European Research Infrastructure supporting Smart Grid and Smart Energy Systems Research, Technology Development, Validation and Roll Out – Second Edition

Project Acronym: **ERIGrid 2.0**

Project Number: **870620**

Technical Report Lab Access User Project

Resilience-oriented Microgrid Control and Protection (resiMG)

Access Duration: 20/09/2021 to 01/10/2021

Funding Instrument:	Research and Innovation Action
Call:	H2020-INFRAIA-2019-1
Call Topic:	INFRAIA-01-2018-2019 Integrating Activities for Advanced Communities
Project Start:	1 April 2020
Project Duration:	54 months
User Group Leader:	Athanasios Krontiris (Hochschule Darmstadt)

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 870620.

Report Information

Document Administrative Information	
Project Acronym:	ERIGrid 2.0
Project Number:	870620
Access Project Number:	02.124-2021
Access Project Acronym:	resiMG
Access Project Name:	Resilience-oriented Microgrid Control and Protection
User Group Leader:	Athanasios Krontiris (Hochschule Darmstadt)
Document Identifier:	ERIGrid2-Report-Lab-Access-User-Project-AccessProjectAcronym-draft-vn.n
Report Version:	2.0
Contractual Date:	21/09/2021
Report Submission Date:	28/02/2022
Lead Author(s):	Athanasios Krontiris (h_da)
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Keywords:	microgrid, protection, islanding detection, European Union (EU), H2020, Project, ERIGrid 2.0, GA 870620
Status:	final

Change Log

Date	Version	Author/Editor	Summary of Changes Made
23/02/2022	v1.0	Athanasios Krontiris (h_da), Ingo Jeromin	Draft report
18/04/2022	v2.0	Athanasios Krontiris, Ingo Jeromin, Alkistis Kontou, Dimitris Lagos	Hosting institute review. No major changes needed.

Table of Contents

List of Figures

List of Abbreviations

BYOD	Bring Your Own Device
CO	Project Coordinator
CHIL	Control Hardware in the Loop [test]
DG	Distributed Generation
EC	European Commission
HIL	Hardware in the Loop [test]
LA	Lab Access
NTUA	National Technical University of Athens (host facility)
PHIL	Power Hardware in the Loop [test]
RTDS	Real-Time Digital Simulation
ROCOF	Rate of Change of Frequency
RSCAD	Development software for the RTDS simulator (trademark)
SCADA	Supervisory Control and Data Acquisition
SLD	Single-Line Diagram
UG	User Group
UP	User Project

Executive Summary

The lab-access user project “Resilience-oriented Microgrid Control and Protection” (resiMG) was conducted at the host lab of National Technical University of Athens (NTUA) in the time period 21/09/2021 to 01/10/2021.

The resiMG project investigated the potential for increasing the resilience of electricity distribution grids by implementing small energy cells in the form of microgrids, which can be disconnected from the main grid in the event of a severe upstream fault, sustain island operation for the duration of the fault, and be resynchronized and reconnected after the fault is cleared. Aspects related to the design of a microgrid for stability, the requirements for protection as well as practical questions for the design of a low-voltage laboratory-scale microgrid were investigated during the lab access. Tests included:

1. Solar inverter in PHIL
2. Controller integration into SCADA of the lab microgrid
3. Island detection in CHIL
4. Protection blinding in CHIL

The user group from Hochschule Darmstadt is currently building up a low-voltage smart grid laboratory for the “Smart Grid Lab Hessen” project (SGL Hessen). SGL Hessen is a project funded by EU structural funds with the primary objective to investigate practical issues commonly perceived by distribution system operators as hurdles to the successful establishment of smart grid technologies. General learnings from the resiMG project have been very useful for our upcoming research in SGL Hessen. We could gain investigate most of the envisaged research questions, reproduce cases reported by other researchers in the lab, gain hands-on experience with the laboratory equipment and identify best practices for the design and operation of a lab-scale low-voltage microgrid. In summary, we can confirm that our main objectives could be reached, not at least due to the excellent support we received by the scientific and technical personnel of the host lab at NTUA.

1 Lab-Access User Project Information

1.1 Overview

The lab-access user project “Resilience-oriented Microgrid Control and Protection” (resiMG) was conducted at the host lab of National Technical University of Athens (NTUA) in the time period 21/09/2021 to 01/10/2021. The User Group consisted of two visitors (Athanasios Krontiris and Ingo Jeromin, both from Hochschule Darmstadt) and was assisted by the scientific personnel of the host lab (Alkistis Kontou and Dimitrios Lagos) during the 8 access days.

1.2 Research Motivation, Objectives, and Scope

The resiMG project investigated the potential for increasing the resilience of electricity distribution grids by implementing small energy cells in the form of microgrids, which can be disconnected from the main grid in the event of a severe upstream fault, sustain island operation for the duration of the fault, and be resynchronized and reconnected after the fault is cleared.

The overall goal is threefold: (i) understand the impact of structural features of the microgrid (generation and load characteristics, grid topology and power flow contraints), (ii) develop a protection scheme which can identify upstream faults before the propagate into the microgrid, and (iii) investigate the influence of microgrid high-level controls as well as inverter low-level controls on the stability of the microgrid with special focus on the transition process between interconnected and island operating mode following an upstream fault.

More in detail, the addressed scenario is a smart microgrid including an Energy Storage System (ESS), photovoltaic generators, and loads representing residential, industrial, and commercial profiles. The mentioned microgrid is connected to the main distribution grid through a Point of Common Coupling (PCC). A grid simulator at the PCC allows for the simulation of different fault cases.

The proposed approach opens an opportunity for producers, consumers and aggregators to participate in future advanced demand-side management markets and, interestingly, in markets for system restoration services. It may also open up additional revenue streams for distribution grid operators to finance the required hardware and control and protection equipment for microgrid deployment. For system operators it offers a new approach to cope with the challenge of increasing dispersed generation during system restoration.

1.3 Structure of the Document

This document is organised as follows: Section 2 briefly outlines the state-of-the-art/state-of-technology that provides the basis of the realised Lab Access (LA) User Project (UP). Section 3 briefly outlines the performed experiments whereas Section 4 summarises the results and conclusions. Potential open issues and suggestions for improvements are discussed in Section 5.

2 State-of-the-Art/State-of-Technology

The increase in the cost of energy produced with conventional fossil fuels, not to mention the growing concern for the environmental problems related with their usage, has fostered the interest in alternative energy sources, such as Renewable Energy Sources (RES). Besides being cleaner, these energy sources can often be placed in the vicinity of the end users, thus reducing the energy losses related to electricity transmission. This entails a radical change in the structure of the energy system, where the electricity network includes many small and distributed generators, as opposed to few large generators.

Electricity generation from highly volatile renewable sources such as wind and sun has to synchronized with demand and transported from the place of generation to the place of demand. With regards to future challenges in electricity distribution grids with high share of renewable generation, the main challenges are [1,2]:

- Decentralized renewable energies and new electrical applications such as electric vehicles and heat pumps will lead to high feed-in and withdrawal powers in electrical grids in the future.
- These outputs are very expensive to manage with existing grid construction and operation principles.
- The addition of active components and data-based control algorithms (smart grids) to the existing passive grid infrastructure can significantly increase the existing grid capacity.
- The new sources and sinks represent a highly non-linear load for grids. For example, power peaks with 5% energy content occupy 50% of the grid capacity. Thus, the timing of these peaks is key to increasing capacity.
- Violations of the voltage band are the most common consequence of the discussed grid peaks.
- In principle, control algorithms and concepts for smart grids exist and a number of technical practical tests are being carried out.

One solution proposed to cope with these challenges is the use of cellular energy systems, which try to balance generation and demand locally in a subsidiary manner [3]. The generation and consumption of energy is balanced at the lowest level in small-scale "energy cells". Here, energy is generated and directly consumed again without being fed into the overall grid. After all, the most efficient solution is to consume the electricity where it is generated: at the local supply level. The concept also offers attractive economic prospects, especially with a view to developing new business models and markets. Clearly defined energy cell interfaces mean that the operation of energy cells, as well as the selection of technology and its installation, can be offered on the market by new service providers or even investors. In addition, private individuals can market their energy storage as a buffer if they wish to do so.

From a technical perspective, the so-called "energy cells" are interconnected by energy networks and communication systems and form superordinate larger energy cells with specific interfaces and characteristics. The grouping of energy cells takes place over several levels and the cellular approach is applicable to both small and larger units and systems. A complete energy cell consists of the components generator, converter, storage, grid connection, loads, and protection and control equipment. Although the energy cells comprise all energy sectors (electricity, gas and heating) [4] the backbone is the electricity distribution grid, starting from the low-voltage level in the range of tenths of kW and extending to the medium-voltage level in the range of tenths or hundreds of MW.

The local aspect of power demand and supply is represented by the internal structure of the energy cells. For this purpose, the network structure within the cells must be designed flexibly, since the utilization of the power capacities is extremely nonlinear. Rare power peaks occupy significant portions of the available line capacities without significantly supporting the energy transmission. To improve this situation, intelligent networks - smart grids - must be established. These recognize power peaks as they occur. They use grid- and customer-related flexibilities autonomously and can thus actively and flexibly control these peaks. This eliminates the need to design grids statically for maximum power. The energy transmitted by the primary network infrastructure - cables, lines, transformers - increases significantly as a result. This is not only a technical issue in terms of the functioning interaction of various active and passive components. Aspects of data security, standardization, communication, certification, personal safety and, last but not least, the appropriate further development of the regulatory framework also play a central role here [5].

One important operational advantage of an energy system designed based on energy cells is that - in case of contingencies in the overlaying network - the cells can fall back into island operation. This significantly increases the overall *resilience* of the systems and the reliability and availability as seen by the end consumer [6,7]. The precondition in order to achieve the stated increase in resilience are:

- Energy management in the microgrid for the (potentially limited in time) island operation [8,9]: sufficient generation/demand structure, market mechanisms to allow for real-time power balancing and control and protection schemes to avoid overproduction / overconsumption.
- Reliable identification and localization of fault conditions in the overlaying grid and separation of the microgrid before the fault propagates downstream [10].
- Transition to a stable operation of the microgrid for the time needed to clear the fault in the overlaying grid: the absence of larger, synchronous generating units in the microgrid means that many static inverters need to operate in parallel and control voltage and frequency. Many solutions have been proposed for this problem and implemented e.g. in board electrification systems. Recently, grid forming control is also being deployed in PV and wind energy generating units [11]. However, the transition from interconnected operation under fault conditions to island operation adds additional challenges in terms of dynamic behaviour, control stability (absence of reference voltage during the disturbance) and grid impedance characteristics [12-14].
- Stable transition from islanded to interconnected operation: A big challenge for power system resilience nowadays is that transmission system operators, responsible for the restoration procedures after major outages, has no information about the availability of, nor can they directly control dispersed generation units in the distribution grid [15,16]. The topic has been addressed in Europe since 2017 with the Network Code on electricity emergency and restoration [17], but obviously the ideal solution would be that generation and load are already balanced at the lowest possible voltage level before reconnecting islanded subsystems with each other. Thereby, individual cells can support network restoration procedures by balancing generation and demand at the lowest level [18-20].

3 Executed Tests and Experiments

3.1 Test Plan, Standards, Procedures, and Methodology

3.1.1 Initial design of the test plan

The goal of this project work is to analyse aspects of power system resilience and the potential for enhancing resilience by employing microgrids and energy cells as discussed in the previous section. When proposing the lab access project, following research questions have been formulated (compare project proposal):

- *Research Question 1*: How must a microgrid be designed so that it can safely fall back into island operation e.g. in the event of a major disturbance in the overlaying grid? This question relates on structural characteristics of the microgrid, namely (i) the capacity of controlled and volatile generation as well as storage units compared to controllable and base load, as well as (ii) the topology of the low-voltage grid.
- *Research Question 2*: What are the requirements on protection to allow for a reliable transition of a microgrid between grid-interconnected and island operation? Transition of the microgrid from interconnected operation to island operation following a fault in the overlaying grid needs to happen fast enough, so that the fault does not propagate into the microgrid. On the other hand, as with any other protection, fault identification must be selective, secure and dependable. But also during re-synchronisation, the protection system must ensure that all necessary preconditions (voltage magnitude and angle, frequency) are met before the main switch is operated.
- *Research Question 3*: What are the requirements on control, especially for non-synchronous dispersed generation units, to allow for a robust transition of a microgrid between grid-interconnected and island operation? During the transition from interconnected operation to island operation and vice versa, the grid impedance as seen by the converters in the microgrid change drastically. In addition, if the overlaying grid has been faulty before islanding, there is also a dynamic change of the grid impedance even before islanding. Such changes are challenging for the stable control of inverters, since the control loops (commonly using phase-locked loops) need to be stable over a large bandwidth. During island operation voltage and frequency control is ensured by inverters in the microgrid; at least some of them need to be grid forming. To reach settling, some kind of droop control is also necessary. Before reconnection, the microgrid needs to be synchronized with the overlaying grid; for this purpose, the set-point of several inverters needs to be adjusted in a coordinated manner.

Based on the available time during the access period and the capabilities of the host lab, four work packages / tests were designed along abovementioned research questions:

1. Solar inverter in PHIL
2. Controller integration into SCADA
3. Island detection in CHIL
4. Protection blinding in CHIL

In the following subsections the applied test plan, used standards and procedures as well as the corresponding methodology are given for each test.

3.1.2 Solar inverter in PHIL

In recent years, distribution networks have been increasingly integrating Dispersed Generation (DG) units, often from renewable energy sources, which pose new challenges for system operation. In order for DG to replace conventional production units, they must be actively involved in the operation of the system by providing ancillary services, i.e. by contributing to voltage regulation, frequency regulation, etc.

In this test, the capability of a solar inverter to provide frequency control during sudden load changes as well to assist in voltage support during fault conditions has been investigated. The functions under investigation were:

- temporary provision of additional active power during a load step increase,
- the inverter's ability to remain in operation and provide short-circuit current during a fault on the AC side as well as to re-synchronize after the fault was cleared.

Purpose of the investigation was to characterize the inverter's response during the tests (additional active power and short-circuit current waveform) and compare it to typical grid code requirements. Comparison was made based on visual waveform assessment.

3.1.3 Controller integration into SCADA

One objective of the lab access project has been to gain hands-on experience in line with ongoing research at daFNE Lab at Hochschule Darmstadt. Currently at daFNE a low-voltage smart grid laboratory is being built for the “Smart Grid Lab Hes-sen” project (SGL Hessen). SGL Hessen is a project funded by EU structural funds with the primary objective to investigate practical issues commonly perceived by distribution system operators as hurdles to the successful establishment of smart grid technologies. The project would therefore like to provide a "proof of concept" utilizing equipment from several manufacturers, communicating with its other in an interoperable way via various protocols.

For this purpose, the second test focusses in the integration of a commercial controller used in LV network automation into the host lab's SCADA system.

3.1.4 Island detection in CHIL

Detecting islanded network conditions is important for various reasons. Typically, grid codes require DG units to disconnect from the grid if the network or feeder to which they are connected is tripped. On the other hand, grid-forming converters may be able to continue operation even if islanded, but may need to adjust their control scheme or parameters upon islanding.

Although island detection algorithms are already implemented in DG nowadays, details of algorithms are proprietary. In this test, a custom island detection algorithm based on abnormal voltage and frequency protection as well as ROCOF protection (29, 57, 81) should be implemented and tested in a Controller Hardware in the Loop (CHIL) simulation environment. Unintentional islanding should be triggered manually in HIL, and the correct detection and breaker trip order from protection controller be monitored in real-time using a scope in the protection design environment.

3.1.5 Protection blinding in CHIL

Due to the increasing feed-in of DG in the last years, the demands on grid operators for secure and stable grid operation are also increasing. The power grids where originally planned and built up as top-down grids. Now, new problems, especially in the area of protective devices, such as blinding of feeder overcurrent (OC) protection occur mainly due to the feeders of decentralised generation facilities into the low-voltage grid levels.

In order to understand the effects of distributed, decentralised generation systems on the protection devices installed in the grid, methods such as HIL simulation have become established in recent years. Here, hardware devices are tested in a simulation environment. Thus, real devices can be tested in a safe environment under conditions that are almost identical to real operating conditions due to the simulation environment. The effects of the network and the effects of the hardware influence each other, which means that errors and phenomena can be detected at an early stage that would have remained undetected by pure simulations.

The aim of the experiment is to simulate the effects of DGs on a protective device and to simulate the blinding effect. Blinding is the effect of attenuation of the fault current at the measuring point of the protective device. Classically, power grids have been designed and built vertically, with large central generation facilities. Based on this top-down approach, in low and medium voltage feeders were usually only protected against overload and short circuit at their start. In the case, there is a decentralized power supply between the fault location and the measuring location of the protective device, it will not be detected by the protective device due to its contribution to the fault current.

In this test, the capability of a feeder protection relay to identify a downstream fault based on overcurrent is investigated. The implemented protection settings for a sample feeder configuration were verified for different operating points of the DG connected downstream in the feeder as well as for different strength (short-circuit capacity) of the upstream grid. Upon manual fault inception, signals from HIL simulator and from the protection relay web interface were captured and the tripping time of protective relay has been documented. The test was designed in close alignment with reference [21].

3.2 Test Set-ups

3.2.1 Solar inverter in PHIL

The Object under Investigation was a single-phase solar inverter (Figure 1a). The inverter was connected on its DC side to a PV simulator (Figure 1b), featuring maximum power point (MPP) tracking. The AC side was connected to a linear amplifier which was driven by an RTDS simulator (Figure 1c).

(a) (b) (c)

Figure 1: Hardware used for the test. (a) solar inverter, (b) PV simulator, (c) RTDS control unit.

The test was carried out as a PHIL simulation. For the first function under test (frequency control), parallel operation of the solar inverter with a synchronous generator is assumed. Since the object under test was a single-phase inverter, while the simulated generator in RTDS was a three-phase synchronous machine, it is necessary to read the terminal current of the inverter and artificially model the inverter in the two other phases. The SLD as used in RSCAD is shown in Figure 2 below.

For the first test sequence, a dual load step was applied: an additional load was connected for 150 ms and then disconnected again. The expected system response is therefore an approximately linear decrease of frequency (inertial response), followed by a recovery of frequency potentially with an overshoot (primary response). Two cases were studied for the inverter control: i) only primary P/f control, or ii) additional provision of synthetic inertia.

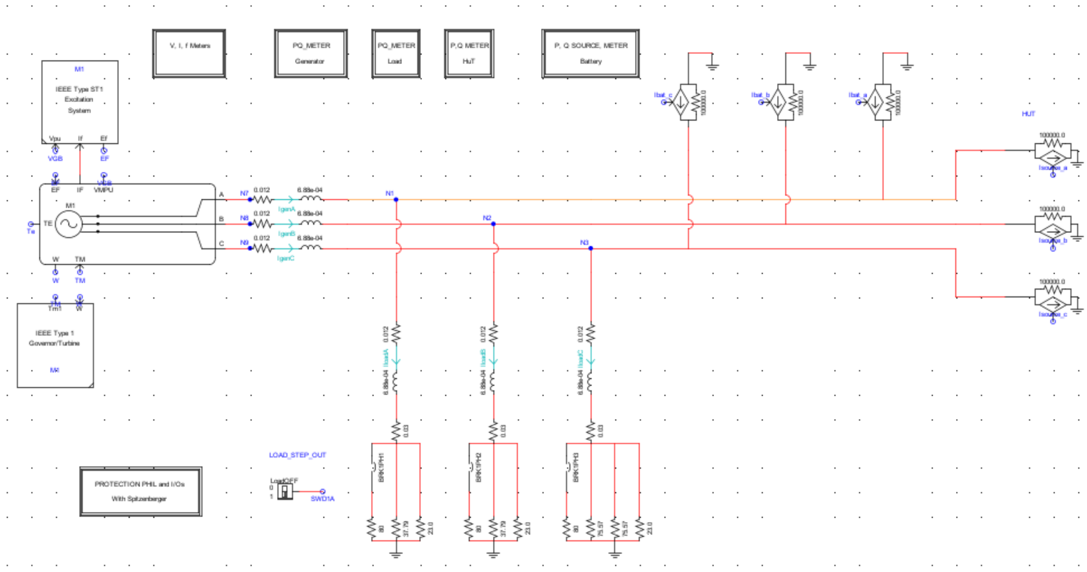


Figure 2: SLD of system under test for frequency control.

The second test sequence was used to study the short-circuit current contribution of the inverter during a fault on its a.c. terminals. The SLD of the model in RTDS is shown in Figure 3. The a.c. network is modelled as a fixed-frequency source behind an impedance, the additional load is used in order to vary the pre-fault operating point of the inverter.

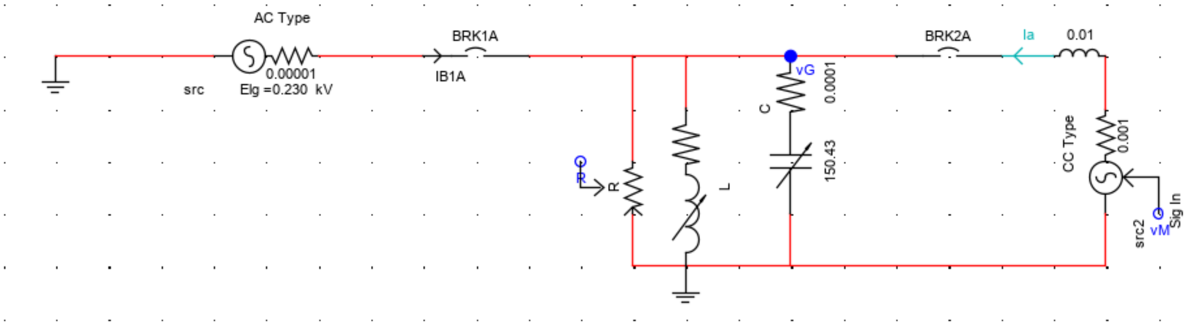


Figure 3: SLD of system under test for fault current contribution.

3.2.2 Controller integration into SCADA

In the host lab a single phase microgrid is available comprising a PV generator, a small Wind Turbine, battery energy storage, controllable loads and a controlled interconnection to the local LV grid (Figure 4). The battery unit, the PV generator 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 SCADA system used to operate the microgrid in the lab is a general-purpose commercial system (Schneider IGSS 15.03). All secondary equipment is connected to a lab-wide LAN using TCP/IP protocol.

Figure 4: Low-voltage microgrid in the host lab.

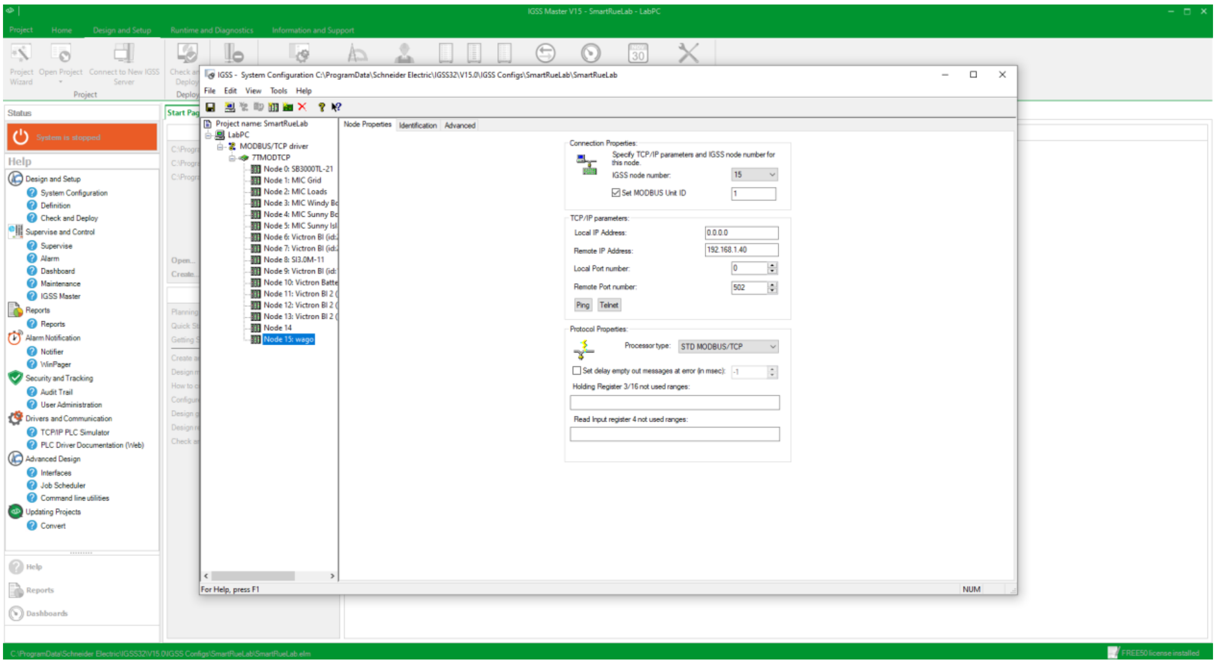
The objective of the test has been to check the integration and connectivity of a Bring-your-own-device (BYOD) controller into the SCADA system. The controller is a PFC 200 from WAGO (Figure 5). The hardware integrated into the lab comprised one digital I/O card and four analogue I/O cards.

Figure 5: WAGO PFC 200 controller to be integrated into the lab SCADA system.

The test was performed in two stages:

- Initially the secondary integration was performed using primary signals created from a simple load circuit (incandescent and energy-saving fluorescent light bulb) connected to the LV distribution in the lab office. In addition, a switch was used to provide input signals for the digital I/O. The controller was connected to the SCADA system via Modbus/TCP protocol. The controller was added as new node (Figure 6 shows the node definition and atom mapping). The test was passed when the signals are depicted in the correct order in the SCADA overview diagrams. Verification of the measurements was done by comparison of the values (voltage, current, power, frequency) shown in the SCADA with the values in the web browser interface of the device. The second TCP/IP port of the device was used to obtain the latter.

- After primary verification, the controller was integrated into the LV distribution of the lab, obtaining voltage and current measurements of the feeder to the PV inverter. The measurements when cross-compared to the already installed measurement units. Due to the physical arrangement in the lab, it has been easier to provide external connections using a current clamp.



IGSS - System Configuration C:\ProgramData\Schneider Electric\IGSS32\V15.0\IGSS Configs\SmartRueLab\SmartRueLab

Project name: SmartRueLab
- LabPC
  - MODBUS/TCP driver
    - 7TMODTCP
      - Node 0: SB3000TL-21
      - Node 1: MIC Grid
      - Node 2: MIC Loads
      - Node 3: MIC Windy Bo
      - Node 4: MIC Sunny Bo
      - Node 5: MIC Sunny Isl
      - Node 6: Victron BI (id:
      - Node 7: Victron BI (id:
      - Node 8: SI3.0M-11
      - Node 9: Victron BI (id:
      - Node 10: Victron Batte
      - Node 11: Victron BI 2 (
      - Node 12: Victron BI 2 (
      - Node 13: Victron BI 2 (
      - Node 14
      - Node 15: wago

Connection Properties:
Specify TCP/IP parameters and IGSS node number for this node.
IGSS node number: 15
☑ Set MODBUS Unit ID 1

TCP/IP parameters:
Local IP Address: 0.0.0.0
Remote IP Address: 192.168.1.40
Local Port number: 0
Remote Port number: 502

Protocol Properties:
Processor type: STD MODBUS/TCP
☐ Set delay empty out messages at error (in msec): -1
Holding Register 3/16 not used ranges:
Read Input register 4 not used ranges:

Figure 6: Node definition and atom mapping of the BYOD controller in the lab SCADA system.

3.2.3 Island detection in CHIL

The simulation of the microgrid was carried out in the laboratory using the existing RTDS simulator. The protection logic was designed in MATLAB and loaded on a controller by Tri-phase. The communication between the two systems is achieved through analog and digital signals (Figure 7). The test setup is therefore a CHIL simulation environment.

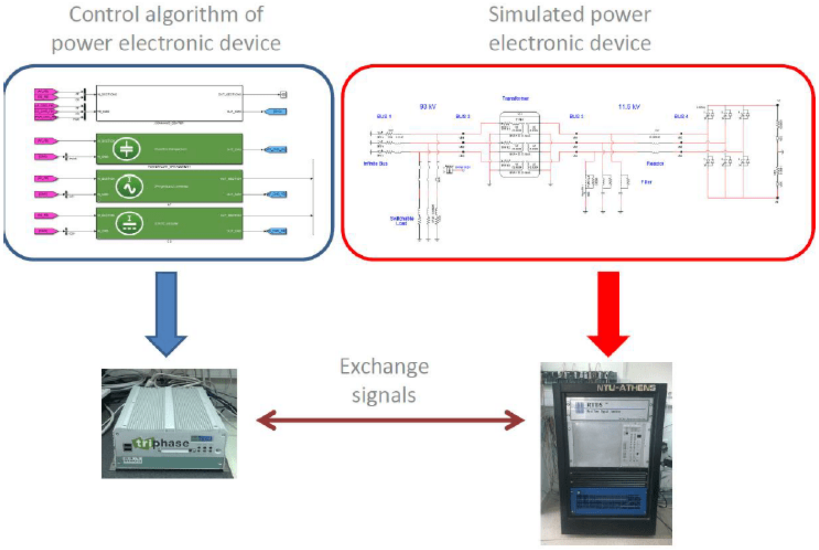


Figure 7: CHIL simulation environment for islanding protection [host lab website].

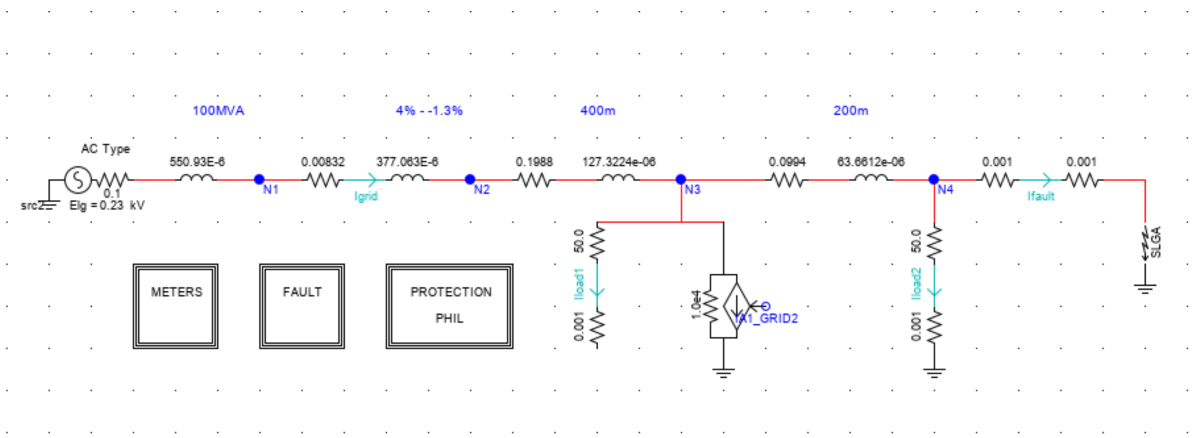


Figure 8: Single-phase feeder for islanding detection.

The test was initially designed in two stages: In a first stage, the integration of the protection design software environment (MATLAB) with the controller hardware and the RTDS simulator should be operationally verified. For this purpose, the single-phase network shown in Figure 8 was simulated in the RTDS simulation environment. A benchmark case already available at the host lab eased this task significantly. A simple protection logic was implemented in MatLab (Figure 9) and transferred to the Triphase controller via Beckhoff I/O fieldbus components. The Triphase controller was then connected to the RTDS.

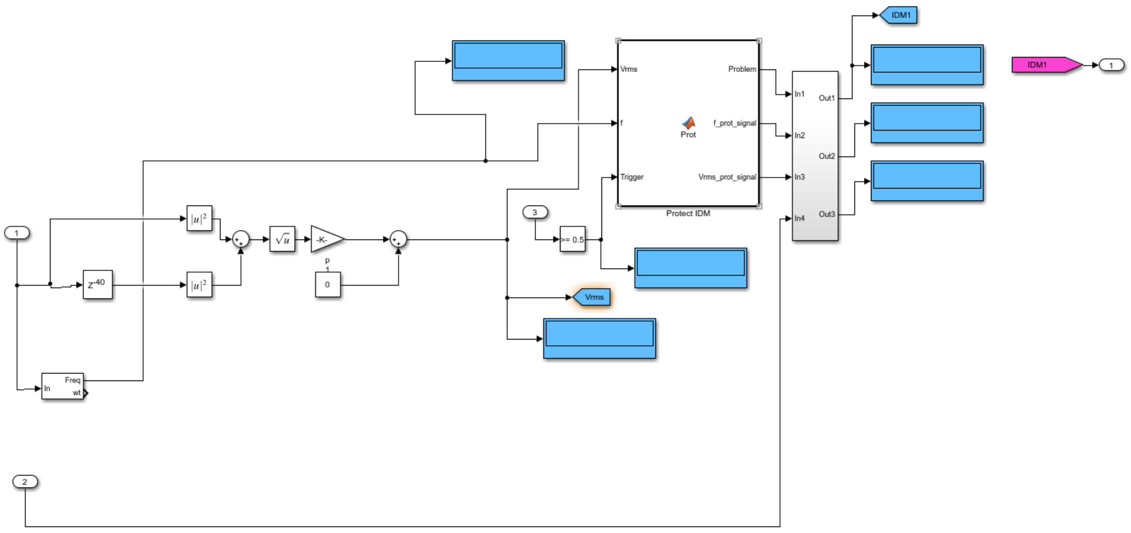


Figure 9: Overview block diagram of the interface for the islanding protection logic (single-phase case).

In a second stage, a three-phase grid should be developed to simulate the behaviour in typical distribution grids. The plan was to use this network, integrate the custom protection logic, and test the protection logic and the behaviour of grid-forming converters in the event of islanding. Contrary to our expectations, this task proved to be significantly more difficult than initially estimated. The library of the RTDS simulator contained many components, but no inverter with islanding capability that was fundamental to our research question. This meant that the example grid could not be simulated using standard components.

The inverters available in the library are normal grid-connected inverters. In the event of a failure of the upstream grid, they stop operating due to the loss of the grid frequency, which serves as their reference variable, and are therefore not suitable for solving the research question. For the islanding of the microgrid, the inverters must therefore stabilise themselves independently when the grid frequency is lost and synchronise with the grid later when the grid is rebuilt. The development of grid-forming converter thus became one of the main tasks of this part of the research, which was not anticipated in advance. The grid could be implemented using RSCAD and the control of the protection logic using MatLab. However, creating and verifying the grid-forming converter model in RSCAD turned out to be a problem that could not be solved in the available time.

3.2.4 Protection blinding in CHIL

In order to analyse the effects of the blinding effect described in 3.1.5 on a protection relay, a feeder protection relay from Schweitzer Engineering Laboratories (SEL 751, Figure 10) was connected to the RTDS simulator through analogue and digital signals (Figure 1c). The relay is programmed to protect a feeder of the electrical network and receive voltage and current signals from the RTDS. It also controls the status of the simulated breaker in the RTDS while its condition is fed back to the relay.

The electrical networks are designed and studied in RTDS. Using the network set up in RSCAD from Figure 11, the relay was first tested for the case of a three-pole short circuit at node N6 without the feed-in of DG. In a second step, a current-controlled source representing the DG is introduced into the grid at node N2. Again, a three-pole short circuit was performed and the behaviour of the protective relay was analysed.

(a) (b)

Figure 10: Protective relay used for the test, (a) front plane, (b) back plane showing direct connection of voltage and current signals.

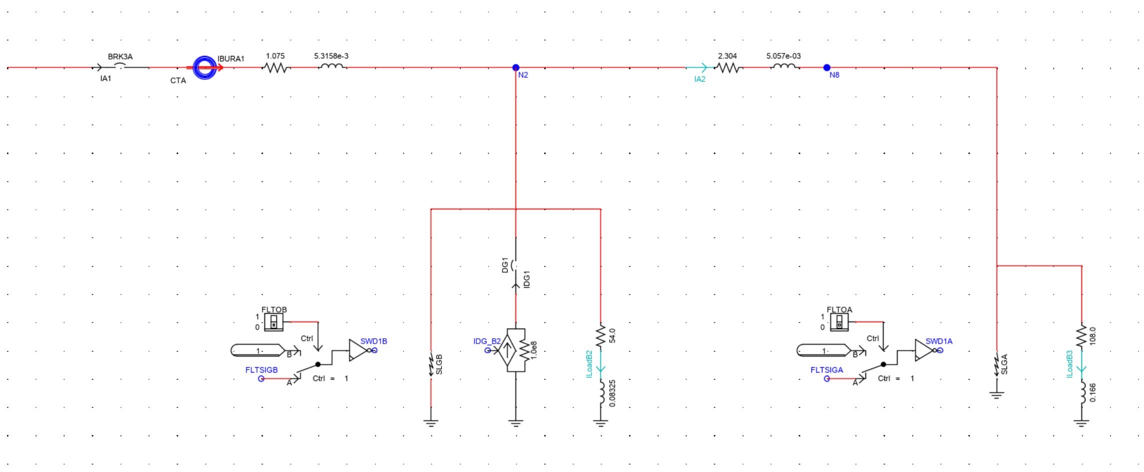


Figure 11: SLD of feeder used for protective blinding test.

3.3 Data Management and Processing

As can be seen from the sections above, the test plan consisted of several small-scale tests with the objective to gain hands-on experience on the equipment and highlight questions for further investigation. In addition, the time duration of the lab access was not design with the aim of running extensive tests and, thus, generating lots of data.

Data management and processing did not represent any challenge during the lab access project. Data was stored locally on the personal computers of the user group members and processed using MATLAB and MS Excel.

4 Results and Conclusions

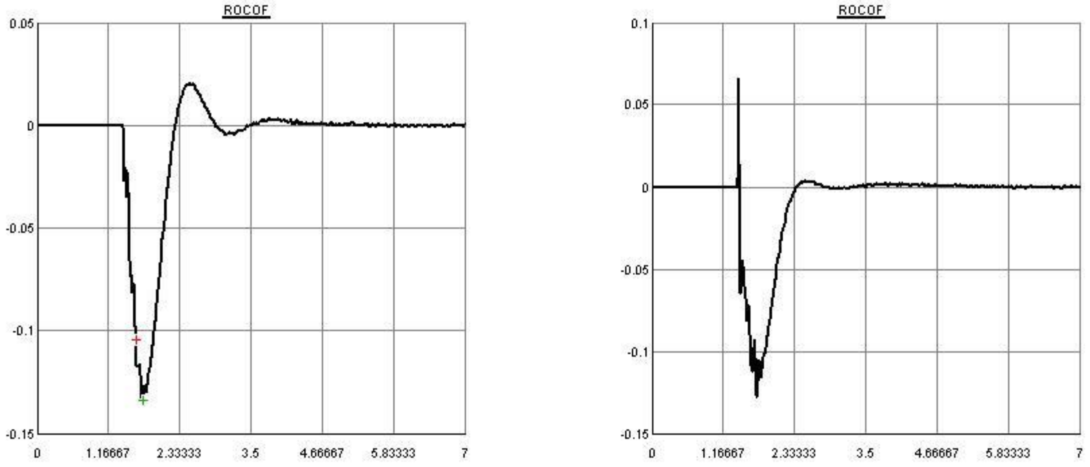
4.1 Discussion of Results

4.1.1 Solar inverter in PHIL

In the first test the response of system frequency was studied. Figure 12 shows the results for (a) de-activated and (b) activated synthetic inertia control. Figure 13 shows a close-up in the initial inertial response at load step increase. The results were largely as expected and indicate:

- Synthetic inertia no only reduces the rate of change of frequency (ROCOF) but also reduces the overshoot during primary frequency control.
- For the same duration and magnitude of the disturbance, lower ROCOF results in small maximum frequency deviation.

However, it was observed that for the case of activated synthetic inertia control (Figure 12b), the measured frequency signal was more “noisy”. Since the measurement is fed into the inertia control loop, it is important to reduce the noise to avoid possible control instability. During the test, the washout constant for frequency measurement was varied and the effect was analysed.



(a) (b)

Figure 12: System frequency for different control options:
(a) w/o synthetic inertia, (b) with synthetic intertia.

In the second test, a fault of variable duration was applied at the a.c. terminal of the inverter. The fault-through behaviour of the inverter was at large in accordance with grid code requirements (VDE AN 4105).

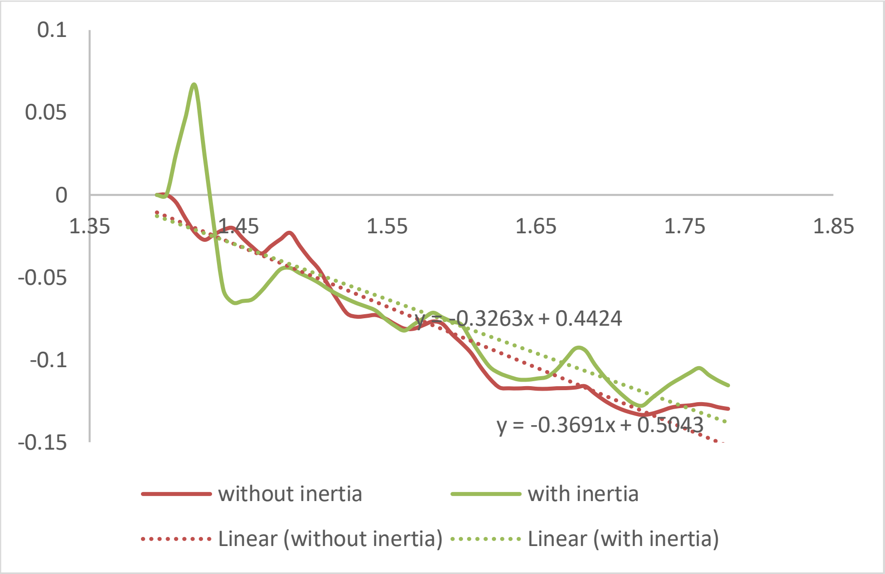
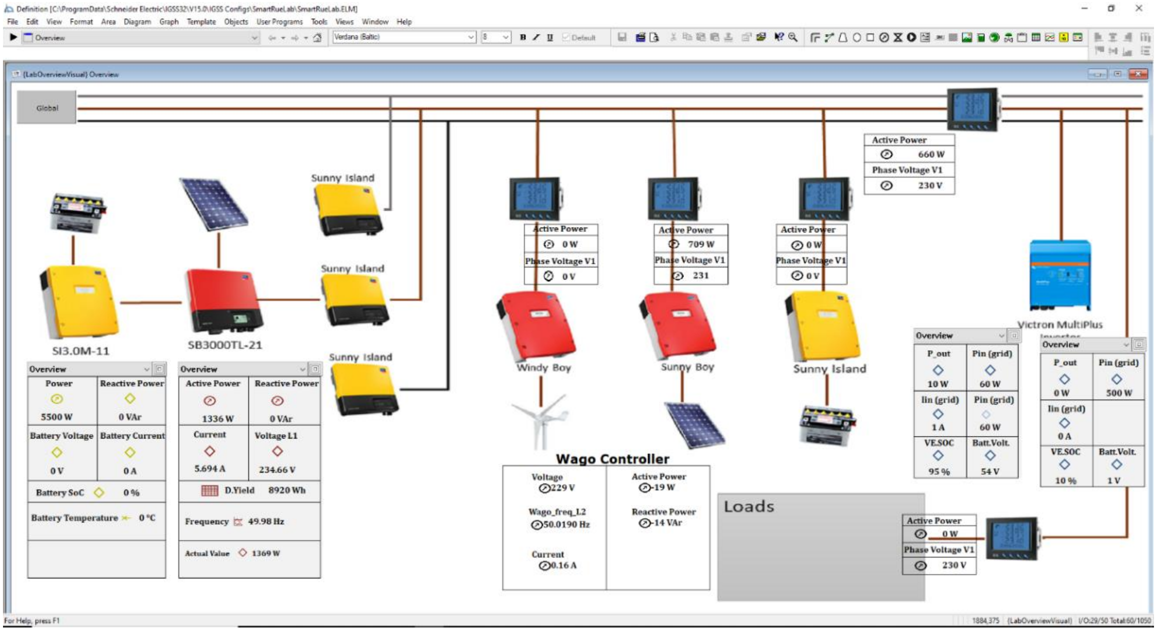


Figure 13: Comparison of ROCOF for different control options.

4.1.2 Controller integration into SCADA

Integration of the BYOD controller has been straightforward, although the user group members had no prior knowledge of the SCADA system used in the lab. Due to the physical arrangement in the microgrid distribution panel, it has been easier to connect the controller externally using current measuring clamps instead of the built-in current transformers. Nevertheless, differences in current measurement were negligible.

The controller output has not been used to drive any switches in the distribution panel, although this would have been possible. The group members considered the proof of concept to be sufficient and decided to focus on the other tests instead.



Power 5500 W
Reactive Power 0 VAr
Battery Voltage 0 V
Battery Current 0 A
Battery SoC 0 %
Battery Temperature 0 °C

Active Power 1336 W
Reactive Power 0 VAr
Current 5.694 A
Voltage L1 234.66 V
D.Yield 8920 Wh
Frequency 49.98 Hz
Actual Value 1369 W

Active Power 0 W
Phase Voltage V1 0 V

Active Power 709 W
Phase Voltage V1 231

Active Power 0 W
Phase Voltage V1 0 V

Active Power 660 W
Phase Voltage V1 230 V

Voltage 229 V
Wago_freq_L2 50.0190 Hz
Current 0.16 A
Active Power -19 W
Reactive Power -14 VAr

P_out 10 W
Pin (grid) 60 W
Iin (grid) 1 A
Pin (grid) 60 W
VE.SOC 95 %
Batt.Volt. 54 V

P_out 0 W
Pin (grid) 500 W
Iin (grid) 0 A
VE.SOC 10 %
Batt.Volt. 1 V

Active Power 0 W
Phase Voltage V1 230 V

1884,375 (LabOverviewVisual) I/O:29/50 Total:60/1050

Figure 14: Measurements from the BYOD controller shown in the lab SCADA overview diagram (first test phase).

4.1.3 Island detection in CHIL

Due to the challenges related to modelling a feeder/network with grid-forming converters described in section 3.2.3 above, this test had to be aborted. Nevertheless, the experience gained during the process is of decisive importance for us, especially for the planned laboratory "SmartGrid Lab Hessen", as this means that significantly more time must be allocated to such issues in field application.

4.1.4 Protection blinding in CHIL

The impact of DG on feeder overcurrent protection has been analysed. For high short-circuit current contribution from the DG unit and/or high line impedance in the part of the feeder downstream from the DG to the fault location, protective blinding could be observed. Moreover, the sensitivity analysis reported in reference [21] has been reproduced.

4.2 Conclusions

General learnings from the resiMG project have been very useful for our upcoming research in the laboratory "SmartGrid Lab Hessen". We could gain investigate most of the envisaged research questions, reproduce cases reported by other researchers in the lab, gain hands-on experience with the laboratory equipment and identify best practices for the design and operation of a lab-scale low-voltage microgrid. In summary, we can confirm that our main objectives could be reached, not at least due to the excellent support we received by the scientific and technical personnel of the host lab at NTUA.

The proposed Holistic Test Description proved helpful not only when preparing the visit and executing the tests, but also while writing the report.

5 Open Issues and Suggestions for Improvements

During the lab access project, the user group members identified some issues for further work:

- Models of components expected to play a role in future power systems should be easily available for real-time simulation. So far, test systems are defined primarily for network / feeder structures while the custom components (e.g. grid-forming converters) are the focus of research. However, due to inter-dependencies in research (e.g. converter control vs. network protection) it would be helpful to also implement basic models of components in real-time simulation environments.
- Commercial controllers designed to be used in LV distribution grids like the BYOD used in the project are easy to integrated in the microgrid control systems. They can be efficiently used both for measuring and control purposes e.g. for operational optimization. The computational capabilities of commercial controllers are increasing over time, so that slow-acting protection functions can be integrated. It would be interesting to benchmark existing controllers for various protection functions.

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This project has received funding from the European Union's
Horizon 2020 research and innovation programme under
Grant Agreement No. 870620.