabilities at the Power Hardware In the Loop Lab in the Energy Lab 2.0 [9] at the Karlsruhe Institute for Technology have been described, showing its latest testing performance for a high-speed flywheel energy storage system and a micro gas-turbine for independent supply systems.

II. Power Hardware In the Loop concept

The Power Hardware In the Loop consists of 3 main elements:

- Digital Real Time Simulator: the grid scenario, where the technology to be proved shall be installed, is simulated in real time conditions. It means that in each discrete time step (e.g., $50\,\mu$s), the simulator provides the new status of the grid at its output [5], [10]. The predetermined time step allows to synchronize and exchange signals between the simulated grid and external components.
- Power Amplifier: the power amplifier receives signals from the simulated grid (e.g., the point-of-common-coupling voltage) and translate a low-voltage digital signal to an high-voltage power signal, that shall represent accurately the simulation waveform. The power amplifier is then connected physically with the hardware under test.
- Hardware under Test: it is the technology that shall be evaluated by means of the PHIL system. The hardware under test will behave as connected to the real grid and one of its coupling variable (e.g., the line current) is measured and sent back to the digital simulator, where it is represented as a controlled current (or voltage) source. This allows to close the loop. Any change in the simulated grid are seen from the hardware side, and the reaction of the hardware has an impact on the simulated grid.

III. Testing facilities at Energy Lab 2.0

In this section, two of the main power hardware in the loop facilities at the Energy Lab 2.0 of the Karlsruhe Institute of Technology are described.

This work has been supported by the Helmholtz Association under the program "Energy System Design" and under the Helmholtz Young Investigator Group "Hybrid Networks" (VH-NG-1613).

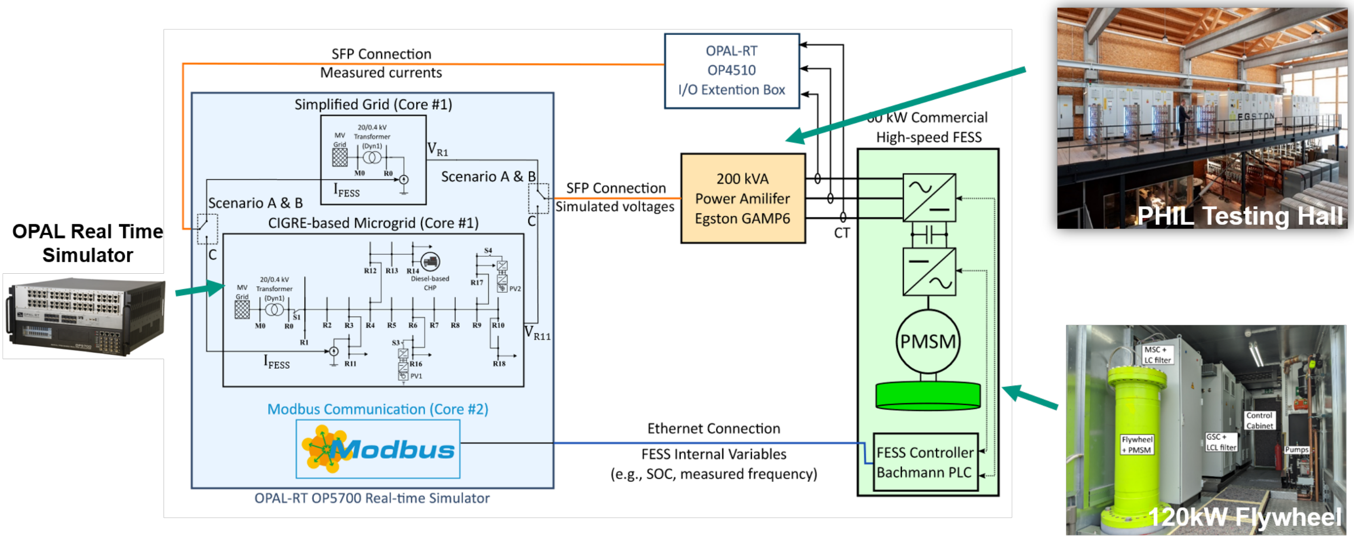

Fig. 1. Overview picture of the Power Hardware In the Loop testing setup for high speed flywheels.

A. 1 MVA PHIL facility for high-power energy technologies performance assessment

In the Energy Lab 2.0, the Institute for Technical Physics has realized a 1 MVA Power Hardware In the Loop lab (Fig.1), with the goal to assess the performance of any energy technology at the low-voltage level. In particular, the setup that we are considering in this article is the one realized for testing the performance of an high-speed flywheel.

The PHIL lab consists of:

- A digital real time simulator OPAL-RT 5700, that is in charge of simulating the electrical grid. It allows to simulated different grid conditions and adapt the grid parameters in flexible way. In this setup, two grids have been considered: a simple Thevenin equivalent, used to validate the grid codes compliance of the Flywheel; and the CIGRE microgrid [11], that allows to validate the performance of flywheel in managing a local unintentional islanding.
- 5 200kVA Egston Compiso power amplifiers, that can be connected either in parallel or in series, and in different power groups. It allows to perform testing up to 1.5 kVdc if connected in series, or up to 4.5 kA if connected in series.
- A 120 kW 7.2 kWh high-speed Stornetic Flywheel, that is able to provide fast power support to the grid, and to offer services as primary frequency regulation.

B. 15kW PHIL facility for micro-gas turbine integration

The aim of this PHIL setup is the investigation and subsequent modeling of the micro gas turbine shown in Fig. 2. To ensure that the investigations are reliable, safe and reproducible, a test facility is set up. The microturbine is the central component of the laboratory setup. The operation of the microturbine requires fuel, a power supply and a cooling system.

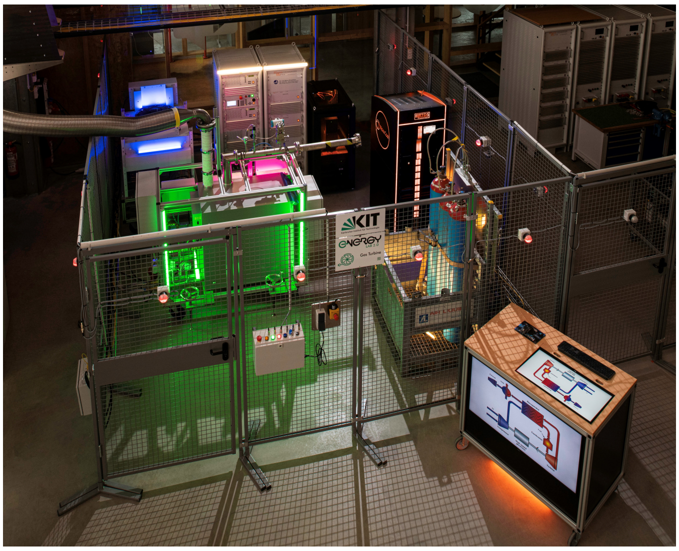

Fig. 2. Photograph of the laboratory setup with the main components and their arrangement in the test field

The laboratory setup consists of six main components. From a functional point of view, these are the microturbine, the fuel supply and the cooling system for heat dissipation. From a measurement and control perspective, the air mass measurement system, the real-time simulator, and the power amplifier are added to the system. The main components are shown schematically in Fig. 3.

The investigated micro gas turbine of the Dutch company ”Micro Turbine Technology BV” (MTT) is one of these commercial products on the market. With a thermal output (heating power) of 15.6 kW and an electrical output of 3.1 kW, the unit is designed for private households and offices. Further characteristics are listed in Table I.

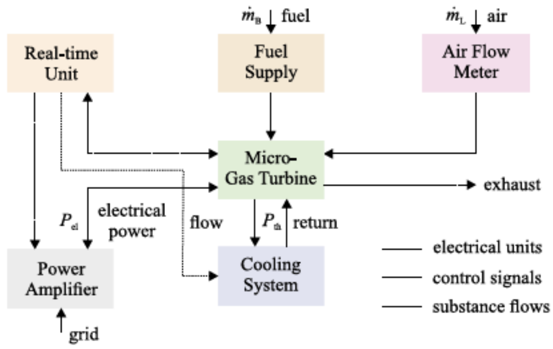

Fig. 3. Representation of the main components (with color assignment), the control signals (dotted line), the material flows (dashed line) and the electrical quantities (continuous line) in the laboratory setup

TABLE I
OVERVIEW OF THE PRIMARY CHARACTERISTICS OF THE MICROTURBINE USED (MANUFACTURER'S DATA)

Description	Value
Manufacturer/Model	Micro Turbine Technology EnerTwin
Working range thermal power	10.0 bis 15.6 kW
Electrical power range	0.9 bis 3.1 kW
Rated voltage	230 V single-phase
Mains frequency	50 Hz
Turbine speed range	3000 - 4000 rpm/s
Control of microturbine	2.5 V to 10 V (<2.5V = 'Stop')
Fuel	methane and hydrogen
Dimensions (WxHxD)	(0.6x1.1x1.1) m
Weight	215 kg

The microturbine with combined heat and power generation consists of the eight main components, compressor, turbine, combustor, heat exchanger, recuperator, water pump and generator-inverter unit. The arrangement and interaction of the components are shown schematically in Fig. 4.

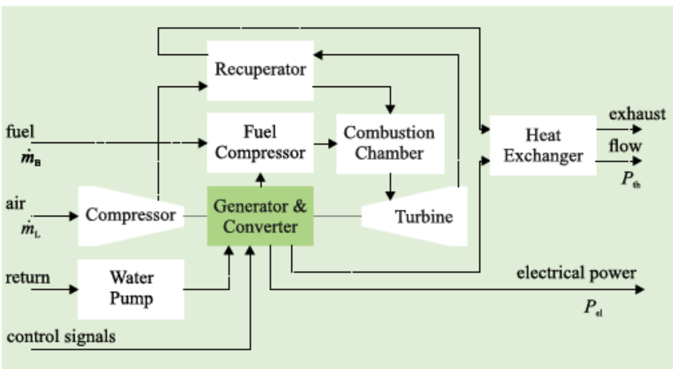

Fig. 4. Overview of the internal structure of the micro-turbine), the control signals (dotted line), the material flows (dashed line) and the electrical variables (continuous line)

The mechanical and thermal operation of the micro-turbine is described below. The combustion process is the Brayton cycle. This is characterized by four steps. In the first step, the supply air is compressed by the compressor to a higher pressure of approximately 2.8 bar. After compression, in the second step the supply air is preheated by means of a heat exchanger. The heat exchanger extracts the required heat from the turbine exhaust gas. Preheating increases the efficiency of the process. In the third step, the supply air and fuel are mixed and then ignited in the combustion chamber. The temperature in the combustion chamber is approximately 1060 K. The combustion causes the air-fuel mixture to expand. The expanding gas mixture drives the turbine at a speed of 4000 revolutions per second. This creates a mechanical torque on the turbine shaft. The turbine, the compressor and the generator are mounted on a continuous drive shaft. For this reason, the mechanical torque from the turbine is directed into the compressor and the generator. The compressor uses the torque generated by the turbine to compress the supply air. As soon as the turbine produces more torque than the compressor consumes, the generator produces electrical power. The various losses are also included in this total calculation, but are not described in detail. The exhaust gas discharge with heat transfer to the cooling circuit characterizes the fourth and final step of the Brayton cycle process. The heat from the exhaust gas is used to generate thermal power. This final step is instrumental in determining the overall efficiency of the combined heat and power system. The overall efficiency is about 90 percent. The better the heat transfer, the higher the efficiency.

Each measurement is subject to uncertainties. To evaluate the measurement results, the measurement uncertainties are determined in this work using the procedure according to "GUM" (Guide to the Expression of Uncertainty in Measurement). In this procedure, a certain range of variability with "possible values" is allowed. The aim of measurement uncertainty analysis is to quantify this variability and express it in a numerical value.

For indirect measured quantities such as electrical and thermal power, error propagation is considered. The error propagation describes the interaction of several measurement uncertainties. Further details are described in the source [Pfe98]. In the following, the error propagation is first derived for the electrical power and later for the thermal power.

Eq.1 shows the calculation of the electrical power. Eq.2 is used to calculate the uncertainty of the electric power. After the total derivative, the uncertainty is obtained from Eq.3.

$$P_{\text{el}} = U_{\text{MGT}} \cdot I_{\text{MGT}} \tag{1}$$

$$u_{\text{P,el}} = \sqrt{\left(\frac{\partial}{\partial U_{\text{MGT}}} P_{\text{el}}\right)^2 \cdot u_{\text{U}}^2 + \left(\frac{\partial}{\partial I_{\text{MGT}}} P_{\text{el}}\right)^2 \cdot u_{\text{I}}^2} \tag{2}$$

$$u_{\text{P,el}} = \sqrt{I_{\text{MGT}}^2 \cdot u_{\text{U}}^2 + U_{\text{MGT}}^2 \cdot u_{\text{I}}^2} \tag{3}$$

Analogous works the derivation of uncertainty for thermal power in Eq.4 to Eq.6.

$$P_{\text{th}} = c_{\text{KW}} \cdot \varrho_{\text{KW}} \cdot \dot{V}_{\text{KW}} \cdot (T_{\text{V}} - T_{\text{R}}) \tag{4}$$

TABLE II

OVERVIEW OF THE UNCERTAINTIES OF THE ELECTRICAL AND THERMAL PERFORMANCE OF THE MICROTURBINE AT MINIMUM AND MAXIMUM CONTROL OF THE MICROTURBINE.

Control of the microturbine	Electrical power	Thermal power
Minimum 30%	0.9 kVA +- 35 VA	10.0 kW+-275 W
Maximum 100%	3.2 kVA +- 35 VA	15.6 kW +-474 W

$$u_{\mathrm{P,th}} = \sqrt{\left(\frac{\partial}{\partial \dot{V}_{\mathrm{KW}}} P_{\mathrm{th}}\right)^2 \cdot u_{\dot{V}_{\mathrm{KW}}}^2 + \left(\frac{\partial}{\partial T_{\mathrm{V}}} P_{\mathrm{th}}\right)^2 \cdot u_{T_{\mathrm{V}}}^2 + \left(\frac{\partial}{\partial T_{\mathrm{R}}} P_{\mathrm{th}}\right)^2 \cdot u_{T_{\mathrm{R}}}^2} \tag{5}$$

$$u_{P,th} = \sqrt{c_{KW}^2 \cdot \varrho_{KW}^2 \cdot \left((T_R - T_V)^2 \cdot u_{\dot{V}_{KW}}^2 + \dot{V}_{KW} \cdot (u_{T_R}^2 + u_{T_V}^2)\right)} \tag{6}$$

To determine the uncertainty numerically, the manufacturer data from Table I are used. Table II shows the uncertainties of the outputs for the minimum and maximum outputs of the microturbine.

IV. ISLANDED HOME ENERGY PROVISION BY MICRO-GAS TURBINES

The term "Power Hardware in the Loop" refers to a methodology for linking simulation and equipment. Through the connection, the actual behavior of a device can be implemented in a simulation. A complex modeling of the equipment is thereby bypassed. This can concern the entire modeling or only parts of the modeling. In addition to saving time by eliminating the need for modeling, PHIL investigations offer the highest level of integrity. There is no better model than the real equipment. For complex systems, there may be more than one resource.

To apply the PHIL methodology, a power amplifier, measurement equipment, a real-time simulator and a workstation are used. The power amplifier and the microturbine are connected on the power side. The electrical measurement equipment is located between the power amplifier and the microturbine. It records the microturbine current and voltage. An input card with A/D converter is used to digitize the analog measured values (current and voltage). The digital measurement signal is coupled into the real-time simulator via optical fiber. Outgoing control commands from the real-time simulator are transmitted to an output card via optical fibers. The task of the output card is the digital to analog conversion of the control commands. Based on the analog control commands, the setpoint is set in the power amplifier and the microturbine. A workstation is used to control the real-time simulator and its implemented model. Fig.5 shows components of the PHIL methodology.

Two different real-time simulators are used in this work. These are simulators from the manufacturers "RTDS Technologies" and "OPAL RT Technologies". Thus, experience in

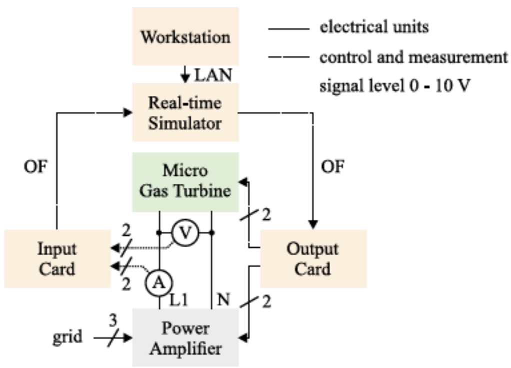

Fig. 5. Schematic representation of the power hardware in the loop components in the test setup

TABLE III

COMPARISON OF THE SIMULATORS USED WITH REGARD TO HARDWARE-RELATED PARAMETERS

Simulator type	NovaCor	OP4510
Manufacturer	RTDS	OPAL RT
Simulation Software	RSCAD FX1.2	RT-LAB 2020
CPU Cores a)	bis 10 cores	bis 4 cores
CPU Clock	3,5 GHz	3,5 GHz
CPU Type	IBM Power8	Intel CPU
Analogue input voltage	± 10 V	± 20 V
Analogue output voltage	± 10 V	± 16 V
Input voltage resolution	304 µV	488 µV
Output voltage resolution	304 µV	610 µV
Isolation	potential free	not potential free
Data acquisition	gapless	not gapless

the use of both simulators can be gained for future projects. Table III provides a tabular comparison of the simulators.

Fig.6 compares the results of the simulation and the PHIL system. The rate of change model is used as the basis here due to its low computational effort and high accuracy. In addition to the electrical power, the thermal power is also compared.

V. CONCLUSIONS

The testing of new energy technologies plays an important role in their fast introduction in the market. In order to test these resources in realistic conditions field tests can be employed, however, at high expenses and high costs. For this reason, Power Hardware In the Loop testing became a more interesting solutions in the last years. Connecting a digital real time simulated grid with the energy technology under test, offers a flexible and time-effective way to explore the performance of these technologies in realistic grid conditions.

In this work, some of the Power Hardware In the Loop capability at the Karlsruhe Institute for Technology have been described. Particular focus has been given on the 1 MVA PHIL testing setup and the micro-gas turbine test bench developed by the Institute for Technical Physics in the Energy Lab 2.0. Studies cases have been described and exemplary results have been offered in order to understand the testing capability of such labs.

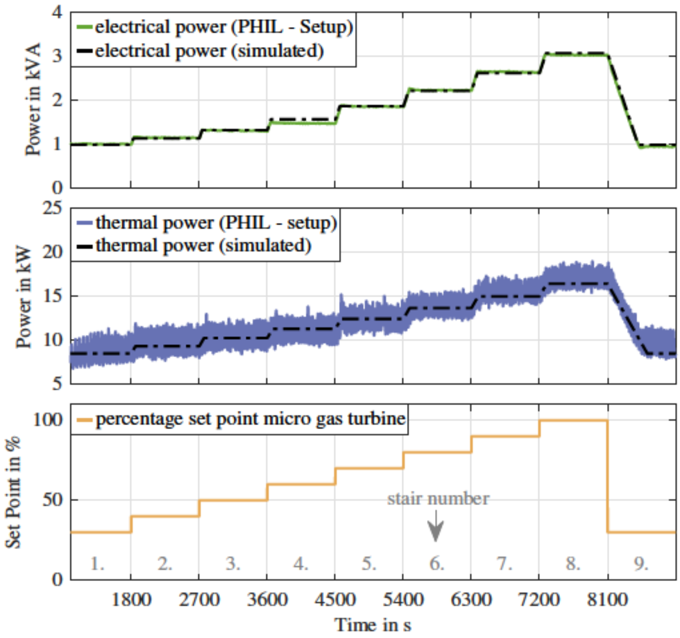

Fig. 6. Schematic representation of the power hardware in the loop components in the test setup

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