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Abbreviations

<i>API</i>	Application Programming Interface
<i>CIM</i>	Common Information Model
<i>CDIO</i>	Conceiving, Designing, Implementing, Operating
<i>CHIL</i>	Controller Hardware-in-the-Loop
<i>CPES</i>	Cyber Physical Energy Systems
<i>CVC</i>	Coordinated Voltage Control
<i>DER</i>	Distributed Energy Resource
<i>DG</i>	Distributed Generation
<i>DRTS</i>	Digital Real-Time Simulator
<i>DSO</i>	Distribution System Operator
<i>ECTS</i>	European Credit Transfer and Accumulation System
<i>FMI</i>	Functional Mock-up Interface
<i>FMU</i>	Functional Mock-up Unit
<i>GUI</i>	Graphical User Interface
<i>HIL</i>	Hardware-in-the-Loop
<i>HuT</i>	Hardware under Test
<i>ICT</i>	Information and Communication Technologies
<i>IEC</i>	International Electrotechnical Commission
<i>IEEE</i>	Institute of Electrical and Electronics Engineers
<i>JRA</i>	Joint Research Activity
<i>MPPT</i>	Maximum Power Point Tracking
<i>PHIL</i>	Power Hardware-in-the-Loop
<i>PV</i>	Photovoltaic
<i>RAMI</i>	Reference Architecture Model Industry 4.0
<i>SCADA</i>	Supervisory Control and Data Acquisition
<i>SGAM</i>	Smart Grid Architecture Model
<i>STEM</i>	Science, Technology, Engineering and Mathematics
<i>TSO</i>	Transmission System Operator
<i>VPP</i>	Virtual Power Plant
<i>WP</i>	Work Package

Executive Summary

This document reports on the educational and training material developed in ERIGrid. Educational and training needs addressing the higher complexity of intelligent energy systems are identified. The developed material/activities target university students, young researchers, professionals and high school students. In this framework, e-learning tools and hands-on laboratory exercises dealing with important aspects of smart grids and distributed energy resources have been developed. These include the delivery of three webinars (on co-simulation with real-time simulation, hardware-in-the-loop simulation and information and communication technology standards for smart grids), the development of software tools (e.g., on co-simulation and Jupyter notebooks) and the creation of several presentations.

Most notably, the learners gain remote access to advanced laboratory infrastructures allowing to control equipment and monitor variables (i.e. remote labs). In addition, hands-on laboratory exercises are reported focusing on real-time simulation. Real-time power hardware-in-the-loop simulation was used for the first time for power engineering education on important topics of distributed energy resource integration, which was appreciated by the students as shown from questionnaire statistics. Finally, educational activities targeting the younger generations are presented to disseminate the advantages of the smart grid and increase the interest in pursuing a distributed energy resource engineering-related career path. The developed material and tools are publicly available at the dedicated section of the ERIGrid website in order to allow efficient use and foster the replicability of the approaches. The material is strongly linked with the JRA 2 (co-simulation) and JRA 3 (real-time simulation) activities of the ERIGrid project.

1 Introduction

1.1 Purpose of the Document

The rapidly changing landscape in the power and energy sector - aiming to foster the energy transition – rises the need for appropriate education and training of the future and current workforce. Tackling the contemporary significant challenges requires a skilled workforce and students with problem solving skills and out of the box thinking. Technological advances already available today can revolutionise education by making use of e-learning and new technical tools. This affects the education and training of university students, but also young researchers, professionals and school students.

In this context, the work described in this document and the available material at the corresponding section on the ERIGrid website (<https://erigrid.eu/education-training/>) aim to:

- Improve the existing education practices by making use of the tools, procedures and methodologies developed in the ERIGrid project.
- Enrich the academic curriculums with new tools and methods.
- Guide and support early stage researchers on their first research steps.
- Support and enhance the thorough understanding of Distributed Energy Resource (DER) and smart grid related topics by power system and Information and Communication Technology (ICT) professionals.
- Inspire school students to pursue a smart grid related education and career path and to embed environmental awareness at an early stage.
- Promote replicability of the developed tools and methods.

A variety of educational tools and approaches are presented, including state-of the art tools such as Hardware-in-the-Loop (HIL) simulation and co-simulation, combined with appropriate educational methods, such as experiential learning.

1.2 Scope of the Document

Traditional power systems education and training is flanked by the demand for coping with the rising complexity of energy systems, such as the integration of renewable and distributed generation, the need for automation, information and communication technologies etc. A broad understanding of these topics by current/future researchers and engineers is becoming more and more necessary. This deliverable identifies educational and training needs addressing the higher complexity of intelligent energy systems, such as the development of systems-oriented skills and cross-disciplinary learning. Education and training possibilities as well as necessary tools are presented focusing on e-learning and laboratory-based learning methods. In this context, experiences of using co-simulation, notebooks, HIL methods and virtual/remote lab experiments are presented, among others.

1.3 Structure of the Document

Learning needs and requirements for modern power/energy education are discussed in Section 2. Section 3 describes several e-learning tools developed in the framework of the project. Section 4 reports on the developed hands-on laboratory educational activities making use of real-time simulation. Additional educational activities targeting mainly high school students are reported in Section 5. Section 6 provides the main conclusions of this work.

2 Learning Needs and Requirements for Modern Power and Energy Systems Education

2.1 Motivation

The rise of renewable energy systems, electrification of transportation, technology improvements that foster a more resilient network and the push towards a low carbon society are the main drivers for the ongoing transition towards an intelligent energy system [1]. The integration of the electricity network with ICT and other networks (e.g., heat networks) gives rise to Cyber Physical Energy Systems (CPES).

With the surge of complexity due to the myriad of players and actors, the need to understand the interconnections between all energy infrastructure components increases steadily [2]. Technically speaking, there is a higher need for the integration and interaction between these actors. This does not include only the physical layer (network and power devices), but also the corresponding automation and control systems, which are becoming more important in the power and energy domain, in the bid to master the increased complexity [3]. The ongoing developments in the area of Information and Communication Technology (ICT) play a key role in this process. As a result, a strong focus should be put on further research but also on education and training covering the ever rising complexity in energy systems [1], [2], [4].

In this section learning needs and requirements are discussed, which are mainly derived from the ERIGrid project publication [5].

2.2 A Complex Environment

Intelligent power and energy systems involve the communicative coupling of relevant actors (producers, consumers, network operators etc) to optimize and monitor their interconnected parts aiming to achieve efficient and reliable system operation. In parallel, an increasing number of decentralized, renewable energy resources (photovoltaics, wind energy, biomass etc) are integrated to the power system. However, this creates a challenging situation as only an integrated view of all influencing factors (such as user acceptance, security of the socio-technical system, reliability and ecological sustainability) can produce practically realizable solutions that adequately take into account the complex interrelations.

For this reason, energy informatics and automation not only provide the system with intelligent algorithms for adaptive control and continuous dynamic optimization of the complex and power and energy system, but also provide the methods to create and orchestrate overall system competences (complexity control through decomposition and abstraction, identification and focus on general principles, finding decoupling points for effective governance, avoiding bottlenecks etc).

In such complex systems of systems, the design and validation is a multi-stage process, as briefly outlined in Figure 1. Conceptual development stages already involve rough tests leading to a “proof of concept”. When the development subject is refined, so are the tests. This allows for early identification of errors and thus makes the development process more efficient.

The earliest testing stages may oftentimes be realized by pure mathematical calculations. However, as soon as interactions of different components in CPES are considered, test cases become too complex for analytical approaches to be feasible. Hardware experiments, on the other hand, excel at reproducing interaction dynamics close to reality – especially if installed in the actual energy system as field tests; however, it is important to bear in mind the possible safety and cost consequences in the event of malfunctions affecting hardware. Therefore, hardware setups are only suitable for the late stages of the development and testing process [4].

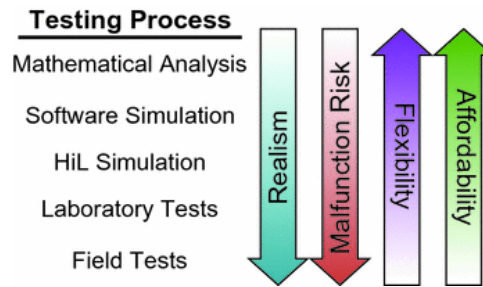


Figure 1: Steps in the testing process for smart grid components [6]

The harsh trade-offs between analytical assessments and hardware testing underline the increasing importance of software simulations for the research and development of power and energy systems. Various software tools exist for simulation-based analysis of CPES. Review articles like [7], [8], [9] typically suggest that different tools are needed for different purposes. Also, domains of expertise are wide spread, including electronics, ICT, automation, politics, economics, energy meteorology, sociology and much more. Each domain requires a specialised set of skills, but also the ability to interact and coordinate the solution of trans-disciplinary challenges.

2.3 Learning needs and requirements

Due to the additional complexity of intelligent power and energy systems, current and future engineers and researchers should have a broad understanding of topics of different domains, such as electric power, heat and definitely ICT related topics. Appropriate education on modern topics is essential at university level, both for undergraduate and postgraduate studies, so that future engineers will be able to understand and tackle the challenges and propose/implement new methods. Education and training in this area can be based on communicating the concepts of modelling and simulating components [10] to understand how they work as a system. When engineers design intelligent concepts (e.g. energy management systems, voltage control) [11], they need to understand the paradigms of centralized and distributed control, the ways to use different tools, their strengths and weaknesses and how to interconnect them [12], [13].

The classic electrical power engineering education usually does not sufficiently cover smart grid topics, posing challenges to young researchers, students and industry. Recently, several universities have incorporated new courses in the undergraduate engineering curriculum or have enriched their existing courses with more modern material. Some universities have also created dedicated master courses with relevant topics. The instruction is performed using traditional methods, such as class lectures, but also with programming, advanced simulations [9] and laboratory exercises [14], [15], that occasionally include the application of modern learning methods such as problem-based learning and experiential learning [16].

Moreover, the ongoing training of current professional engineers on modern topics is important. In some cases, professionals may tend to be hesitant of change and prefer to use proven technologies and methods. By taking part in proper training, professional engineers can better understand the benefits of modern solutions and ways to apply them in order to improve their work. For effective training, the material should be carefully designed, for example by focusing more on the practical aspects on top of the underlying theory. At this point it is important to highlight that power system professionals frequently lack thorough understanding of ICT topics. On the other hand, ICT professionals often find it hard to understand the operation of the power system. As these areas are closely connected due to the emergence of intelligent power and energy systems, it is important to create links between them. Of course, a thorough understanding of all domains (electric power, heat, ICT, automation, etc.) is difficult to achieve, however an understanding of the fundamentals of each area, without sacrificing the expert focus in each particular field, will become increasingly important in order to advance the technologies in all domains. The same applies to researchers who are working to find solutions beyond the state of the art.

The future experts require the relevant insight and abilities to coordinate and execute design and validation of CPES intelligent solutions. These abilities are facilitated by both generic engineering and cross-disciplinary technical competences.

The generic competences include the conception, design, implementation and operation of systems (the CDIO skills catalogue [17]), which can be supported, for example, by project-oriented teaching methods. With increasing problem complexity, systems-oriented skills can be strengthened, such as problem decomposition, abstraction and multi-disciplinary coordination of engineering challenges.

Cross-disciplinary learning is also required as the integration and interdependency of software and hardware systems is increased. Engineering students who aim to design and work with CPES solutions like complex control, supervisory and decision support systems, data analytics, require an increased level of programming and system design competences, as well as a pragmatic view on the applicability of methods. This means that some familiarity with domain specific system architectures and description methods is useful (reference architectures like Smart Grid Architecture Model (SGAM) and Reference Architecture Model Industry 4.0 (RAMI), use cases, test cases, etc. [18], [19]). Moreover, basic familiarity with distributed software system problems is important, as they are not addressed sufficiently within contemporary engineering education. In addition, simulation-based tools are useful for the emulation and understanding of physical behaviour and cyber-physical system couplings.

Summarizing, the following learning needs in the domain of intelligent power and energy systems are identified:

- Understanding the physical behaviour of CPES and its interconnected sub-systems and components.
- Understanding automation and control systems.
- Understanding communication networks.
- Understanding advanced control, optimization and data analytics.
- Understanding the mutual interactions/influences amongst components and domains.

Therefore, a holistic understanding of the physical and the cyber part of intelligent power and energy systems is necessary in order to design and develop a future reliable and sustainable energy system. This should be reflected in current and future education and training. In this direction, the developed tools and methods in the ERIGrid project are presented in the following sections.

3 E-learning Material

E-learning material of different types has been developed in the ERIGrid project which includes:

- Webinars
- Software tools
- Remote laboratories
- Presentations

3.1 Webinars

In the framework of the ERIGrid project three webinars have been delivered.

Link to the ERIGrid website: <https://erigrid.eu/education-training/#webinars>

3.1.1 Co-simulation with Real-time Simulation using OpSim

The first ERIGrid webinar, entitled “OpSim – a smart grid co-simulation environment” took place on the 27th of June 2017 presented by Fraunhofer IEE. The webinar was related to the joint work of the ERIGrid Work Packages (WP) JRA2 and JRA3.

The webinar introduced the Co-simulation platform OpSim, the status of the product, the related national funded project by the German government and its application area. Outcomes of projects that are using the OpSim tool were presented, followed by a more detailed description on how the Co-simulation platform works. In essence, the main base of the tool, called ‘MessageBus’, interacts with different actors (e.g., simulation tools or hardware components), which can be connected to the central interface manager MessageBus.

After the presentation, a live Co-simulation demonstration was performed. The demonstration included the implementation and use of the Co-simulation platform, the set-up of several actors like (Transmission System Operator (TSO)/ Distribution System Operator (DSO) management tools) and the connection of a real-time simulation executing and running a power system model. Afterwards, the webinar ended with an open discussion between the webinar participants and the host.

The webinar hosted 32 participants and the material was uploaded to the ERIGrid project website, along with a forwarding link to the [OpSim homepage](#). Statistical information about the three webinars is shown in Table 1.

3.1.2 PHIL Simulation for DER and Smart Grids: Best Practices and Experiences from the ERIGrid Project

The second ERIGrid webinar took place on the 5th of December 2017, and it was co-organized by ICCS-NTUA, AIT, GINP, UST and IEE. The webinar was based on the work of JRA3 and it was entitled “PHIL simulation for DER and smart grids: best practices and experiences from the ERIGrid project”. The webinar involved presentations from the co-organizers, with each one focusing on a different aspect of PHIL simulation, based on their expertise and research interests. The webinar started with an introduction of the basic characteristics of Power Hardware-in-the-Loop (PHIL) simulation and its advantages, and then delved deeper into topics such as stability and accuracy of PHIL, interface algorithms and more. Subsequently, an overview of typical PHIL tests that showcase its value was given, namely DER inverters, microgrids, voltage/frequency control, etc. Finally, the methodologies and improvements to the PHIL approach that have been developed in the context of the ERIGrid project were presented.

After the presentations, a live PHIL demonstration was performed by ICCS-NTUA, where the participants got an inside look on how to design, execute and run a PHIL simulation. Two test-cases

were demonstrated in this manner. Firstly, the parallel operation of a synchronous generator and a Photovoltaic (PV) inverter, where the PV inverter was the Hardware under Test (HuT) of the PHIL setup. Then, a Centralized Coordinated Voltage Control (CVC) was applied on a low voltage network with high penetration of DER, where again a PV inverter acted as the HuT of the setup.

The webinar received 88 registrations. 59 participants attended the webinar (67% attendance rate), with 33 of them being users external to the project (56% external users rate). The webinar was fully recorded (video and audio) and was uploaded on the project website, as well as on the project's dedicated [YouTube](#) channel. Statistical information about the three webinars (including attendance, views on YouTube etc) is shown in Table 1.



Figure 2: Snapshot of the webinar recording on PHIL simulation available on YouTube

3.1.3 ICT Standards for Smart Grids: IEC 61850, CIM and their Implementation in the ERIGrid Project

The third ERIGrid webinar, entitled “ICT standards for smart grids: IEC 61850, CIM and their implementation in the ERIGrid project”, was presented by RSE on the 23rd of March 2018 and was based on JRA 4 work. The purpose of JRA 4 is the implementation of a Virtual Research Infrastructure that interconnects the research infrastructures for performing on-line joint distributed tests.

The webinar introduced the main concepts related to the ICT interoperability for system integration in a smart grids context, as a basis on which the Virtual Research Infrastructure could be realized. The framework represented by the IEC core standards for information exchanges was then introduced as the foundation for the implementation of the interoperability between systems, with a specific focus on IEC 61850 and CIM (Common Information Model) standards. The IEC 61850 standard's original purpose is to streamline device management inside a substation from a functional point of view. It has led to various proposals for extending its use in many smart grid domains, making it a valuable candidate for the Virtual Research Infrastructure implementation close to the field devices.

The CIM-based standards were then introduced with a focus on the representation of electrical networks topology. It is also used for energy market and enterprise systems integration. The distributed service-oriented architecture open source implementation in ERIGrid, which is based on the IEC 61850 and CIM standard, was then illustrated.

The webinar received 119 registrations. 76 participants attended the webinar (64% attendance rate), with 45 of them being users external to the project (59% external users rate). The webinar was fully recorded and uploaded to the website and it's available on the [YouTube](#) project's channel. It should be noted that two IEEE Technical Committees (IES TC-SG, IEEE SMCs TC-IIS) supported the webinar. Statistical information about the three webinars (including attendance, views on YouTube etc) is shown in Table 1.

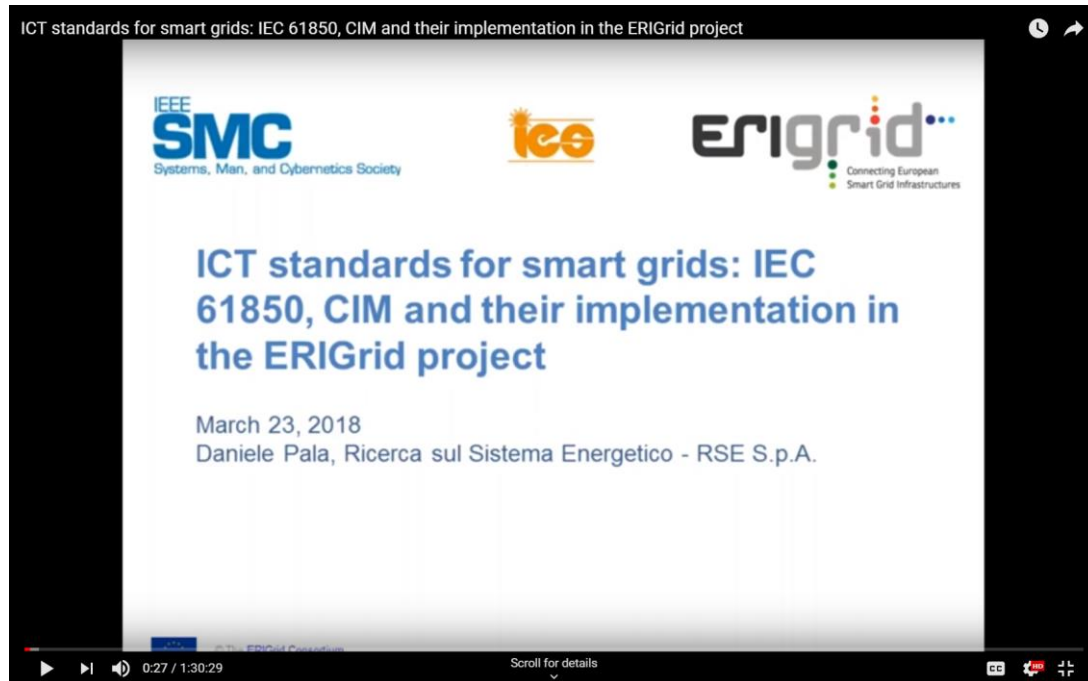


Figure 3: Snapshot of the webinar recording on ICT standards available on YouTube

Table 1: Webinar participation statistics

Webinar Name	No. Registered Persons	No. of Attended Persons	Attendance Rate (%)	No. of Project External Persons	External Attendance Rate*	Views on YouTube (22/12/2018)
Co-simulation with real-time simulation using OpSim	35	32	91%	1	3%	-
PHIL simulation for DER and smart grids: best practices and experiences from the ERIGrid project	88	59	67%	33	56%	322
ICT standards for smart grids: IEC 61850, CIM and their implementation in the ERIGrid project	119	76	64%	45	59%	434

* (of those attended %)

Overall, the webinars had a satisfactory attendance. It should be noted that it was possible to attract several participants outside of the ERIGrid consortium. Moreover, the dissemination of the work performed is progressing well by using the YouTube platform. Table 1 shows that a significantly larger audience has been reached via the YouTube platform and these numbers are expected to increase.

3.2 Software Tools

Given the cross-disciplinary nature of intelligent power and energy systems as outlined above, students should be exposed to a wide set of tools and concepts related to different knowledge domains. Thus, new educational methods and tools must be developed, capable of bringing the different knowledge domains together and allowing the students to understand the coupling and interaction of elements within intelligent solutions.

It is clear that simulations will play an important role in the testing process of new solutions. It is therefore natural that students should learn to use domain-specific simulation tools, both in standalone use cases and in co-simulation setups. Moreover, students should know the limitations of such tools. From an educational perspective, methods that support students to bridge the gap of theory and application are required.

In this section, four software tools of the ERIGrid partners are presented. The tools are used for e-learning but also in classroom education at the relevant universities.

Link to the ERIGrid website: <https://erigrid.eu/education-training/#software>

3.2.1 Virtual Laboratory for Voltage Control and Microgrid Operation

The Virtual Lab is an online educational simulation tool that mimics the operation of the actual laboratory microgrid of ICCS-NTUA. A mathematical model of the laboratory microgrid has been developed along with a friendly Graphical User Interface (GUI). The tool is web-based which eliminates the need for downloading software, while it allows the simultaneous use by several users. The user can access the web platform with a simple sign up process. Once the user has logged-in, he can observe several variables (e.g., voltage, active power, reactive power etc) and perform several actions (e.g. change the power factor of the inverter). The simulation tool includes two different laboratory setups and corresponding experiments which are described below, along with some theoretic background:

- Voltage control
- Microgrid operation

Apart from the use of the tool by individual users, the Virtual Lab has been demonstrated at several events:

- ERIGrid Summer School at DTU: “Quantify the quality of Smart Energy Solutions via testing” (Roskilde, August 2018).
- European researcher’s night (Vienna, September 2018).
- HEDNO-NTUA Workshop for professionals: “RES Integration in Smart Grids” (Athens, October 2018).
- European Utility Week (Vienna, November 2018).

In parallel, a Remote Lab has been developed where the user gains access to the SCADA of the actual laboratory microgrid of ICCS-NTUA and can monitor and control remotely hardware equipment. The GUI and the laboratory setups used are exactly the same with the Virtual Lab. More information on the Remote Lab is provided in Section 3.3.1.

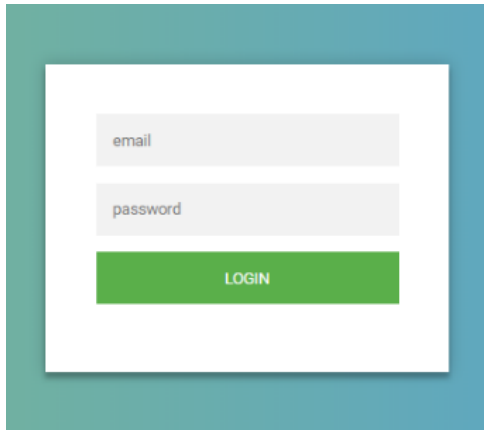


Figure 4: Login interface of the Virtual Lab

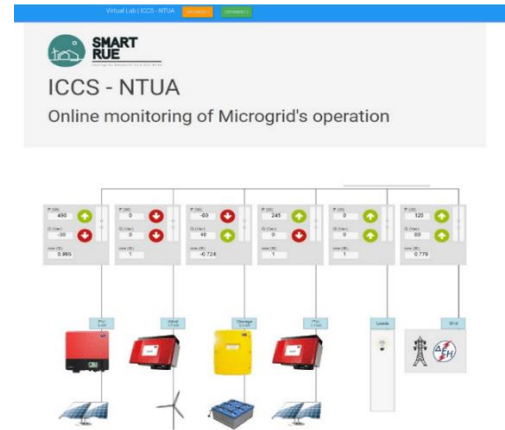


Figure 5: Monitoring page of the Virtual Lab

i) Voltage Control

The main objectives of this experiment are to demonstrate the voltage rise issue that can occur in distribution networks, due to the high production of Distributed Generation (DG) (mainly Photovoltaics), but also the ancillary services that modern DG inverters offer in order to mitigate the aforementioned voltage rise.

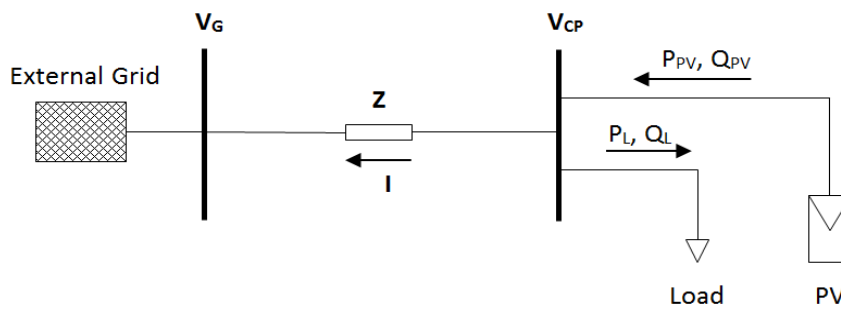


Figure 6: Two bus system

According to power system theory, the voltage drop or rise along a line (R , X) where at the end a load and/or PV is connected (Figure 6), can be approximated with the following equation:

$$\Delta V \approx \frac{(P_{pv} - P_{Load}) \cdot R + (Q_{pv} - Q_{load}) \cdot X}{V_G}$$

Therefore, if $P_{pv} \cdot R > (P_{load} \cdot R + Q_{load} \cdot X)$ and $Q_{pv} = 0$, the voltage of the coupling point (V_{CP}) will be higher than the grid voltage (V_G). The impact of active and reactive power on the voltage depends on the resistance (R) and inductance (X) of the line (e.g. in low voltage networks where R is higher than X , the impact of the active power is stronger than the reactive power). The voltage rise can be mitigated if the PV inverter absorbs reactive power (Q_{pv}), according to the above equation.

The laboratory setup that is simulated for this experiment can be seen in Figure 7. It should be noted that at the Remote Lab (described in Section 3.3.1) the below laboratory setup is actually implemented in the hardware laboratory (i.e. a hardware R-L line module is connected between the utility grid and a hardware PV inverter). In order to better demonstrate the voltage rise problem there is no load connected at the end of the line. Therefore, if the reactive power of the inverter is also zero, there will always be a voltage rise due to the PV production. The GUI for this experiment is presented in Figure 8 and Figure 9.

As shown in Figure 8, the user can monitor the voltage, active power, reactive power and power factor of both the PV inverter and the main grid. From the control panel on the left side of the screen, the user can perform three main actions:

- Adjust the operating power factor of the inverter (available values are 0.8, 0.85, 0.9, 0.95 and 1, according to the capabilities of the inverter). All power factor values that are less than unity represent absorption of reactive power.
- Adjust the active power set-point of the inverter (i.e. in order to curtail active power). If the set-point is set above the Maximum Power Point (P_{mpp}) value, the inverter will operate at P_{mpp} instead.
- Activate or Deactivate the Voltage-Reactive Power Q(V) droop control. Activating the Q(V) droop control, disables the power factor set-point that the user has set on the 1st input field.

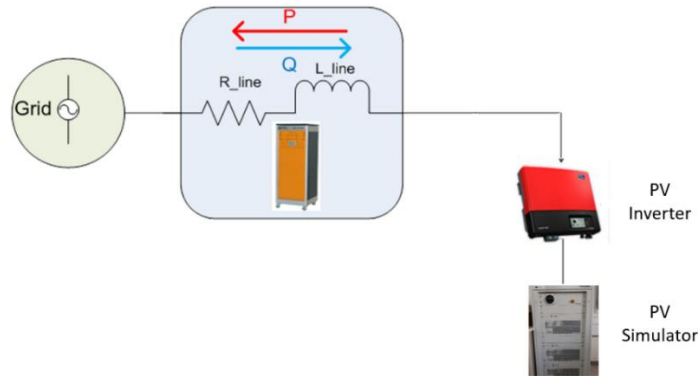


Figure 7: Setup of the voltage rise experiment

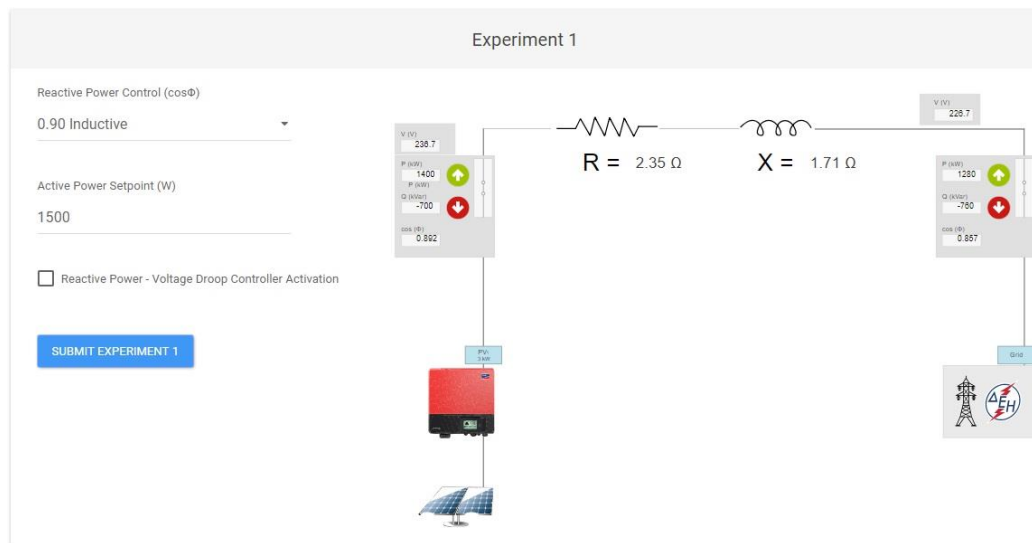


Figure 8: Graphical User Interface of the voltage control experiment

Below this part of the GUI, the user is presented with four-line charts displaying the voltage, active power, reactive power and power factor of the PV inverter respectively. The X-axis of the charts displays the UTC time. A new data point is added on the charts every 5 seconds. At the Virtual Lab the presented values are results of the mathematical model. At the Remote Lab (Section 3.3.1), the data points are imported from the SCADA system's database. Figure 9 shows the four-line charts of the experiment during a change of the power factor of the inverter from unity (1) to 0.85 inductive (e.g. according to a command by the distribution system operator). The change occurs at 08:59:35 UTC, as seen on the charts. It is shown that when the power factor is set to 0.85 inductive, the PV inverter starts absorbing reactive power (850 VAr) in order to mitigate the voltage rise (the voltage is reduced from 245.5 V to 238 V).



Figure 9: Voltage, active power, reactive power and power factor of the inverter via the GUI of the Virtual Lab

ii) Microgrid Operation

The objective of the second experiment is to familiarize the user with the concept of microgrids in both grid-connected and islanded operating modes. The single phase microgrid of the laboratory of ICCS-NTUA is mathematically modelled. Access is provided from the same web platform as the previous experiment. The online GUI can be seen in Figure 10 and Figure 11. Figure 10 displays

the main part of the GUI, where the user can monitor the state of all the units that comprise the microgrid, which are (from left to right): a wind turbine with its inverter, a lead-acid battery bank with its inverter, PV panels with their inverter, resistive and inductive loads and the utility grid. The active power, reactive power and power factor is monitored for each unit, as well as the voltage and frequency of the AC bus where all the units are connected on. On the left side of this part of the GUI, the user can select different values for the microgrid's resistive loads. The available values are: 250 W, 750 W, 1250 W, 1750 W and 2250 W according to the capabilities of the laboratory.

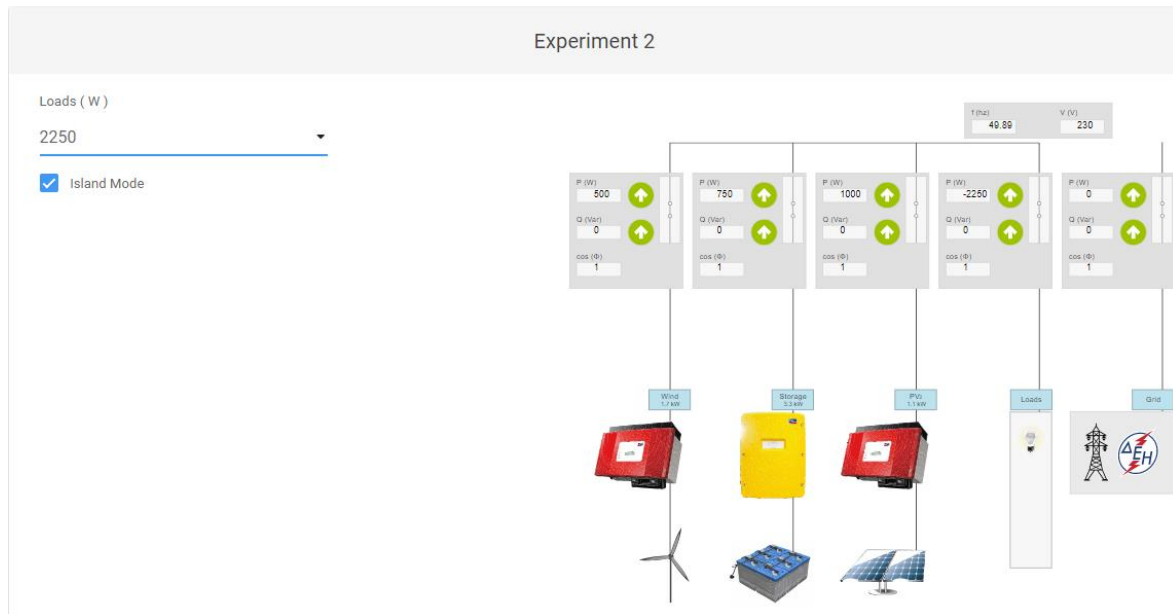


Figure 10: Graphical User Interface of the microgrid operation experiment

Figure 11 depicts two charts. The top chart represents the microgrid active power balancing, showing the active power of all the microgrid's units and the utility grid. The user can select or deselect a specific unit's graph line by using the legend on the bottom side of the chart, which allows an efficient visual representation. The bottom chart displays the microgrid's AC bus frequency.

It must be noted that at the Remote Lab (described in Section 3.3.1), the active power of all the microgrid's units and the utility grid are imported from the SCADA system's database and added on the chart every 5 seconds, while control of the loads is also performed via the SCADA.

The experiment starts with the microgrid in grid-connected mode, where the user observes that the utility grid is responsible for the power balancing of the microgrid's units when changes in the loads and production occur, while the battery inverter is in idle state, acting according to its Battery Management System (BMS).

Next, the microgrid is switched to islanded mode. In this state, the user again performs changes in the loads and monitors the response of the battery inverter, which is now responsible for the power balancing, since the utility grid is disconnected. The frequency of the microgrid is also monitored which depends on the $f(P)$ droop characteristic of the battery inverter (similar to synchronous generators). Figure 11 shows that at the transition to islanded mode the frequency rises, because the RES production exceeds the load and the battery inverter absorbs active power. Next, the load is increased leading to a reduction of the frequency.

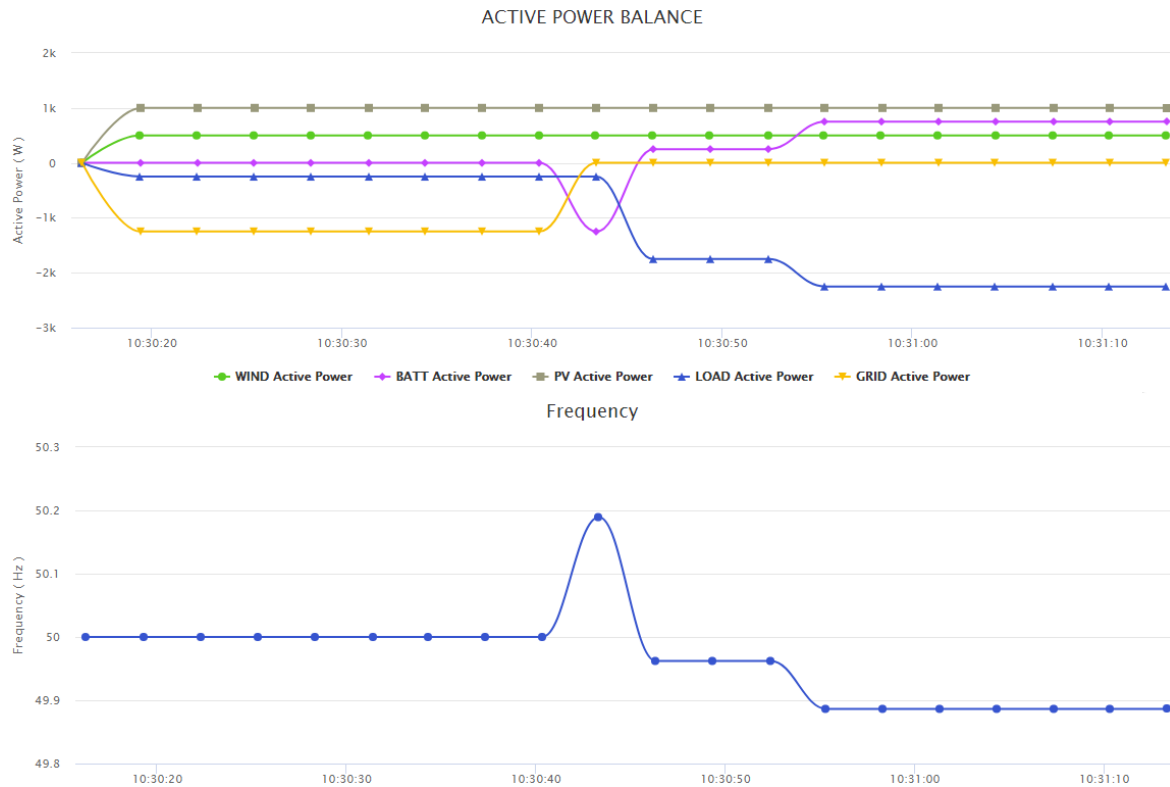


Figure 11: Active power balance and frequency of the microgrid

3.2.2 Mosaik-Based Co-simulation

The mosaik co-simulation framework (developed in Oldenburg-OFFIS) has been developed to provide researchers with an easy-to-use yet powerful tool for simulation-based testing [20], [21]. The open-source software is purely Python-based and possesses a slim code base so that it is fast and easy to install on any desktop computer. Additionally, it comes with a simple power system simulation scenario to give users an immediate understanding of the functionality and capabilities of the framework.

For the integration of further simulation models into the framework, different programming languages, standards and protocols are supported, like Java, Python, MATLAB, FMI or ZeroMQ. Accordingly, there is a flat learning curve for researchers/learners wishing to test their simulators in common scenarios with others. To set up an executable co-simulation setup, a single Python file is sufficient. The required API is slim and easy to learn. Additionally, a GUI is available for demonstration purposes, allowing intuitive co-modeling of basic power system scenarios (available on the [ERIGrid website](#)).

Next to its research applications, mosaik is especially used for training and education of students in the field of cyber-physical energy systems at the master specialization in energy informatics at the University of Oldenburg. In a practical course, students learn to plan, execute, and analyze co-simulation-based experiments. The target audience includes computer scientists, environmental modelling students and participants of the post graduate program in renewable energies. They learn how to model controllable and flexible electrical loads and generators, as well as integrating them into smart grid scenarios along with appropriate control and optimization mechanisms. The learners first derive and evaluate the differential equation-based models from the physical model, then transform them into discrete simulation models and finally use mosaik.

One of the main objectives is to have students understand and engineer the function of distributed agent-based control and regulation concepts, as well as algorithms for distributed generators and consumers, and all the way up to the operation of electrical energy systems. In addition, they analyse the requirements for real-time performance, resource utilization, robustness and flexibility. The

students are taught the basics in planning, execution and evaluation of simulation-based experiments. Special focus is put on the trade-off between accuracy and reliability of expected results and the necessary effort (Design of Experiments, Statistical Experimental Planning) to determine, as closely as possible, the interrelationships between influencing factors and observed target variables. In terms of professional competences, the students learn to:

- Evaluate and derive discrete (time-stepped) models from continuous physical models.
- Use the smart grid co-simulation framework mosaik.
- Model simple controllable and flexible electrical loads and generators.
- Analyze distributed agent-based control concepts and algorithms for distributed generators and consumers for the operation of electrical energy systems, with regards to the requirements of performance balancing, equipment utilization, robustness and flexibility.
- Simulate appropriate control and regulation mechanisms in smart grid scenarios for electrical consumers and generators.
- Design the basis for the planning, execution and evaluation of simulation-based experiments.
- Recognize the importance of the trade-off between accuracy and reliability of expected results and the effort required (Design of Experiments, statistical experiment scheduling) in order to investigate the interrelations between influencing factors and observed target values with as few attempts as possible – but as accurately as necessary.

Moreover, regarding methodological competences, the students learn to:

- Evaluate simulation results.
- Search information and methods for implementing the models.
- Present their own hypotheses and check them by means of experimental planning and statistical scenario design.

Finally, the social and self-competences to be imparted are to:

- Apply the method of pair programming.
- Discuss the design decisions taken.
- Identify work packages and take on responsibility.
- Reflect on their own behaviour within limited resource energy.
- Take criticism and understand it as a proposal for the further development of their own behaviour.

For the application of mosaik as a testbed in smart grid research, annual workshops are organized by OFFIS for interested scientists. The participants learn about the basics of co-simulation of cyber-physical energy systems and see how mosaik approaches the challenges of the domain. The capabilities and limitations of the framework are explained. In practical sessions the researchers learn how simulation scenarios can be set up with mosaik, extended and scaled up.

The code of mosaik and all its additional modules can be found on <https://bitbucket.org/mosaik/>. Different installation options for a variety of operating systems are provided on the official mosaik website, along with an extensive tutorial and comprehensive documentation.

3.2.3 Functional Mock-up Unit (FMU)-as-a-Service Approach

Co-simulation is an innovative approach to study the behaviours of the multi-domain cyber-physical energy system. However, the synchronization of the signals exchanged between simulators and the appropriate Application Programming Interface (API) are still challenges of the co-simulation method. The Functional Mock-up Interface (FMI) is a standard in co-simulation that allows interoperability among models from different domains, in terms of code. The FMI encloses the dynamic model and generates compiled C code (the Functional Mock-up Unit (FMU)), which can be integrated to other environments as a black box.

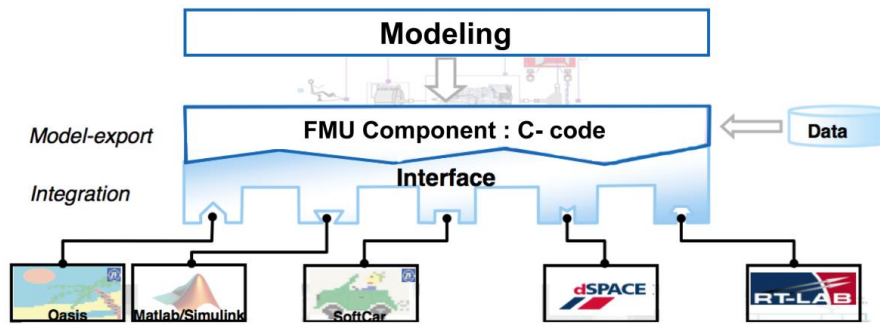


Figure 12: Generating and interfacing the FMU components

While promoting the interoperability of models in smart grids, it is currently not easy for novice users without an informatics background to understand and to successfully implement a FMI in practice, due to the lack of supporting tools for FMI. In order to use the FMI, the user has to implement either independent FMU solvers in popular programming languages (e.g. Python, Java or C) or toolboxes that are associated with simulation software (e.g. matlab, dymola). Moreover, these existing tools often work only at a predefined platform (e.g. Windows 32 bits, Window 64 bits, Linux 64 bits, etc.). This limits the development of FMI and hinders the learning curve as well as the utilization of FMI from new users.

In this context, Grenoble INP has proposed and developed a software tool allowing the delivery of FMU in a Software-as-a-service manner (hence the name FMU-as-a-service). The approach (Figure 13) delivers the power system FMU library for co-simulation and model exchange in security and confidentiality via a user-friendly GUI. Since the FMU is launched and simulated on the server, no installation is needed from user side. On one hand, it allows novice users to run an FMU without further requirements (e.g. toolbox, solver request, etc.); on the other hand, the FMU-as-a-service provides a better performance as the server is usually of better specifications in terms of computational power.

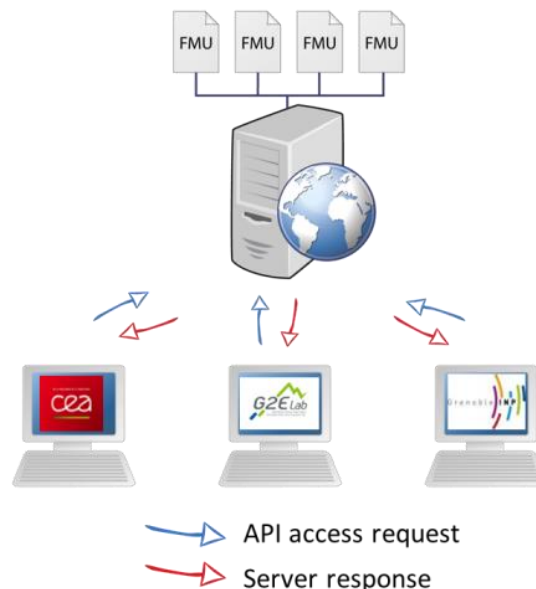


Figure 13: FMU as a service approach

Moreover, the software provides the possibility to instantiate one FMU into several instances. It allows multiple users working on the same model at the same time. It is particular adapted for utilisation in classroom. The user also has the possibility to deposit and encrypt (RSA) their own FMU

model to the server, either to execute a test without required installations on their computer, or to share with other users while keeping the code confidential to themselves. The interaction of different modules in the software is given in Figure 14.

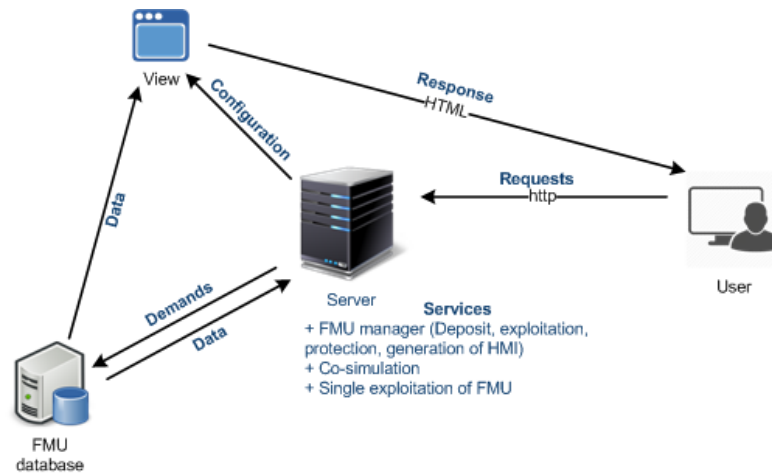


Figure 14: Interaction of different modules in the software.

The software provides two methods to co-simulation:

- Step by step
- With fixed step

It also supports vectorial input with API.

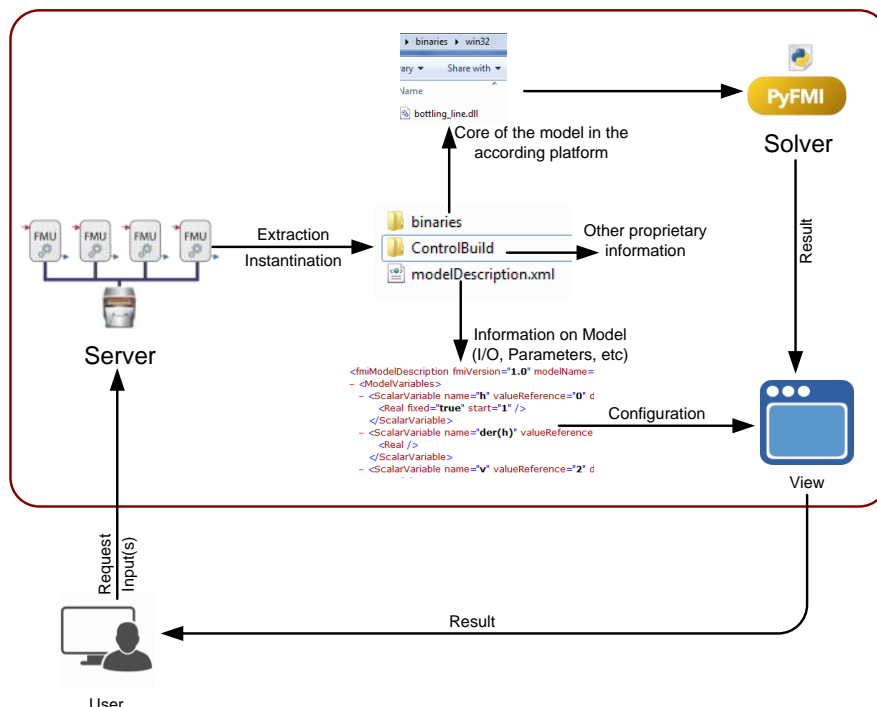


Figure 15: The software helps users to understand the functionality and structure of a FMU

One of the main objectives of this software is to help students and interested users to understand the functionality and structure of a functional mock-up unit and to become familiar with planning, execution and evaluation of simulation-based experiments. Initially developed to serve only in the

smart building validation domain, it can be used for various courses involving (co)simulation, such as mechatronics or robotics or eventually complex cyber-physical systems. Moreover, the software can be used to provide a comprehensive course on different type of simulations, models of computation and on how they should interact.

The server is developed on Django with PyFMI as solver. The server is currently compatible with FMI 1.0 and FMU Co-simulation. Results are available in JSON-CSV-HTML or can be represented at the graphical web interface. The solver is being upgraded to the new FMI++ module that allows integration and execution of FMI 2.0. The new version is expected to be available to the public in 2019.

The software is open source and is available at: <https://sourceforge.net/projects/westsandbox/> (permission required for access) and on the ERIGrid website as the “WEST tool” (Web Energy Services and Tools).

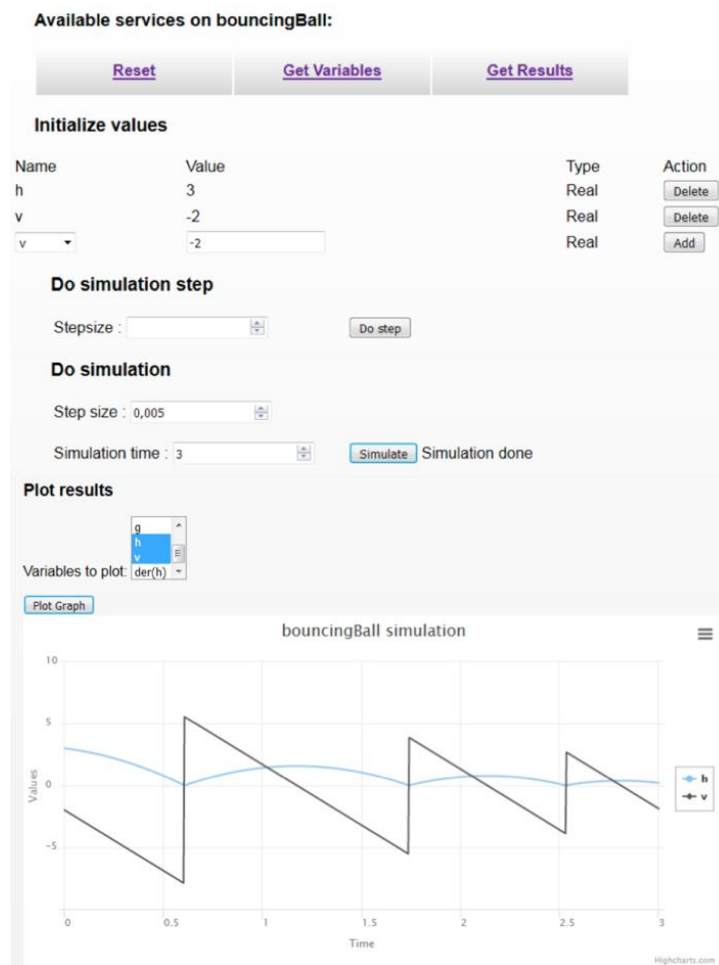


Figure 16: Interface of the software for the simulation of the Bouncing Ball FMU

3.2.4 Jupyter Notebooks (Minimizing the need for programming skills)

Jupyter notebooks are a merge between a standard text book and what real programming in python looks like. The notebooks can contain explanatory text and figures, while running on an IPython [22] kernel allowing the student to execute python code. The use of these notebooks provides a way to narrow the gap between theoretical concepts and application by setting up code examples, where the student is able to directly see real life examples of the theoretical concepts explained in the text. Notebooks of this kind can be developed to cover a wide spectrum of intelligent energy systems concepts.

These notebooks are used in several courses at the Technical University of Denmark. As part of the ERIGrid Summer School 2018, a pair of notebooks were given to the students for hands-on experience with a co-simulation environment and Design of Experiments. The example used consisted of a typical Home Energy Management System (HEMS) in which a scenario is built up step by step, to include a house with solar panels, battery and a controller that can connect the house to the grid or discharge the battery. All the components and interconnections were modelled in behind-the-scenes python scripts and the simulation ran using the python module mosaik (see Section 3.2.2). An example of the final notebook can be seen in Figure 17. The two notebooks are linked on the ERIGrid website.

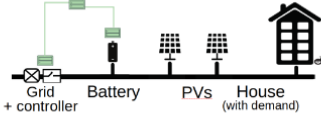
By constructing a framework where students can focus on a problem to solve, instead of dealing with issues related to programming, the students are able to better absorb and understand the core course concepts. In the case of the notebooks developed for ERIGrid, the learning objectives that the notebooks address are to:

- Design a testing procedure to validate a 'black box' algorithm
- Recognize the importance of statistical Design of Experiments to qualifying tests
- Apply Design of Experiments to evaluate the performance of a black box algorithm

So far, students have given positive feedback regarding their learning experience with these notebooks.

3. Initiate "world"

Now we initiate a new world (world_3) the same way as before, but adding the extra entity corresponding to a battery and making sure to save the output from the collector in a different file (datastore_grid_demand_PV_batt):



```
In [19]: world_3 = mosaik.World(SIM_CONFIG)
filename_3 = 'grid_demand_PV_batt_output'
sim_dict, entity_dict = init_entities(world_3, filename=data_path+filename_3)
sim_dict, entity_dict = add_entities_1(world_3, sim_dict, entity_dict)
sim_dict, entity_dict = add_entities_2(world_3, sim_dict, entity_dict)

Starting "DemandModel" as "DemandModel-0" ...
Starting "SimpleGridModel" as "SimpleGridModel-0" ...
Starting "CollectorSim" as "CollectorSim-0" ...
Starting "PVModel" as "PVModel-0" ...
Starting "PVModel" as "PVModel-1" ...
Starting "BatteryModel" as "BatteryModel-0" ...
Starting "ControlModel" as "ControlModel-0" ...
```

4. Connect components

The controller is connected to the grid and to the battery. The keyword argument "time_shifted" is added in order to have a loop in the network, something that is otherwise not allowed in mosaik.

```
In [20]: # Connect units to grid busbar
world_3.connect(entity_dict['demand1'], entity_dict['grid1'], ('P', 'P'))
world_3.connect(entity_dict['pv1'], entity_dict['grid1'], ('P', 'P'))
world_3.connect(entity_dict['batt1'], entity_dict['grid1'], ('P', 'P'))
world_3.connect(entity_dict['pv2'], entity_dict['grid1'], ('P', 'P'))
```

Figure 17: Example of a Jupyter notebook, where markup language and Python code can be used to showcase complex examples

3.3 Remote Laboratories

In this section two Remote Lab applications are presented, which allow the user to connect remotely to actual laboratory infrastructure, obtain measurements and control devices.

Link to the ERIGrid website: <https://erigrid.eu/education-training/#remotelab>

3.3.1 Voltage Control, Microgrids and Virtual Power Plants

Apart from the Virtual Lab for voltage control and microgrid operation described in Section 3.2.1, a Remote Lab has been developed which provides online access to the actual laboratory of ICCS-NTUA. At the Remote Lab, measurement and control of hardware equipment (e.g. PV inverter, loads) is performed via the laboratory SCADA, whereas the Virtual Lab uses a mathematical representation of the system. The GUI and control options offered to the user are exactly the same at the Remote Lab and Virtual Lab application.

Obviously, the Remote Lab is more realistic than the Virtual Lab, as the operation of the real system is observed, providing a more meaningful experience to the user. In addition, phenomena such as noise, equipment inaccuracies, communication delays, etc which are inherent in a real-life system are taken into account at the Remote Lab. Moreover, at the Virtual Lab several variables of the experiments are pre-defined in the algorithm (e.g. grid voltage, PV production), so the application has to be modified and re-uploaded on the web in case of the need for changes. This is not the case at the Remote Lab, where all parameters are direct measurements/control signals from/to real laboratory equipment.

On the other hand, the use of the Remote Lab presents some challenges. Most importantly, only one user can typically have access to the Remote Lab application at a time (because there is only one laboratory setup available to control), whereas at the Virtual Lab a large number of users can use it at the same time through the online platform. Therefore, it is more difficult to offer the Remote Lab to a wide audience. In addition, for safety reasons it is recommended that laboratory staff monitor the process of the experiment and if necessary communicate with the user. Moreover, the test setup has to be actually implemented in the laboratory, requiring additional effort. It should be noted that tests that might stress actual equipment can be safely implemented in the Virtual Lab.

To sum up, the Remote Lab offers important advantages, but its actual implementation is more challenging. Future work in ERIGrid will deal with tackling these challenges in order to further demonstrate the advantages of Remote Labs.

The specific Remote Lab application supports the following experiments:

- Voltage control
- Microgrid operation
- Virtual Power Plant using a Multi Agent System

The first two experiments were described in Section 3.2.1 for the Virtual Lab application, which provides the same functionalities with the Remote Lab. The third experiment is available currently only as a Remote Lab application and is described next. The Remote Lab application has been used by students of ICCS-NTUA and will be made available at the ERIGrid website soon.

i) Virtual Power Plant using a Multi Agent System

This remote experiment aims to familiarize the user with the concept of Virtual Power Plants (VPP) and Multi Agent Systems. A VPP platform was developed by ICCS-NTUA in the framework of the H2020 SmarterEMC2 project (www.smarteremc2.eu) and was extended and enhanced for educational purposes in the ERIGrid project. The VPP platform has been developed using Java programming language, and its GUI is presented in Figure 18.

The VPP platform monitors and controls several DER and loads. Some of them are actual hardware units, while some are simulated. Specifically, the actual laboratory microgrid's units (wind turbine, PVs, batteries and loads) act as the real controllable DER of the VPP, whereas 6 households with controllable loads are simulated. The platform imports the power measurements of the hardware units from the SCADA system's database in real-time and sends the calculated set-points back to the SCADA.

The main purpose of the VPP is to participate in the energy market as an individual economic entity and implement a specific power production daily profile, similar to conventional power plants.

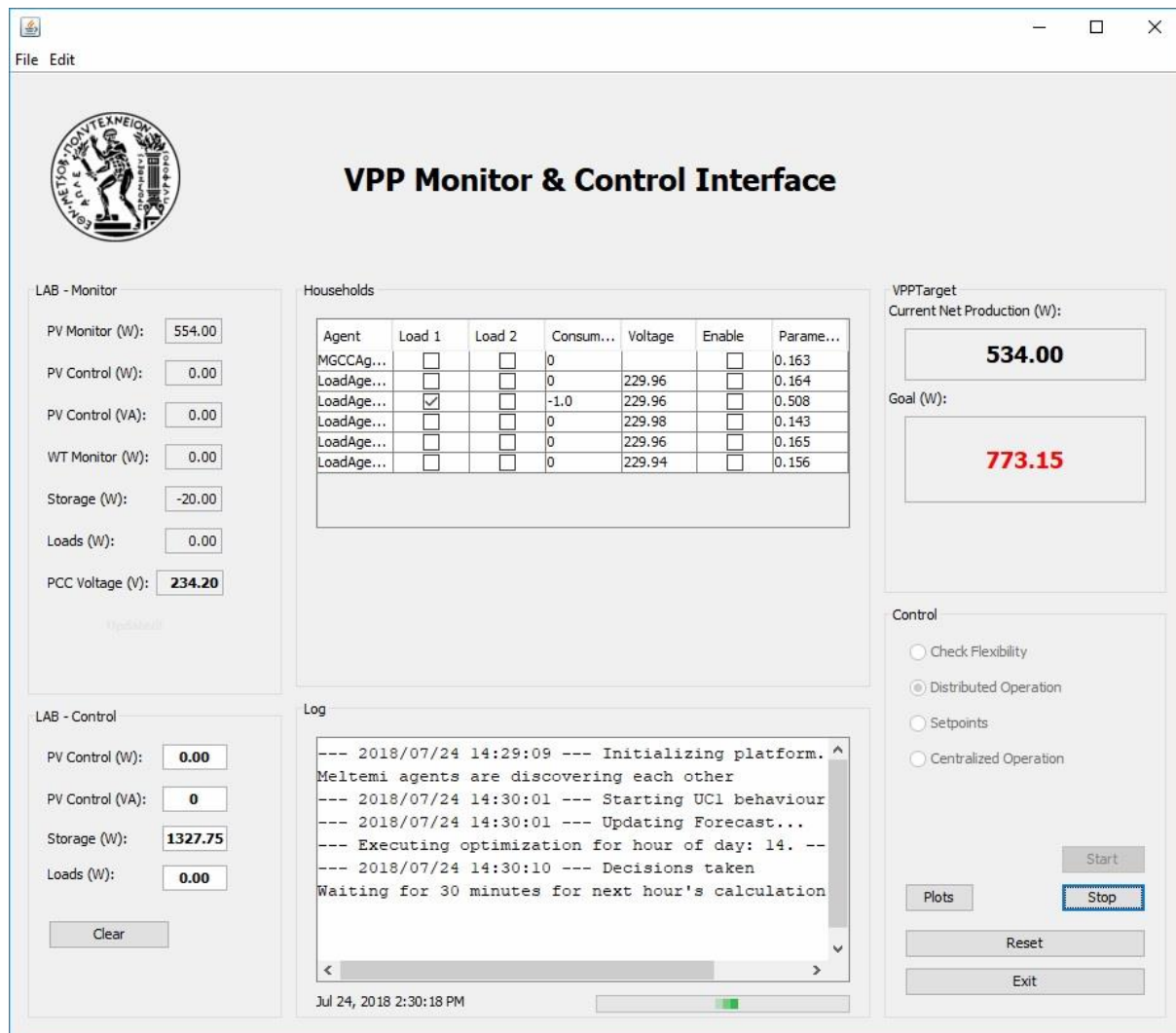


Figure 18: GUI of the VPP platform

In order for the VPP's DER to operate in a coordinated manner to achieve the target net power production, suitable control is required. A Multi Agent System has been developed and incorporated in the VPP platform. Multi Agent Systems are generally used for decentralized/distributed control, where each involved entity has its own agent. When a decision needs to be taken, the responsible agents communicate with their neighbouring agents in order to solve an optimization problem. Once all the agents agree that they have converged to the optimal solution, the calculated outcome is implemented. The main agents implemented in the specific application are listed below:

- Market operator agent
- VPP aggregator agent
- Wind turbine (hardware) agent
- PV (hardware) monitor agent
- PV (hardware) control agent
- Battery (hardware) agent
- Loads (hardware) agent
- 6 agents for the simulated households
- Forecast agent

The user is able to observe the exchange of messages between the agents, using a separate window of the application, which is presented in Figure 19. The red blocks on the top represent the agents of the system, while the pointed lines represent the various messages that are exchanged between them. By double clicking on a specific pointed line, detailed information about the message is displayed (sender, recipients, content, etc.).

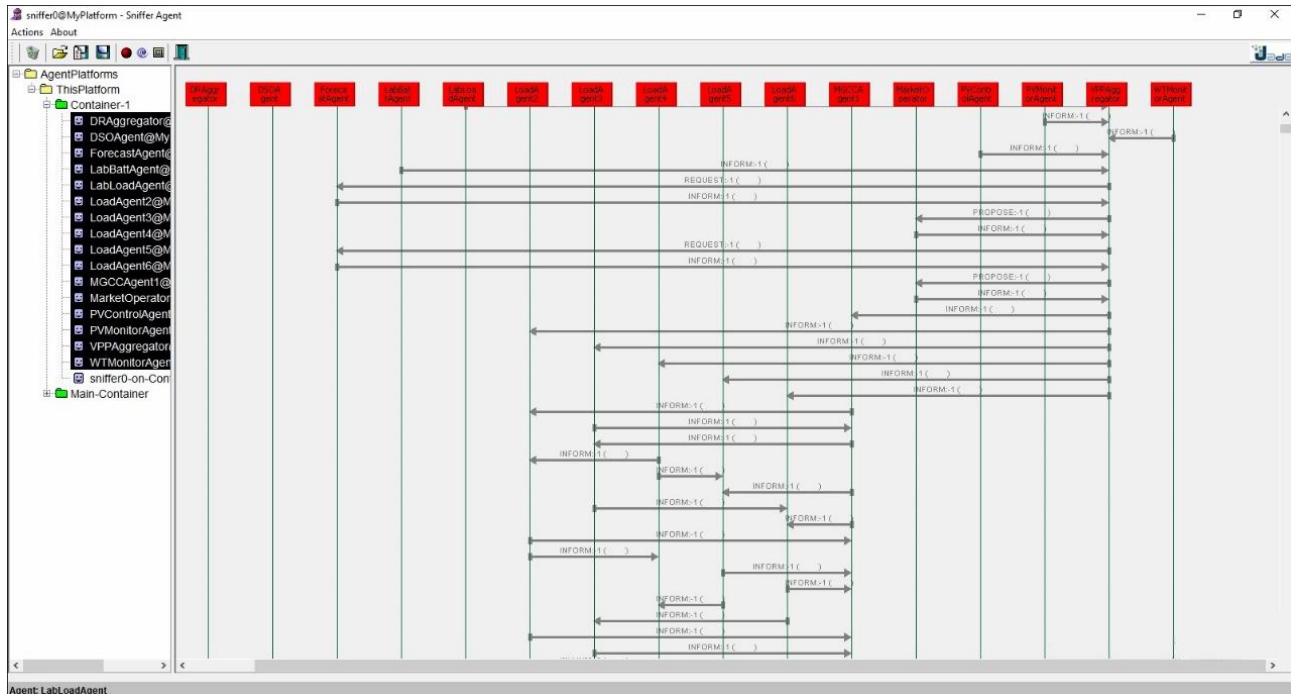


Figure 19: Exchange of messages between the agents

As described before, the main purpose of the VPP is to participate in the energy market and implement the scheduled net power production profile. Ten different such profiles have been created and the user can freely select any of them when using the platform. Additionally, once the agents have converged to the optimal solution for the remaining hours of the day, the user can observe the results in three charts (Figure 20).

The bottom chart (“Total Schedule – Net VPP production”) depicts two graph lines. The light blue one (titled “Schedule” on the legend), displays the power production profile that the VPP has agreed to realize for the rest of the day. The orange line (titled “Realized” on the legend) is the actual net production profile that the VPP manages to implement, based on forecasted data and flexibility, for the remaining hours of the day.

The top right chart (“Lab Scheduling”) depicts the scheduled operation of the laboratory’s DER. If the light blue line (“PV_{curtailed}”) and purple line (“PV_{forecast}”) are identical, it means that no curtailment is required on the power production of the PV panels for the rest of the day in order to realize the requested profile, based on the forecasted values for the PV production.

Finally, the top left chart (“Loads Scheduling”) depicts the usage of the 6 simulated household controllable loads. The X-axis shows the remaining hours of the day and the Y-axis the active power of the loads in kW. For example, in the displayed chart, Load 2 will be turned on several minutes before 15:00, Load 5 several minutes after 16:00, etc. Three of the loads are not used in this specific example.

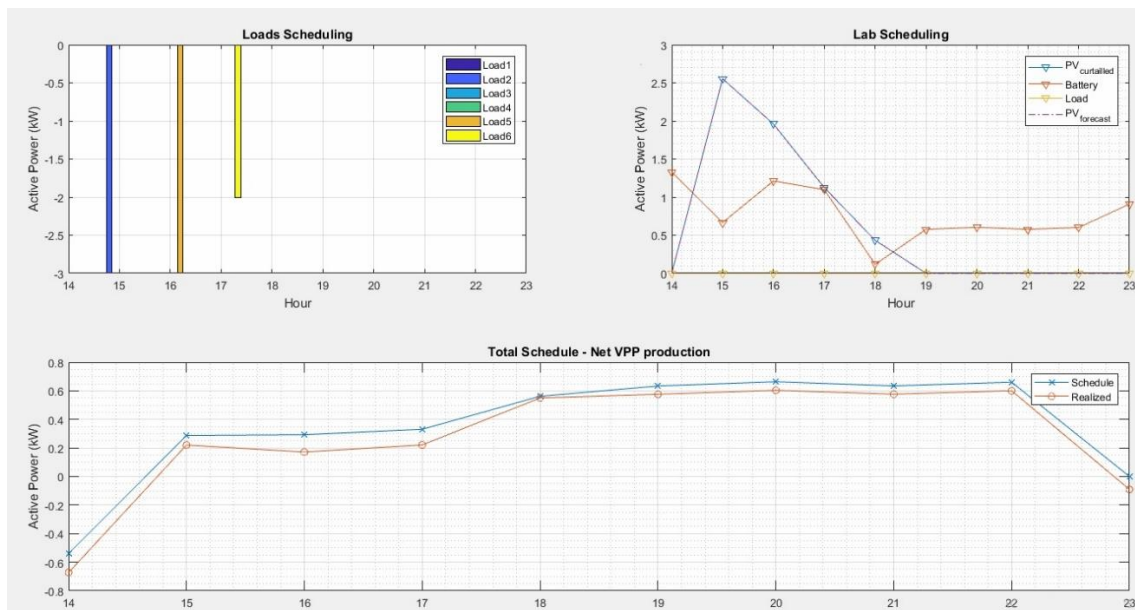


Figure 20: User profile generation results

3.3.2 Microgrid Balancing

In this section the Remote Lab application at CRES laboratory is presented.

i). Laboratory exercise objectives

The specific remote lab exercise aims to make users familiar with the following concepts:

- Power balancing control of microgrids based on specific market policies
- Real-time simulation of photovoltaics based on environmental condition measurements by physical sensors
- Interoperability of SCADA applications by different vendors

ii). Test setup

The diagram below (Figure 21) illustrates the configuration assumed for the lab exercise.

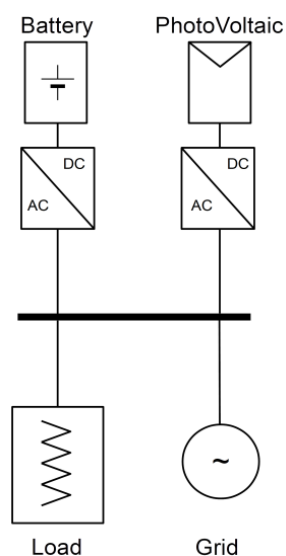


Figure 21: Selected microgrid setup for the CRES' remote lab application

As it is shown in Figure 21, the setup includes four different resources, namely one Battery Storage System, one Load, one PV and one grid interconnection. In the setup the battery, load, and grid connection are all physical equipment, whereas the PV unit was simulated. The reason for selecting the PV as a simulated unit instead of a physical one was to introduce in the setup the analytical mathematical models that one can use for the analysis of PV systems. In our application these models include calculation of irradiance from actual measurements on the horizontal plane to the plane of the simulated PVs, calculation of the I-V characteristic of the selected PV modules, calculation of the Maximum Power Point that the selected PV panel can achieve and finally, calculation of the AC power that the simulated PV system injects to the grid, taking into account the inverter's efficiency. The whole modelling is done in MATLAB/Simulink. The input signals to the PV model are Global Horizontal Irradiance and Ambient Temperature from two actual sensors of the microgrid. In order to obtain the sensors output, the Simulink model communicates with the microgrid SCADA using OPC. Also, by means of the same toolbox, the Simulink model selects the set-point values for the loads and battery inverter. The load set-point is specified by a preset load profile and the battery set-point is determined by a policy controller which calculates the power the battery has to absorb or inject in order to maintain balance. Figure 22 provides an overview of the main blocks used in the Simulink model as well as its interactions with the outside world. It is worth noting that the Simulink model allows also the recording and storage of various parameters of the system that can be used for post processing by the user.

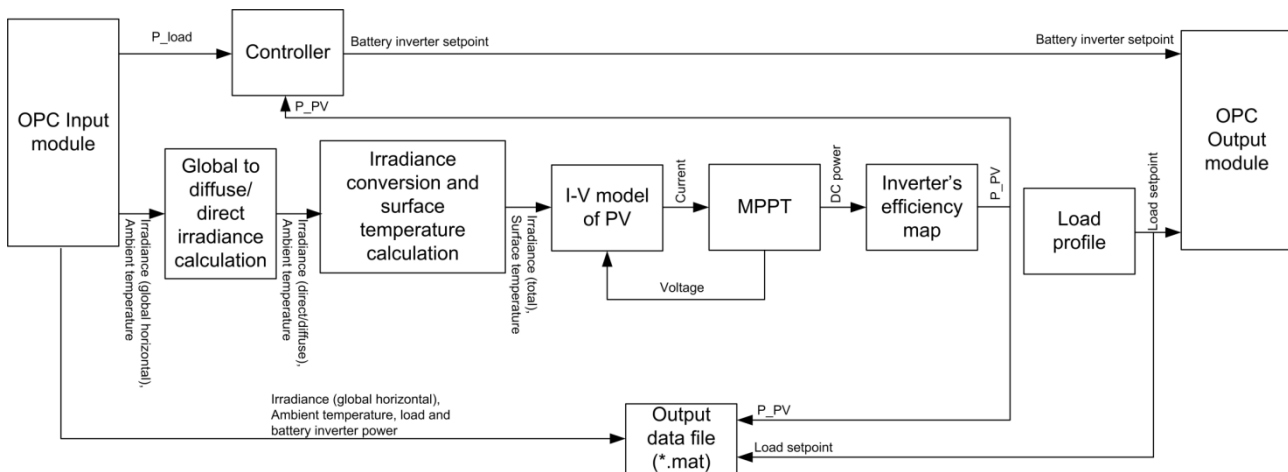


Figure 22: Analytical illustration of the MATLAB/Simulink blocks used in the CRES' remote lab

Concerning the mathematical formulation of the various Simulink blocks, it should be noted that the models concerning the irradiance conversion have been analytically presented in [23]. The reader could refer to the following equations from this book, all of which have been used in this application:

- Conversion of Global Horizontal to Diffuse and Beam (eq. 8.12.1, 8.12.2, 4.2.9, 1.2.3, 1.3.3, 1.2.2, 1.4.1, and 1.4.2)
- Conversion of Beam/Diffuse to Inclined-Plane global irradiance (eq. 11.2.5, 11.3.5, 11.5.7)

The mathematical model for the PV module, in turn, has been presented in [24] and is the same model used in the JRA2.2 activities (FMU model of PVs). The algorithm considered for the MPPT block of the model is based in the widely used 'Perturb & Observe' method [25]. The analytical presentation of these mathematical models is omitted from this document.

The controller, on the other hand, makes use of a simple strategy that selects a set-point value for the batteries based on the current values of the PV and load's power. The strategy is divided into two scenarios, namely "sell priority" and "buy priority". The first scenario prioritises the injection of the PV power surplus to the grid. Thus, when the PVs produce more power than the consumed one, the battery inverter should allow the surplus power to be injected to the grid ($P_{\text{battery set-}}$

point becomes zero). In the case of PV power deficit, the battery inverter is controlled to provide the difference in order not to allow any power flow from the grid to the loads. The operation of the “buy priority” is similar nevertheless, in this scenario the battery allows power import from the grid to the loads and covers the imbalance by absorbing any PV power surplus. The behaviour of the controller can be summarised in the following equations.

Buy priority:

$$P_{bat-setpoint} = \begin{cases} 0, & P_{PV} < P_{Load} \\ P_{Load} - P_{PV}, & P_{PV} > P_{Load} \end{cases} \quad (1)$$

Sell priority:

$$P_{bat-setpoint} = \begin{cases} 0, & P_{PV} > P_{Load} \\ P_{Load} - P_{PV}, & P_{PV} < P_{Load} \end{cases} \quad (2)$$

iii) Graphical User Interface

The operation and remote control of the experiment can be done by means of a GUI developed in MATLAB/Simulink using the Dashboard library elements. A snapshot of the GUI is depicted in Figure 23. By means of this GUI the user can modify some of the model parameters such as the modules parameters (e.g. V_{mp} , I_{mp} etc.) the number of modules and their interconnection in the panel, as well as the load and policy scenarios. In addition to the data logged, the user can in real time see the most important operating parameters in the form of numeric indicators and diagrams.

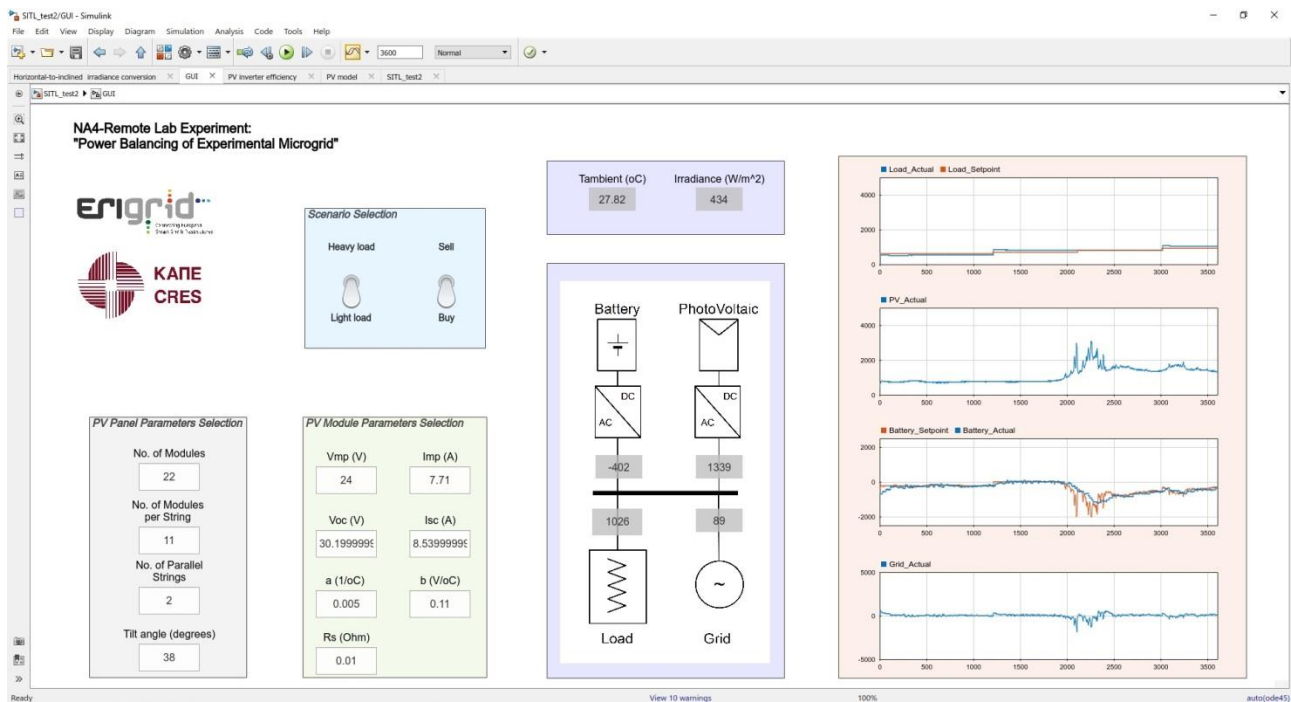


Figure 23: MATLAB/Simulink GUI for the operation of the CRES' remote lab experiment

iv) Test results

Four tests have been conducted to validate the selected setup. These four tests include all possible combinations of load and policy scenarios. Each test has one-hour duration. Two of these test results are depicted in Figure 24.

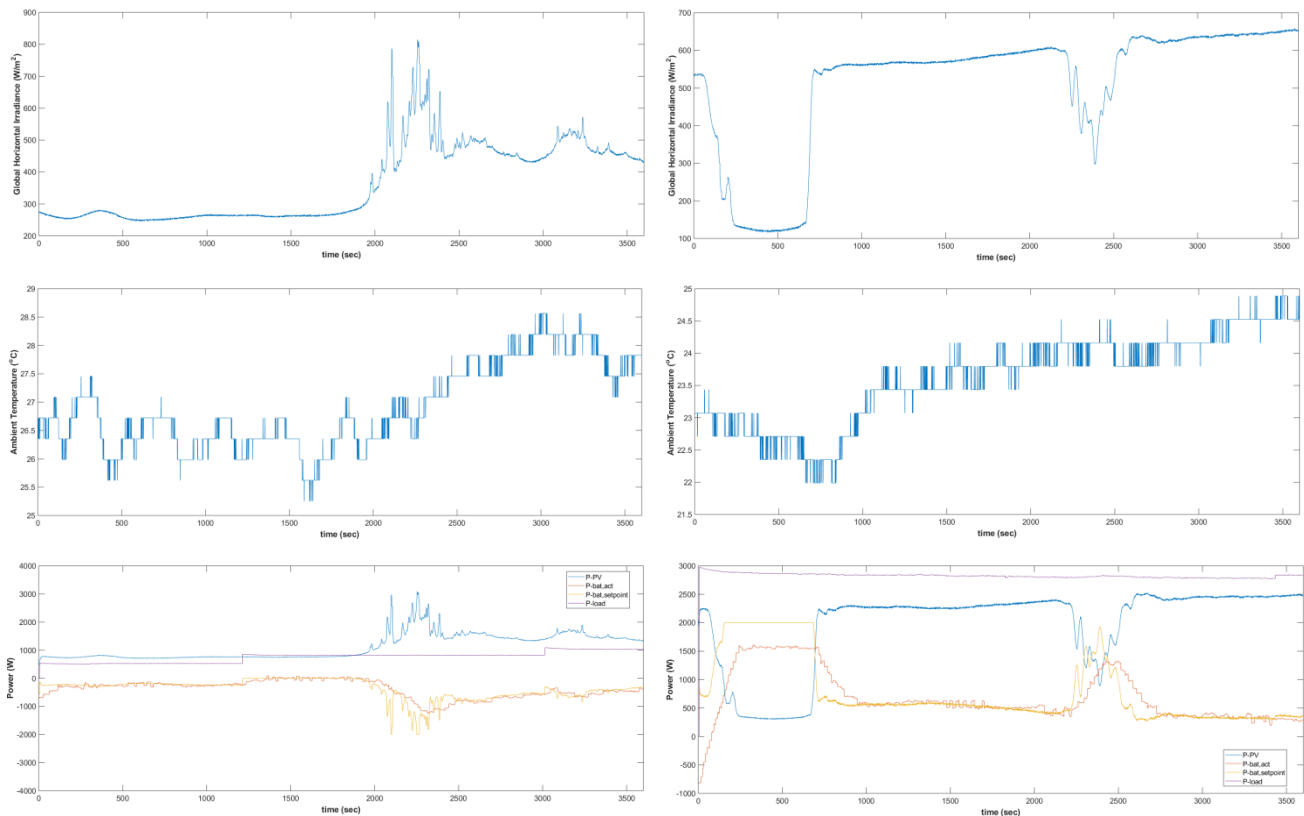


Figure 24: Test results for the light-load sell-policy (left column) and heavy-load buy-policy (right column) scenarios

3.4 Presentations

The presentations with educational/training content, uploaded on the ERIGrid website, are summarized in this section.

Link to the ERIGrid website: <https://erigrid.eu/education-training/#presentations>

i) Metrology for smart grids and testing

These presentations aim to develop awareness on the accuracy of measurement instrumentation used for smart grid applications. Therefore, an introduction into present measurement techniques used within the industry is provided. Furthermore, an introduction into uncertainties and the evaluation of uncertainties in simulation models is also given. Finally, introduction and guidance on the development of PMU algorithms is given, with recommendation on best practices for performing the testing against the standard of these devices in a software environment.

The corresponding lectures are:

- “The impact of power quality on measurements” (University of Strathclyde): in this presentation the importance of accurate power system measurements is demonstrated under future power quality conditions with an increased penetration of inverter interfaced generation. A few measurement algorithms are presented for demonstration purposes.
- “How accurate is a measurement?” (University of Strathclyde): the importance of identifying the accuracies of the measurement instruments, used for purposes such as the validation of power system components, is highlighted in order to understand the results from experiments in an accurate manner.

- “An introduction to measurement uncertainty” (NPL): an introduction to uncertainty evaluation of power system measurements is provided in this presentation.
- “Uncertainties in modelling” (NPL): a number of computational models typically used in the power system domain are presented along with an uncertainty analysis of the models.
- “Adaptive-window PMU algorithms using cascaded boxcar filters to meet and exceed C37.118.1(A) requirements” (University of Strathclyde): this presentation introduces basic PMU architectures and gives guidance on the development on PMU algorithms with an example of an accurate PMU software architecture.
- “PMU (algorithm) testing to C37.118.1(A) in software” (University of Strathclyde): this presentation is an extension to the previous presentation. More specifically, the PMU algorithm described in the previous presentation is tested against the standards in a software environment, offering guidance on how to perform the evaluation.

ii) Co-simulation for smart grids

The following presentations deal with different aspects of co-simulation, which is an important activity of ERIGrid.

- “FMI – Functional Mock-up Interface. Specification and Applications” (AIT). A detailed introduction to the FMI specification and FMI-based applications is provided. The basic concepts of the FMI specification are presented, including the distinction between FMI for Model Exchange (ME) and FMI for Co-Simulation (CS). Furthermore, the XML-based model description scheme of the FMI specification was introduced. Based on this introduction, several FMI-based applications are introduced along with a discussion on interfaces for specific simulation tools.
- “Mosaik introduction” and “The flexible smart grid co-simulation framework” demo (OFFIS). A presentation and an accompanying handout provide an overview of the co-simulation framework mosaik. The material provides the motivation for co-simulation in smart grid research in general as well as the development criteria for mosaik in particular. Furthermore, common co-simulation terminology is explained with the mosaik environment as an example. The mosaik software architecture is briefly explained, along with interfacing simulators and the scheduling of the data exchange between them. The main focus of the presentation, however, is a demonstration of how mosaik can be practically used to establish co-simulation scenarios for smart grid research. This is completed with an overview of application examples and a brief discussion of the possible combination of mosaik and FMI. Finally, links are provided for obtaining the open-source code of mosaik as well as additional documentation.

iii) Holistic testing

The included material is divided into two parts:

- “How to Formulate a Test Specification” (DTU). This presentation introduces the concept of holistic test specification in principle and by example compares it with use cases and summarizes the related system configuration description method. Both use case descriptions and test descriptions are explained, and relevant key concepts are outlined (functions & structure, system boundaries, test criteria, etc).
- “ERIGrid Test Description Templates” (DTU). This document provides core definitions and Word templates for the formulation of a holistic test description. The templates are updated during the course of the ERIGrid project.

The main aim of the presentation on holistic testing is to explain the motivation and provide an overview of the Holistic Test Description approach which was developed in ERIGrid NA5. The presentation thereby serves as an introduction to the holistic test description templates to be used, for example, in conjunction with transnational access projects in ERIGrid.

The holistic test specification / description method was developed in ERIGrid to structure and guide the holistic validation approach. This test description method has been adopted into several ongoing H2020 national and international projects, e.g. SmILES (H2020), ELECTRA IRP (FP7), EnergyLab Nordhavn (Danish), CITIES (Danish). The presentation here is based on lectures held at an ERIGrid summer school and classroom teaching at DTU.

iv) Photovoltaic systems

The main aim of this subset of presentations is to provide practitioners with some guidelines in terms of modelling and simulation of Photovoltaic systems. The proposed modelling methods find application in both real-time and non-real-time simulation approaches. The selected material is divided into three presentations:

- “Autonomous and Grid-connected Photovoltaic Systems Modelling for Simulation Purposes” (CRES). This presentation deals with the mathematical models that a researcher can use in order to simulate the behaviour of PV elements (cells, modules, arrays). The main focus is on static operation models which do not take into account the impedance of the PV cells. The most analytical of the presented PV models are the parametric model, the equivalent circuit and the interpolation model. It is worth noting that the latter model has also been used in the activities of JRA2.2 (FMU of PVs) as well as in the aforementioned Remote Lab experimental setup provided by CRES. The analysis of these models illustrates the way the current varies with voltage and vice versa, as well as the effect that parameters such as irradiance and temperature have on the PV performance. Together with the mathematical formulation of these models, some simple implementation examples are also presented. Another important aspect that this presentation deals with is the modelling of batteries, in particular lead-acid batteries by means of the Kinetic Battery model, which allows the calculation of the voltage and remaining capacity of a battery. Last but not least, the presentation provides some simplified guidelines in terms of modelling PV inverters and diesel generators that can be used as backup systems.
- “Overview of methods for Maximum Power Point Tracking in PVs” (CRES). This presentation deals with a more analytical approach of PV inverter aspects, and in particular the Maximum Power Point Tracking methods (MPPT). The presentation analyses the particularities and algorithmic implementation of various widely used MPPT techniques such as Perturb & Observe, Constant Current, Constant Voltage, Reference Cell, Incremental Conductance and Parasitic Capacitance. The behaviour of PV systems under partial shading conditions is also addressed in the last part of the presentation.
- “Overview of methods for HW Simulation for PVs” (CRES). This presentation shows an important aspect related to the performance evaluation of PV inverters, which is the emulation of PV systems (PV arrays) by means of power electronic converters. Thus, it is possible to reproduce real operating conditions of PV in a fully controllable laboratory environment. To this end, this educational material aims to familiarise practitioners with the basic concept of PV emulators and how it is possible with simple topologies and control techniques to obtain the desired I-V curve from a power converter. Therefore, the presentation addresses emulator topologies based on diodes, switched-mode power supplies and linear power supplies.

4 Hands-on Laboratory Education

This section reports on the developed laboratory exercises using real-time simulation. First, an introduction to the importance of laboratory education and the advantages of real-time HIL simulation in this regard is provided. Then two different sets of hands-on laboratory exercises are presented:

- Hardware in the loop for DER integration and microgrids.
- Introduction to Real Time Digital Simulation and Application in Sustainable Energy Systems.

A description of the laboratory exercises is provided on the ERIGrid website (including software files for the 2nd set of lab exercises).

Link to the ERIGrid website: <https://erigrid.eu/education-training/#labexercises>

4.1 Real-time Simulation for Laboratory Education

Laboratory education provides a link between theory and real world offering valuable practical experience to students. The necessity to incorporate laboratory exercises in the power systems domain has been recognized since decades. In the last years, the wide-spread integration of DG and the on-going transformation of traditional power systems to smart grids demand new material in the power system curriculum. Accordingly, appropriate laboratory exercises need to be introduced. Several institutions have recognized this need and are contributing to laboratory education in this field [9], [14], [26], [27], [28], [29].

Laboratory education on power systems is usually performed with simulation software [9], [30] or less frequently with dedicated hardware setups [14], [26], [27], [28]. On the other hand, laboratory education on power electronics and electric machines is typically performed with hands-on exercises using physical models or real hardware, as the focus is on the component level. The limited use of real hardware on power system education is obviously due to the difficulty and cost of having a realistic power system setup in the lab (including generators, transformers, lines, loads, On-Load Tap Changer (OLTC), DG inverters). As a result, small educational hardware setups usually perform specific functions and cannot be easily used for a wide range of experiments.

Several decades ago, analogue transmission line models and miniature generators were used at universities and AC network analysers at utilities [31]. The emergence of computers and the development of advanced dedicated software packages allowed analysis, research and education in power systems based on digital simulation, due to its flexibility, possibility to create complicated models, friendly graphical user interfaces, low cost etc. Although this evolution opened new paths in education, it deprived the students from the physical understanding of phenomena and their familiarization with power system hardware [31], [32].

Real-time HIL simulation is the connection of hardware equipment to a real-time simulated system (e.g., distribution network) executed in a Digital Real-Time Simulator (DRTS) [33]. At Controller Hardware-in-the-Loop (CHIL) simulation [34] a hardware controller is tested (e.g., controller of an inverter, relay) whereas at PHIL [35], [36], [37] a hardware power device is tested (e.g., inverter, motor). HIL simulation merges simulation and hardware testing providing hardware experience to the students while exploiting the advantages of digital simulation. The following features of HIL simulation are beneficial for educational purposes:

- The students face a real-time system (like a Supervisory Control and Data Acquisition (SCADA) system), where they can perform actions and monitor the operation in realistic conditions. The flexibility, ease of modelling and designing test scenarios of digital simulation are maintained.
- The connection of real hardware devices such as DG inverters, microgrids, relays can be realised, so that students can observe the operation of real apparatus. Measurement of actual

magnitudes and control of real devices is a valuable experience.

- Components that are not available in the lab (e.g., OLTC, diesel generator) can be simulated in real-time and their interaction with hardware devices can be studied.
- Challenging tests, such as faults, can be performed safely and conveniently in a real-time simulation environment without hazardous effects or equipment stress. The type, duration and location of faults can be easily modified by the students, which would be difficult in a fully hardware setup.

Real-time CHIL simulation has been used numerous times for educational purposes [38] in domains such as control systems [39] and machine drives [40]. Concerning power system education, CHIL simulation has been mostly applied for protection system studies, such as in [41], where a commercial hardware relay was tested at different types of faults on a real-time simulated network, as part of a university course. An interactive platform to assess advanced distribution automation on smart grids for educational purposes was implemented in [42], where the users could incorporate protective algorithms and automation solutions (such as adaptive protections and reconfiguration methods to optimize the grid). In [9] real automation infrastructure (SCADA, controller etc) was connected to a simulated PV inverter and R-L-C circuit to perform anti-islanding detection tests for the training of lab personnel. Real-time simulation without connection of hardware devices (i.e. not HIL) was used in [41] for student projects on frequency control, flexible AC transmission systems, voltage stability, transient stability and was proposed in [43] for education on protection coordination studies with multiple fault scenarios.

The potential of PHIL simulation for lab education, however, has been much less explored, as it is a newer and more complex technique than CHIL (amplification is necessary, and stability/accuracy needs to be ensured). PHIL simulation allows the investigation of complex interactions between physical power apparatus and simulated systems in a realistic way, thus promoting the transition from component testing to system testing.

In the ERIGrid project, PHIL simulation is employed for the first time for hands-on laboratory education on important topics of modern power systems and its value as an educational tool is demonstrated. An overview of the laboratory exercises including learning objectives, topics, methodology and lab adaptations is provided next. The four laboratory exercises are described in detail and the feedback of the students is analysed. The description of the laboratory exercises in section 4.2 is derived from [16], which is a publication of the ERIGrid project.

4.2 Lab Exercises: Hardware in the loop for DER Integration and Microgrids

4.2.1 Educational Approach: Experiential Education

Experiential education is a philosophy according to which educators engage their students directly to the object of knowledge and later on to a focused reflection relative to that engagement in order to increase knowledge, develop skills, clarify values, and develop their capacity to contribute to their communities. According to the philosopher and educational reformer John Dewey [44], learning is promoted not through books and lectures, but is left to emerge during the elaboration of the experiences of students themselves. Students are encouraged to get personally involved in projects and experiments and during that involvement they are “internally enforced” to learn. This educational approach has been described as “learning by doing”.

In 1984 Kolb [45] suggested a four-stage learning cycle to describe what is happening during the transformation of the experiences. According to that cycle, the initial concrete experience is being elaborated and reflected upon (reflective observation) in order for the learner to reach an abstract conceptualization, which is the third stage of the learning cycle. That abstract concept is being applied in real life situations (active experimentation) so that a new concrete experience emerges which is elaborated and reflected upon and so on (Figure 25). Kolb's cycle has been used in engineering technology courses [46], where usually lab exercises are incorporated into engineering courses [47].

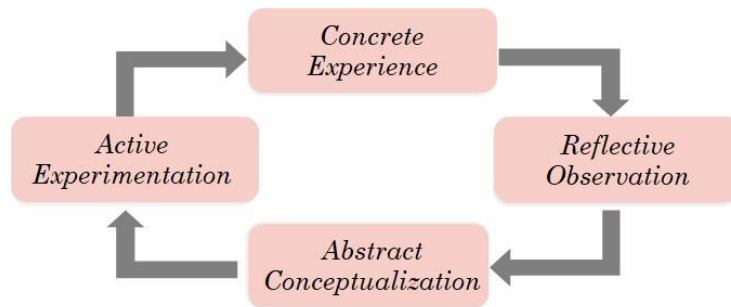


Figure 25: Kolb's four-stage learning cycle [45]

In the following sections, the laboratory exercises performed in the framework of two basic, undergraduate courses on Electric Energy Systems Analysis (5 credits each at the European Credit Transfer and Accumulation System (ECTS)) taught at the School of Electrical and Computer Engineering of ICCS-NTUA are presented, taking into account the four-stage experiential approach of Kolb's cycle. It should be noted that the authors do not claim that experiential education can by any means replace class lectures, but it can very well complement and support the educational process.

4.2.2 Learning Objectives, Selected Topics, Methodology and Lab Adaptations

The main learning objectives of the laboratory exercises are:

- Understanding fundamentals of power system operation.
- Understanding important contemporary issues due to the integration of DG: technical challenges, benefits and perspectives.
- Familiarization with hardware components including measurement and control.

To achieve these objectives the laboratory exercises start from the fundamentals of traditional power system operation, integrating gradually DG related topics in order to assist the students to understand the transition of the traditional system to the more complex decentralized environment. The selection of the topics which is described next is in line with the learning objectives.

During the classroom lectures the students are taught fundamentals of power system operation, such as primary frequency control (synchronous generators – droop control), voltage control (capacitors, OLTC) and short circuit analysis (synchronous generators induction motors/generators models, asymmetric conditions). The challenges of DG integration have been superficially addressed in the two basic courses, while they are taught in detail in later elective courses. During the experiments, the DG integration topics are offered to the students directly in the lab (concrete experience) without in-depth theoretical knowledge. In particular, voltage rise as the main technical constraint for DG integration in rural distribution networks, DG contribution to faults and the operation of microgrids are topics of particular interest, since several non-interconnected medium and small size islands are operated in Greece.

In this context, four topics are selected for the laboratory exercises:

- i) Parallel operation of synchronous generators - parallel operation with DG.
- ii) Voltage control of distribution networks - contribution of DG.
- iii) Short circuit studies – contribution of power electronics interfaced DGs.
- iv) Microgrid operation and control.

The methodology applied is a hands-on approach combined with experiential learning, when possible. Four laboratory exercises are grouped in two sessions with a duration of 50 minutes each. The students are divided in eight groups of five or six students and during a laboratory session

each group attends successively the tests at the two work benches available, thanks to the double PHIL setup (shown in Figure 26). The laboratory sessions are carried out during the weekly two 2-hour blocks of the course. At the end of each laboratory session, the students are asked to fill in short reports based on measurements and reply to simple numerical exercises which account for 10% of the course mark.

After each experiment, suitable questions on real problems are posed to facilitate understanding, taking into account the student's existing knowledge (reflective observation). Guided conversations with the students or direct instruction, when considered necessary, lead to new concepts (abstract conceptualization). On this ground, new experiments are performed (active experimentation and new concrete experience). The reports at the end of the session aim to reflect the laboratory experience (reflective observation).

The laboratory was enhanced in order to provide hands-on experience instead of performing demonstrations. The lab is equipped with the two prevailing technologies of power amplifiers: a linear amplifier and a switched-mode amplifier. In this way it is possible to perform either a single PHIL experiment with two hardware power devices connected to different network nodes, or two independent PHIL experiments, each with its own simulated network and hardware power device. For educational purposes the latter configuration is employed, as it allows two independent experiments to be performed at the same time. Apart from the two amplifiers and the two hardware power devices (i.e. inverters), it is also necessary to run two independent network models in the one DRTS rack controlled by two PCs. The aforementioned double PHIL configuration is illustrated in Figure 26. Two independent PV simulator modules are connected to the DC side of the PV inverters, as the active power of the PVs needs to be controlled from different PCs. Modern PV inverters with advanced functions are used, which allow access to the user (e.g. to send a reactive power set-point, set a specific droop characteristic, curtail the active power) from the dedicated software of the manufacturer.

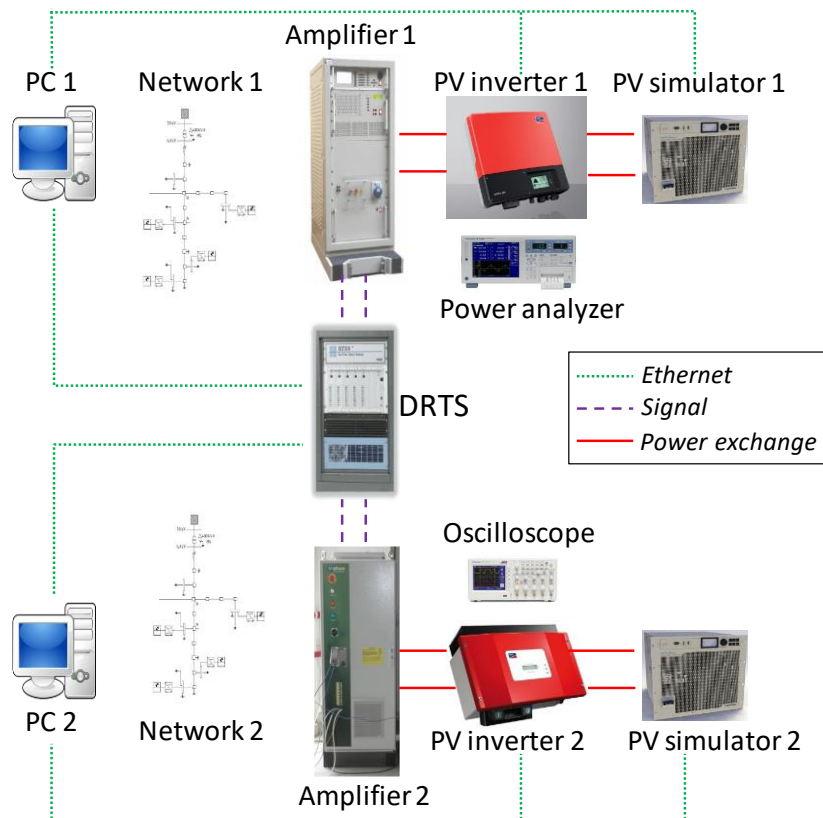
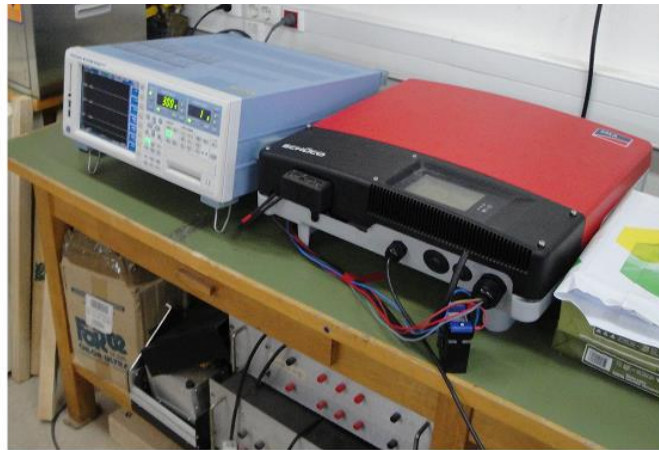


Figure 26: Lab infrastructure for the hands-on training of students: Double PHIL configuration

The laboratory equipment in use during the laboratory exercises and the two work benches are shown in Figure 27 and Figure 28.



Figure 27: Performing the laboratory exercises: switched-mode amplifier, line emulator, linear amplifier, load, DRTS, digital relay (from left to right)



Work bench 1



Work bench 2

Figure 28: Two work benches: inverter, oscilloscope or power analyser and computer (connected to the DRTS, controlling the Photovoltaic simulator and the inverter)

4.2.3 Parallel Operation of Synchronous Generators – Integration of DG

A simple network consisting of two synchronous generators (including prime-movers, governors and automatic voltage regulators), distribution lines and a load is provided in the DRTS. The students change the active power of the load at the DRTS software and measure the active power of each synchronous generator and the operating frequency (steady-state and minimum or maximum value).

An actual PV inverter replaces the one synchronous generator and is connected to the simulated network in the DRTS (PHIL configuration shown in Figure 29). The irradiation from the PV simulator is increased and the students note the increase in the system frequency (concrete experience). A problem-based learning approach is applied based on the “50.2 Hz problem”, which was noted in 2011. According to the standards at that time, the DGs had to disconnect at frequency values exceeding 50.2 Hz, meaning that in this case, several GWs of PV generation would be simultaneously disconnected from the network affecting system stability [48]. The students are asked to solve this problem and comment on how DG can participate to primary frequency control (reflective observation). The students are led to the solution of applying a $P(f)$ droop characteristic at the PV inverter similar to conventional generation (abstract conceptualisation).

Next the $P(f)$ droop characteristic of the PV inverter is activated (required by recent standards [49], shown on the right side of Figure 29). The active power of the simulated load is decreased (step) and again the active load is shared between the synchronous generator and the DG (active experimentation). The active power of the PV inverter with and without droop control is shown together with the system frequency in Figure 30 and Figure 31, respectively. From the results it is clear that the decrease of the active power of the physical inverter based on its droop characteristic leads to an improved frequency response compared to the operation without droop control (Figure 31). It is understood that in cases of low load and high DG production the active power of the DG is controlled without the need of a communication network.

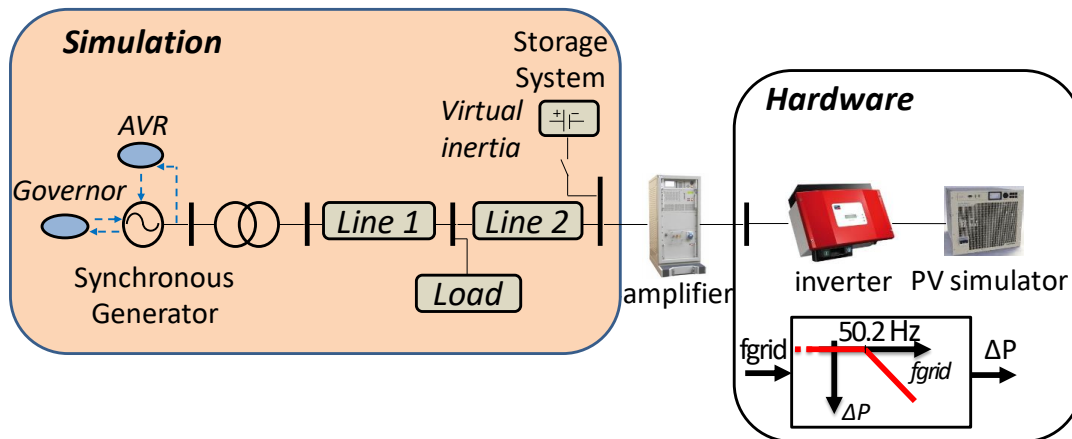


Figure 29: Parallel operation of a synchronous generator, hardware PV inverter and storage with virtual inertia (PHIL simulation)

Moreover, the capability of inverter-based DG and storage to compensate the reduced rotational inertia of the power system due to the increased DG integration is demonstrated, making use of the “virtual synchronous generator” concept [50]. Accordingly, a storage system emulates the rotational inertia of synchronous generators following the below equation. The storage system is simulated in the DRTS and its active power during the PHIL test is shown in Figure 32. The improved frequency response at dynamic conditions is shown in Figure 31.

$$P_{storage} = k_i \frac{d\omega}{dt}$$

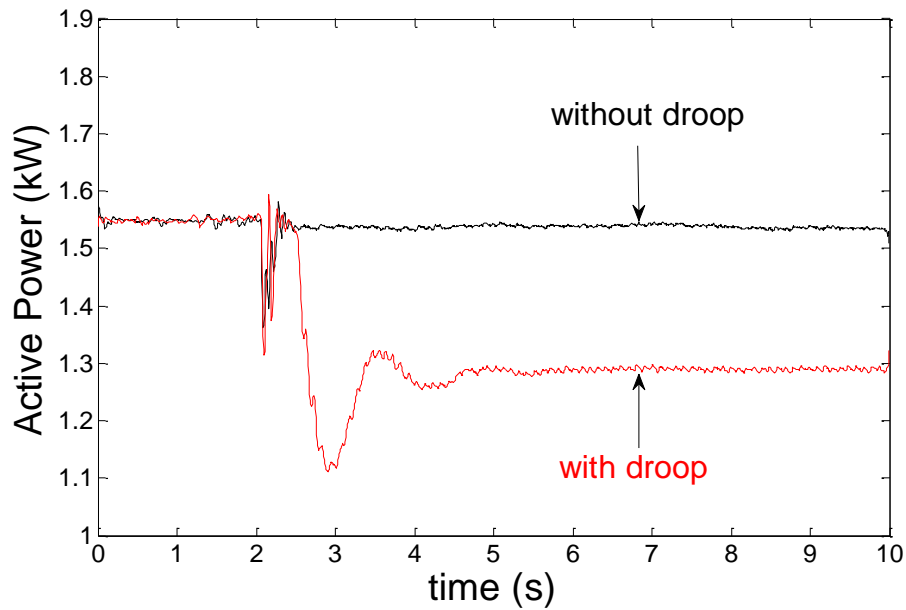


Figure 30: Active power of the hardware PV inverter with and without $P(f)$ droop control

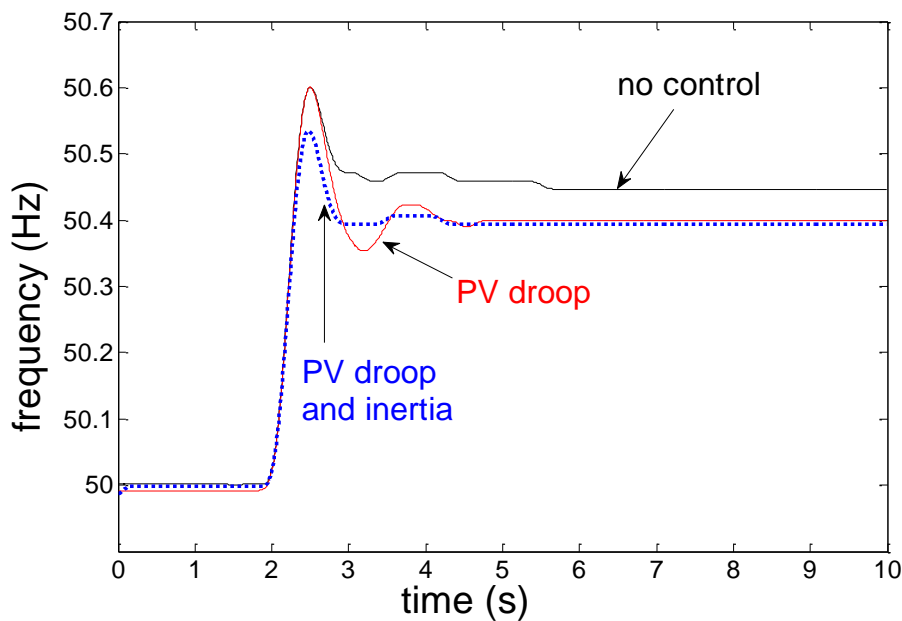


Figure 31: Frequency without $P(f)$ control, with $P(f)$ control of the hardware PV inverter and combination with virtual inertia provided by the storage system

The experiments are designed so that the students are actively involved, e.g. they set the $P(f)$ droop parameters of the PV inverter via its software interface, experiment with different gains of the inertia emulation (k_i) and change the load in the DRTS and the irradiation in the hardware PV simulator. Moreover, the students measure the active power of the hardware PV inverter and the system frequency with a power analyser and the active power of the synchronous generator and frequency in the DRTS. At the end of the exercise, they are asked to provide a report based on the measurements, i.e.: to calculate for the given test-case (synchronous generator and PV operating with droop control) the power sharing and frequency and compare with the experimental results. Additional questions aim to explain why DG droop control is mainly used for over-frequency and not so often for under-frequency events.

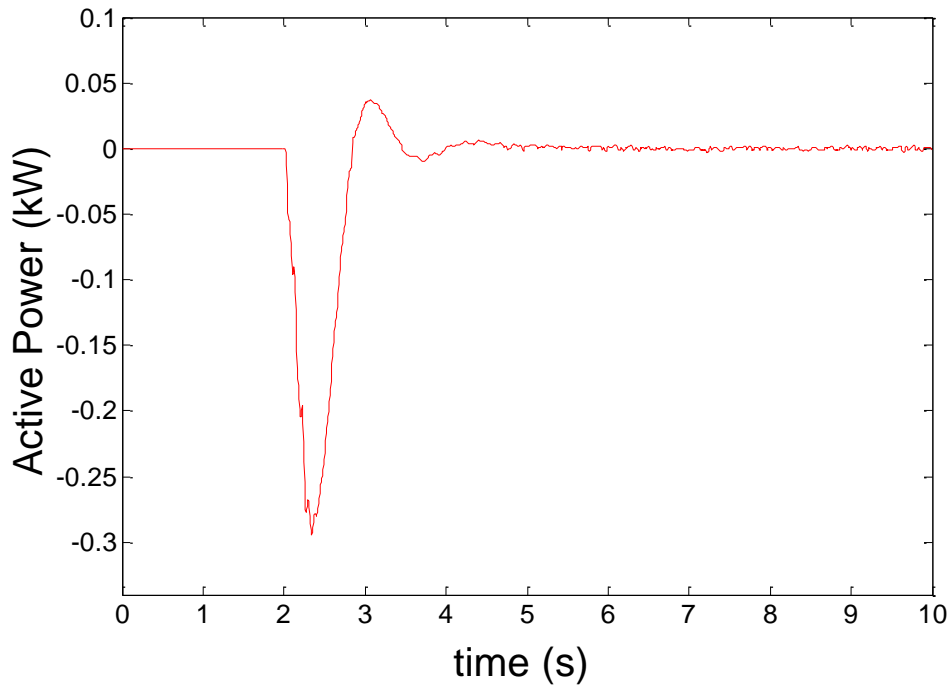


Figure 32: Active power of the storage system providing virtual inertia

4.2.4 Voltage Control of Distribution Networks – Integration of DG

The students are already familiar with the theory of conventional voltage control approaches, such as the use of capacitors and OLTC and the effect of the active and reactive power of the load on the voltage, as shown in the below (voltage drop) equation.

$$\Delta V \approx \frac{P \cdot R_{line} + Q \cdot X_{line}}{V_{load}}$$

Figure 33 shows the overall setup for the second experiment. A hardware PV inverter and a load bank (*Load 2*) are connected to a weak distribution network fed by a transformer equipped with an OLTC. As a transformer with OLTC is not available in the lab it is simulated in the DRTS via PHIL simulation. An additional load (*Load 1*) is inserted in the real-time simulation.

Conventional voltage control is applied first without the presence of the PV inverter and the simulated load (*Load 1*). The OLTC controller employs line-drop compensation, i.e. it estimates the voltage at the end of the feeder based on the measured voltage and current on the secondary side of the transformer. The hardware load (*Load 2*) is gradually increased, leading to a voltage drop below the lower threshold of the OLTC. The OLTC changes the tap position in order to bring the voltage within the desired range.

Next, the physical PV inverter is connected at the end of the long feeder and the OLTC gets deactivated. The students control the active power of the PV simulator by changing the irradiation for a given *I-V* curve via its software environment. While keeping *Load 2* low, they steadily increase the active power of the PVs from zero to nominal and observe the voltage rise occurring at the inverter's terminal (concrete experience). The students try to solve this overvoltage problem, which is one of the main challenges faced by the integration of DG in rural distribution networks (reflective observation).

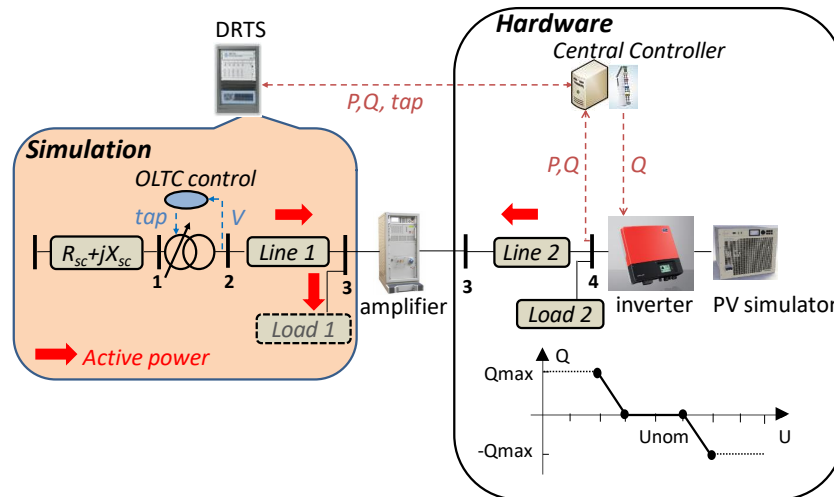


Figure 33: Voltage control by DG, OLTC and centralised coordinated control (PHIL and CHIL simulation)

Extending the aforementioned voltage drop equation to include also generation, the students understand the effect of reactive power absorption by the PV inverter on the voltage rise (abstract conceptualization). The students send reactive power absorption set-points to the PV inverter (until minimum $\cos\phi=0.8$) via its software interface, monitor the voltage and validate its effect (active experimentation). Then a reactive power vs. voltage droop curve is implemented (i.e. $Q(U)$ shown in Figure 33) locally in the inverter's control, as required by recent standards [49], and the experiment is repeated with similar results. The need for DG to support the grid by providing ancillary services is highlighted (as also shown at the exercise in Section 4.2.3). Additional solutions are discussed, which can also be derived from the voltage drop equation (i.e. grid reinforcement, DG active power curtailment).

Another series of experiments involves the use of the OLTC. The OLTC gets activated and regulates the voltage at the end of the feeder, while the PV inverter operates at unity power factor. A large load (*Load 1* in Figure 33) is now connected to the network and the resulting active power flow is shown in Figure 33 (the reactive power is not shown for simplicity as it weakly affects this experiment). Obviously, the previous simple line-drop compensation estimation is not valid due to the presence of *Load 1*, therefore the voltage at the end of the feeder is measured and sent to the OLTC controller. Figure 34 shows that the OLTC manages to reduce the overvoltage at the PV inverter's bus, however it generates a higher under-voltage at the bus of *Load 1*. The necessity of a coordinated operation of existing voltage control appliances (e.g. OLTC) and modern devices (e.g. PV and storage inverters) is noted. More complex interactions of OLTC and DG [37] can be used.

An optimal coordinated voltage control scheme is applied next, where a central controller measures the active and reactive power at all nodes and sends reactive power set-points to the PV inverter and tap changing commands to the OLTC. The objectives of the optimization problem are the minimization of the voltage deviations, number of tap changes and line losses. A hardware controller, executing the optimization algorithm, exchanges signals with the DRTS (i.e. CHIL) and the hardware PV inverter. The implemented setup is shown in Figure 33.

During the experiments the students measure the active-reactive power, voltage-current (rms), vector diagram and waveforms of voltage and current (to see the phase shift and changes in the amplitude of the current) on the hardware PV inverter and the transformer voltage, the number of tap changes, voltage step and time-delay of the OLTC in the DRTS. The students report the influence of active and reactive power on the voltage at different R/X ratios of the lines (i.e. low voltage, medium voltage, high voltage lines) among other topics. In this way, the coupling of active power with voltage in networks with high R/X ratios (e.g. underground low voltage cables) is highlighted, contrary to networks with low R/X ratio (e.g., overhead high voltage lines) where the voltage is predominantly influenced by reactive power.

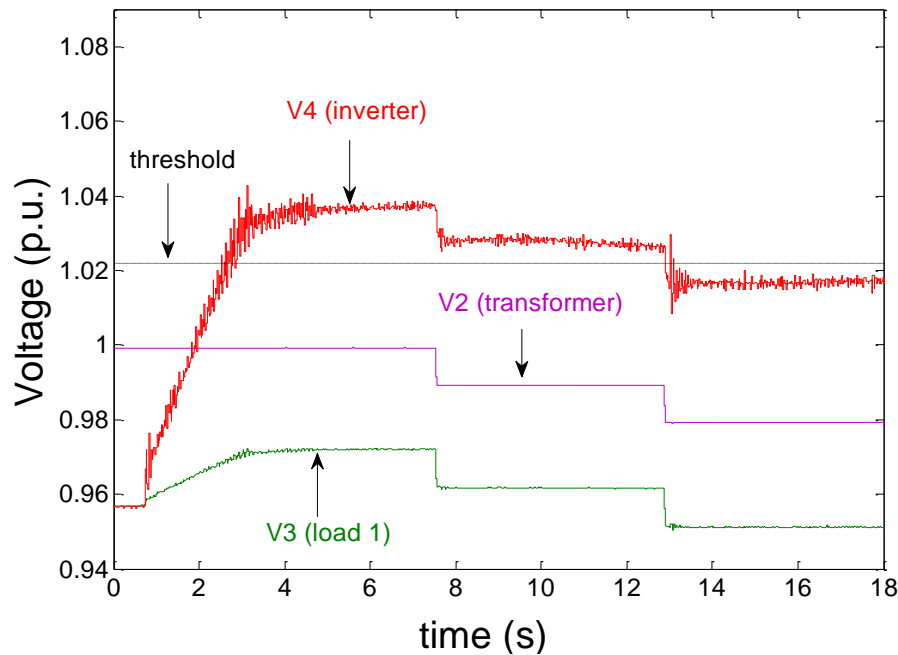


Figure 34: The PV production raises the inverter's voltage (V4) which is then decreased by the OLTC, however reducing further the voltage of Load 1 (V3)

4.2.5 Short Circuit Studies – Integration of DG

These experiments show fundamental concepts of traditional short circuit analysis, but mainly focus on the behaviour of inverter-based DG (e.g. PVs, wind turbines with permanent magnet synchronous generators) during faults.

First, the students apply short circuits at different locations of a simulated low voltage distribution network in the DRTS and measure the resulting current. A hardware relay monitors and controls a simulated circuit breaker at the secondary of the transformer (Figure 35). The students observe that as the location of the fault moves away from the transformer, the short circuit current flowing from the upstream network is decreased (due to the greater equivalent impedance) and the trip time of the hardware relay is increased. Also, the voltage at the different buses is monitored during the short circuits.

Prior to connecting the physical PV inverter to the network in a PHIL configuration, the location of the three-phase short circuit and of the PV inverter need to be determined, (i.e. chosen between buses 2,3,4 of Figure 35), so that during the fault the voltage of the inverter bus drops to approximately $1/3$ of its pre-fault value. The PV inverter is neglected in this approximate calculation, as its nominal power is small and its fault contribution is much smaller than the current drawn from the upstream network. The loads are neglected for the same reason. Having achieved this, the physical inverter is connected to the simulated network and a three-phase short circuit is applied, as illustrated in Figure 35.

The physical PV inverter operates at low power before the fault and its behaviour during the fault is recorded by an oscilloscope, as shown in Figure 36b. The short circuit current is increased to approximately 3 times the pre-fault current in response to the voltage drop at $1/3$ (concrete experience). This happens because the control algorithm of PV inverters is normally designed to maintain operation at fixed active power (and power factor) for a constant input from the DC side (reflective observation). The experiment is repeated with nominal power.

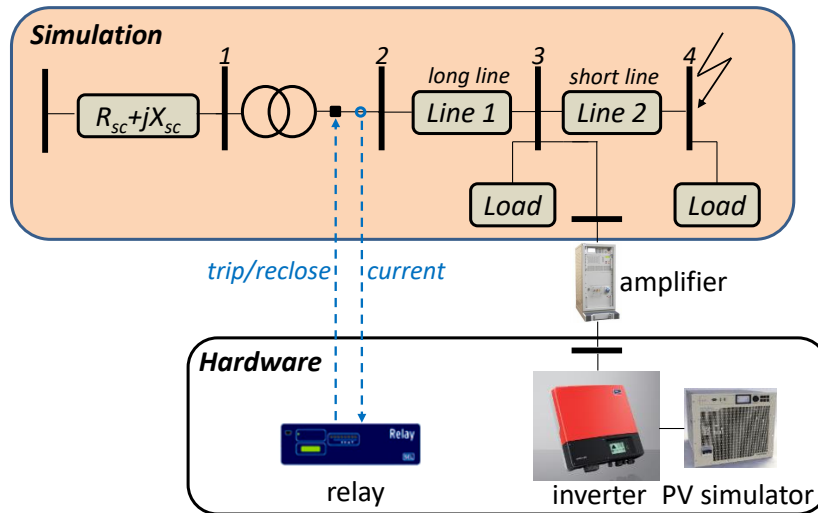


Figure 35: Short circuit testing of inverter-based DG (PHIL and CHIL simulation)

Figure 36c demonstrates that there is a limit at approximately 1.3 times of the nominal current which does not allow a higher increase (concrete experience). It is concluded that the current limitation (typically below two times of the nominal current, depending on the manufacturer) is incorporated in the control algorithm of the inverter in order to respect the thermal limits of its switching devices (abstract conceptualisation). A second PV inverter of a different manufacturer is used and the experiment is repeated (active experimentation). It is noted that the inverters exhibit a partly different behaviour during the fault i.e. gradual increase of the current until the maximum value (Figure 36c) or fast increase of the current until the maximum value and then gradual reduction. In this way, the students learn that the contribution of inverter-based DG depends on the pre-fault operating condition of the inverter, the voltage drop at its terminal and its specific control algorithm. The usual assumption in practical calculations of 1.5-2 times of the nominal current is tested [51]. An interesting analysis of the actual operation of inverter-based DG during faults can be found in [52].

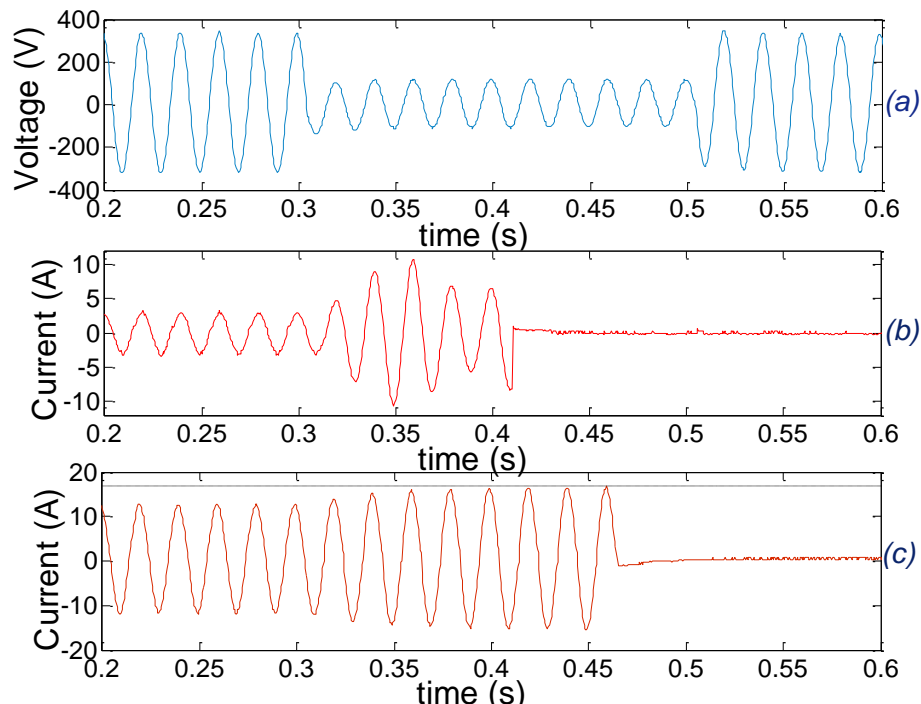


Figure 36: Short circuit behaviour of the PV inverter at low power (b) and nominal power (c). The current limitation is visible.

4.2.6 Microgrid Operation and Control

The laboratory microgrid of ICCS-NTUA is used in a PHIL configuration (Figure 37). At first, the microgrid [53] operates in grid-connected mode and the students note the active power of the PVs, wind turbine, storage and load of the microgrid from the SCADA developed at NTUA and also the active power flow at the secondary winding of the transformer in the DRTS (concrete experience). The key role of the storage system as the most controllable unit is highlighted and its applications, such as balancing the PV and wind turbine production, peak shaving, voltage control, self-consumption, etc, are discussed. For the experiment it is assumed that the network or market operator requires a specific amount of active power from the microgrid as a controllable entity for technical (e.g. congestion, voltage violation) or economic reasons [54].

The students take the role of the microgrid operator who has to implement the required set-point by controlling the storage system and potentially the controllable loads. Based on measurements of the active power of the PVs, wind turbine, and load of the microgrid, the required active power of the battery inverter (absorption or production) is calculated, in order to achieve the required set-point (reflective observation). The set-point is implemented in the commercial battery inverter via software developed in-house (active experimentation). Figure 38 shows the active power of the different components and the upstream network, where the set-point is received (at $t=35s$, the battery starts to absorb active power) followed by an irradiation reduction in the PV simulator (at $t=67s$, the battery decreases the absorption and starts to produce active power). The importance of different layers of control in the smart grid is explained (abstract conceptualization) accompanied with aspects of information and communication technologies.

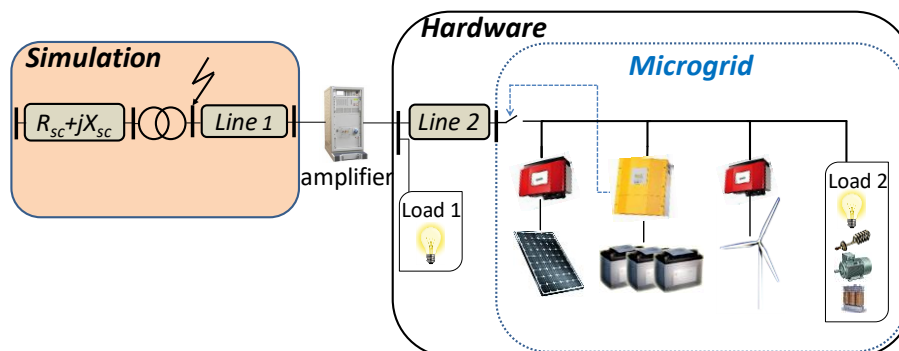


Figure 37: Setup for microgrid experiments (PHIL simulation)

Then a fault occurs at the transformer (in the DRTS at Figure 37) producing a significant voltage dip which forces the microgrid to switch to island mode. Subsequently, the battery inverter becomes the grid-forming unit. The students have the opportunity to experience the seamless transition from grid-connected to island mode by observing that both the PV inverter and the load of the microgrid remain connected (*hardware load 2*: lights on), however the load outside the microgrid is disconnected (*hardware load 1*: lights off). The capability of microgrids to improve the reliability and maintain the power supply during external disturbances and grid interruptions is illustrated.

Island operation of the microgrid is examined next, where the voltage and frequency are defined by the battery inverter. The students observe the active power balance and confirm that the battery inverter balances the difference between the production (PVs and wind turbine) and consumption. Moreover, the capability of the battery inverter to operate with droop control, similar to a synchronous generator, is explained. This is particularly useful when more controllable units (e.g. battery inverters) are connected to the same islanded microgrid (power sharing is achieved similarly to Section 4.2.3 [53]). The students learn that islanded microgrids are installed in remote off-grid locations, such as rural communities in developing regions etc.

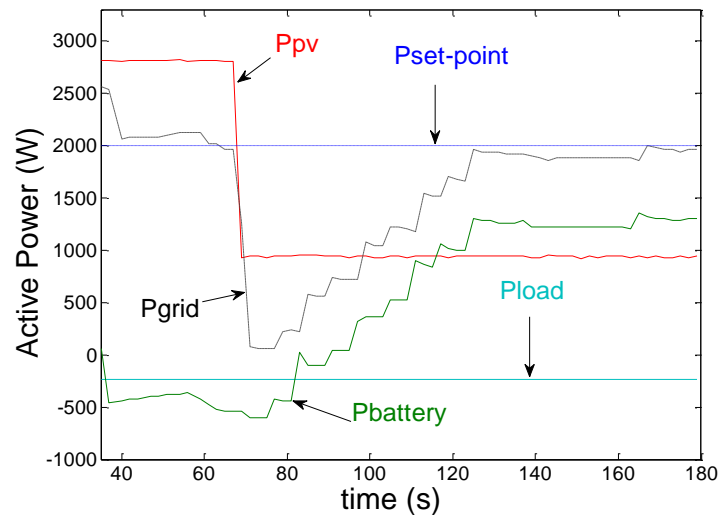


Figure 38: The students control the active power of the battery inverter to fulfil a set-point of 2 kW production from the microgrid; the small deviation between $P_{\text{set-point}}$ and P_{grid} is due to the online approximate calculation by the students

4.2.7 Student Feedback

Questionnaires were prepared in order to get feedback from the students regarding the evaluation of the exercises and the student's opinion on relevant matters. Questions 1 to 6 refer to the evaluation of the exercises and questions 7 to 10 to their opinion on important matters. The students are asked to provide a response from 1 to 5 using the Likert scale (1: I strongly disagree, 2: I disagree, 3: I am neutral, 4: I agree, 5: I strongly agree). Two open ended questions were also included concerning proposals for improvement and general comments. Each exercise is attended by approximately 50 students. The questionnaires were handed to the students at the end of both exercises, therefore about 95 questionnaires were received (96% of the participants provided feedback). The questions and the feedback of the students are shown in the upper part of Table 2.

Table 2: Results of the student surveys

Question	Mean	Standard Deviation
1) The topics of the laboratory exercise are interesting	4.35	0.58
2) The presentation of the laboratory exercise is adequate	4.27	0.63
3) The active participation and use of equipment by the students is encouraged	4.03	0.95
4) The laboratory exercise has helped me understand the operation of traditional power systems	3.61	0.75
5) The laboratory exercise has helped me understand the operation of modern power systems with distributed generation	4.16	0.69
6) The laboratory exercise is interesting (in overall)	4.23	0.63
7) Real-time simulation is a useful educational tool	4.45	0.71
8) The use of hardware equipment by the students is more interesting than a simple demonstration	4.39	0.70
9) The introduction of modern topics (distributed generation) increases my interest in the laboratory exercises and in the power system courses in general	4.46	0.60
10) The introduction of additional laboratory exercises in the power system courses is useful	4.43	0.68

Question	Mean	Standard
Graduates feedback		
i) Real-time simulation is a useful tool for student dissertations	4.75	0.43
ii) The use of hardware equipment at a dissertation is more interesting/useful than pure simulation or literature review	4.75	0.43

A sample of the responses on the questionnaires is shown in Figure 39 (*questions 5, 6 and 7*). The students found the exercises overall interesting (55%) and very interesting (34%) (*question 6*). They highly appreciated the use of real-time simulation for educational purposes (37% *I agree*, 55% *I strongly agree* - *question 7*) despite the complexity of the implementation (amplifiers, sensors etc). They were also satisfied with the level of their involvement and use of equipment (42% *I agree*, 35% *I strongly agree* - *question 3*). Moreover, they prefer hands-on approaches compared to demonstrations (51% *I strongly agree* - *question 8*), they find the introduction of modern topics motivating (51% *I strongly agree* - *question 9*) and are very keen to participate to more laboratory exercises (53% *I strongly agree* - *question 10*).

The lowest rating concerned the knowledge on the operation of the traditional power system (38% *I am neutral* - *question 4*) and will be considered for the exercises next year. The feedback about possible improvements and informal discussions led to the conclusion that it is useful to increase the duration of the exercises in order to allow more use of equipment by the students.

Based on Kolb's theories, the more lab exercises are similar to real life situations, the more attractive they are to students, as shown in their answers in question 7. They were not satisfied with simple demonstration (*question 8*), probably because in that situation only stage 1 and 2 of Kolb's cycle are visited (concrete experience and reflective observation), not necessarily leading to stage 3 (abstract conceptualization) and definitely not reaching stage 4 (active experimentation). On the contrary, performing experiments with the hardware equipment meant that they went through all stages of the Kolb's cycle. Consequently, this experiment seems to have more significance to them, probably due to the involvement of more senses [55] [56] and more complicated mental procedures, which indicates their active involvement.

Another interesting educational aspect is that students become eager to use real-time HIL simulation/experiments for their diploma dissertations. Starting from 2011, ten undergraduate students have selected topics involving real-time simulations at the Electric Energy Systems laboratory of NTUA. The main topics are: stability and accuracy in PHIL simulation, amplifier control for PHIL simulation, voltage rise mitigation by PVs (PHIL), control of hybrid off-grid systems (PHIL and CHIL), PV inverter controls development and testing (CHIL), coordinated voltage control of distribution networks (CHIL), demand response (CHIL) and real-time modelling of wind turbine for frequency control. In particular, the development of the PHIL facility was assisted by the results of two dissertations on the real-time modelling in the DRTS and control of the switched mode amplifier. Since then, seven publications have been co-authored by students (one journal, four international conferences and two national conferences). The dissertations using real-time simulation account for almost 30% of the dissertations performed in hardware at the Electric Energy Systems laboratory.

A questionnaire was distributed to the ten graduates and the feedback is shown at the lower part of Table 2. The participants rated highly the use of real-time simulation for their dissertations (25% *I agree*, 75% *I strongly agree* - *question i*). They noted strong impact on their learning experience, appreciated the resemblance to real life conditions and the novelty of the approach. The main disadvantage noted was the additional difficulty/burden on the modelling phase, the need for well-trained supervisors and physical limitations of the equipment used. Moreover, the graduates find the hardware experience far more interesting and motivating than pure simulations and literature review (25% *I agree*, 75% *I strongly agree* - *question ii*).

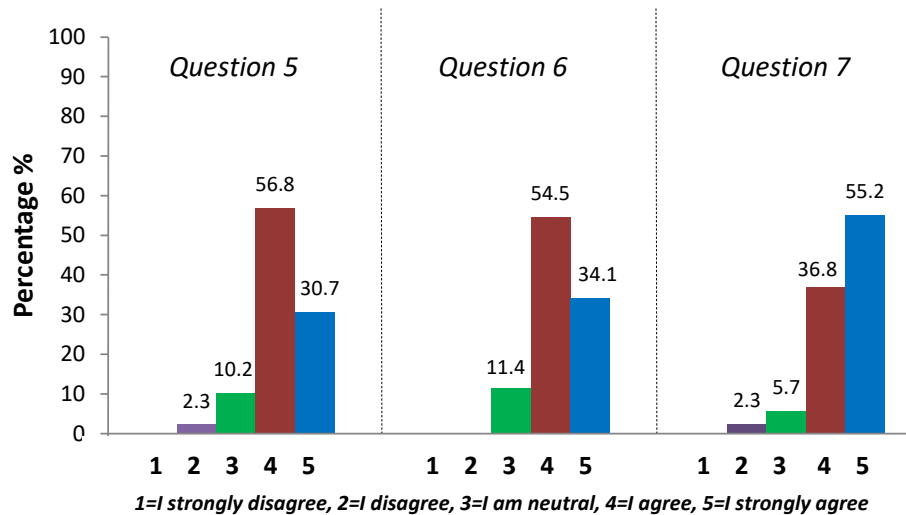


Figure 39: Student's feedback on questions 5, 6 and 7

4.3 Lab Exercises: Introduction to Real Time Digital Simulation and Application in Sustainable Energy Systems

The Intelligent Electrical Power Grids (IEPG) section of Delft University of Technology (TUD) has designed lab-based exercises on introduction real time digital simulations and its application in modern day sustainable energy systems. The exercises aim to introduce master level students to the world of real time simulation and how the various advantages of real time simulation can be used for application in energy systems. The exercise is designed with simulations to be conducted on the RTDS. The entire exercise has been divided into 8 modules which start from basic introduction of real time simulation to more advanced modelling and simulation techniques. The modules have been created by experienced Ph.D. researchers under the supervision of Professor Jose Rueda Torres. The 8 modules are:

i) Overview of RTDS hardware and RSCAD

The objective of this module to provide an overview of the Real Time Digital Simulator (RTDS) hardware and the RSCAD software. The RTDS simulator is used for real time power system simulation. The objective is to provide an overview of the Real Time Digital Simulator (RTDS) hardware and the RSCAD software.

ii) Running cases and basics of scripting in RSCAD

The objective of this module is to start running simple power system cases in RSCAD and learn the basics of scripting a case. In this module several examples have been presented which the students can use to have a hands-on approach to learn RSCAD.

iii) Intro to Interfacing with hardware (control, relays)- including delays

This module focuses on interfacing RTDS with MATLAB and Python applications. This module will help in conducting experiments involving multiple simulators with RSCAD. Hence, this would be an important module for co-simulation related activities also.

iv) C-Builder and Small Time-step modelling

This module will focus on RSCAD's CBuilder software and Small-Time step modelling. CBuilder module enables RTDS users to develop their own custom component models. Both power system and control system type components can be developed using CBuilder. CBuilder includes an inter-

face for drawing the component's icon, a structure to define the parameters which must be entered by the user for the new model and a mechanism to provide input and output signals to/from the component. Electro-Magnetic Transient Program (EMTP) type software typically uses a time-step of 50 μ s for simulation of phenomena ranging from 0 to 3 kHz. To model high frequency power electronic circuits such as those found in static synchronous compensators (STATCOM), wind farms, PV systems, fuel cells and high voltage DC systems, a smaller time-step is needed. The RTDS Simulator utilises processor hardware and optimised calculations to achieve a simulation time-step of 1-3 μ s (small time-step modelling).

v) GTNET, GTFPGA and PMU Applications

The objective of this module is to provide a practical overview of the features offered by the GTNETx2 card of the RTDS. The first section of this module introduces GTNETx2 functionality, and supported protocols such as, SV, PMU and SKT, with example use cases to demonstrate their use. In the second part, the practical centralized based Under Frequency Load Shedding (UFLS) example, utilizing PMU and SKT is described and performed in real-time.

vi) Interfacing with Hardware

The objective of this module is to give attendees a picture on how to interface RTDS with external devices. The method of interfacing of RTDS through the I/O cards is demonstrated in the module through practical examples.

vii) Solar PV models and dynamic loads

The objective of this module is to describe a simulation case to analyse the operation of a grid-connected photovoltaic system using the PV model and dynamic load model in RSCAD library.

viii) MMC and HVDC example

The objective of this module is to provide a practical overview of the Modular Multi Level Converter (MMC) technology in order to build a basic point-to-point High Voltage Direct Current (HVDC) link based on this type of Voltage Source Converter (VSC) technology.

A one-week internal workshop has already been conducted in TUD recently based on the above modules and an ERIGrid winter school is planned in the winter of 2018/19 to impart the knowledge of real time simulations to a wider international audience.

5 Additional Educational Activities

5.1 Educational Activities at High Schools

ICCS-NTUA organized workshops at high schools in Athens aiming to educate the younger generation on renewable energy and smart grids and inspire students to choose relevant career paths. The scope of the visits was twofold. Firstly, the students were introduced to the big picture of climate change, environmental awareness, renewable energy sources etc. Secondly, a hands-on practical session was carried out accompanied with a theoretical background on PV systems (e.g. photovoltaic effect) and electrical principles. The students were able to construct a custom-made 45 W photovoltaic panel with their own hands. They soldered 36 photovoltaic cells in series, in a 6-by-6 configuration, added the necessary wiring and finally enclosed them in 2 sheets of glass, held together by an aluminium frame. The finished panel was then tested in the school yard, by providing power to a LED light bulb.



Figure 40: Snapshots from the construction of PV panels at high schools

The feedback received from the students was heart-warming. The majority was really excited to actually work “hands-on” on the subject that they learned about, instead of only listening to theory. They wished that more such activities could be introduced throughout the school year, because they spark their interest on the related subject and support the understanding.

5.2 European Researcher's Nights – Marie Skłodowska-Curie Actions

The European Researchers' Night takes place every year simultaneously in several hundred cities all over Europe and beyond. The key objective of the event is to increase general public awareness on the diversity of scientific research and also to promote and facilitate greater public participation in the entire scientific process. One of the further goals of the event is to enhance youth's understanding of science and research and encourage them to pursue a career in Science, Technology, Engineering and Mathematics (STEM).

ERIGrid has participated to the European Researcher's night in 2017 and 2018, represented by AIT in Vienna. In 2017 (September 29th) ERIGrid contributed to the Viennese event, called beSCI-ENCED, with a science booth on smart grids providing an overview of trends and research activities in the domain of smart grids and also representing partner project ELECTRA IRP. The programme of the event included various engaging activities ranging from interdisciplinary science booths, workshops, and the dedicated EU corner to science slam sessions and science cafes.

In 2018 (September 28th), ERIGrid contributed to the Viennese event, called Sci4all, sharing knowledge on smart grid research, in particular with topics such as:

- The importance of a higher level of automation in the context of the integration of decentralised and renewable energy sources in the electrical grid
- The role of information and communication technology in this domain
- The importance of the development and validation of cross-domain smart grid approaches

Moreover, the virtual laboratory tool described in Section 3.2.1 was demonstrated.

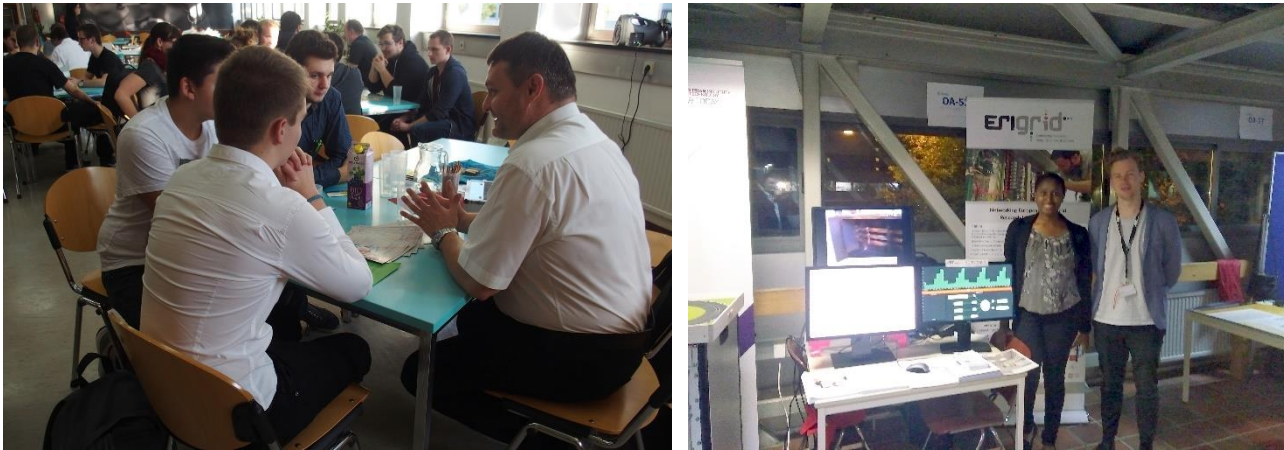


Figure 41: Snapshots from the European Researcher's Night 2017 beSCIENCED event in Vienna

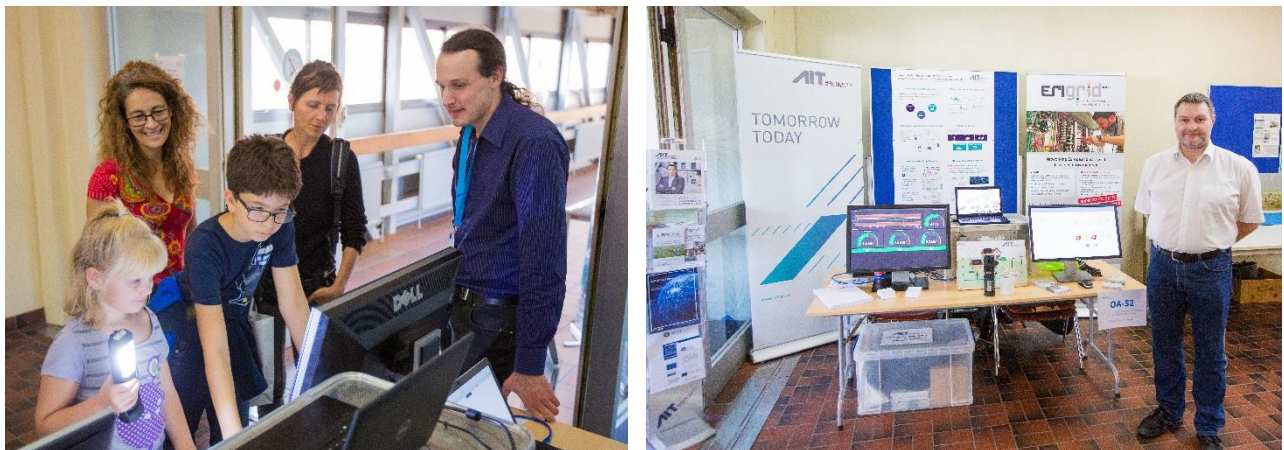


Figure 42: Snapshots from the European Researcher's Night 2018 Sci4all event in Vienna

6 Conclusions and Outlook

The emergence of intelligent solutions in the domain of power and energy systems opens new possibilities but poses new challenges, rendering appropriate education and training methods for students and engineers increasingly important. A broad understanding of several domains is necessary to deal with the increased complexity and diversity, such as electric power systems, automation, ICT, thermal systems etc.

This deliverable identifies educational needs and requirements in the rising complex environment. It is explained that the validation of complex systems is a multi-stage process, while systems-oriented skills and cross-disciplinary learning needs to be cultivated. Programming and system conceptual design competences, together with a pragmatic view, are important. In order to cover the distance between theory and hands-on practice, coding and laboratory education is beneficial. As the required knowledge is too broad, educational methods such as experiential learning and problem-based learning can prove to complement effectively the traditional teaching methods.

In this framework, several tools and methods developed in the ERIGrid project are presented. The delivery of webinars proved to be an efficient way to disseminate the progress and educate researchers on the ERIGrid methodologies. The developed web-based virtual lab gives users the possibility to simulate safely and conveniently laboratory experiments and can be used in different settings (e.g. classroom sessions, e-learning, demos). The mosaik co-simulation framework helps students and interested users to learn to plan, execute, and analyse co-simulation-based experiments in a cyber-physical context. The FMU-as-a-service approach supports users to understand the functionality and structure of a Functional Mock-Up unit and to become familiar with the interaction of different type of simulations. The remote labs give users the possibility to experience real-lab conditions by gaining online access to actual laboratory installations (for both monitoring and control) in more realistic conditions than virtual labs. The use of notebooks can bridge the gap between theory and application, allowing the user to focus on solving a problem, instead of dealing with issues related to programming. Moreover, laboratory education is addressed. It is demonstrated for the first time that PHIL simulation can assist to familiarize students with the hardware lab, while keeping the flexibility and modelling capability of digital simulation. The students evaluated the laboratory exercises clearly positively and highly appreciated real-time simulation for their education. Moreover, they showed keen interest in the integration of modern topics to the lab exercises and in obtaining hands-on experience on actual devices.

It is clear that the ERIGrid approaches and methodologies, developed mainly in the Joint Research Activities (e.g. real-time simulation, co-simulation), can be beneficial for education/training purposes. In future work, new webinars (based on the JRA 2, JRA 3, JRA 4 and NA 5 work) and education material will be delivered, while feedback on using the online tools will be provided by users in order to improve them. A new version of the deliverable will be submitted at the end of the ERIGrid project which will include the advancements in this direction.

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