New trends in laboratory education: HIL simulation and remote/virtual labs

Special Session: "New trends in education and training for the energy transition"

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Overview

- New educational/training needs in a complex environment and new opportunities
- Overview of the ERIGrid H2020 project educational/training activities
- Laboratory education at NTUA:
  - Hardware in the Loop simulation
  - Remote/Virtual labs

New educational/training needs in a complex environment

- Need for new skills and expertise to foster the energy transition
- Increased complexity of intelligent energy systems
- A broad understanding of topics of different domains is necessary, i.e. electric power, heat, markets and definitely **ICT** → a holistic understanding is needed
- Interdisciplinary approach, understanding of interactions
- The need for new educational approaches: lectures combined with simulations, e-learning, laboratories etc. Application of learner centered educational methods

P. Kotsampopoulos, N. Hatziargyriou, T. I. Strasser, C. Moyo, et al, Chapter: "Validating Intelligent Power and Energy Systems – A Discussion of Educational Needs" in "Industrial Applications of Holonic and Multi-Agent Systems", Springer, 2017

A variety of tools for education and training

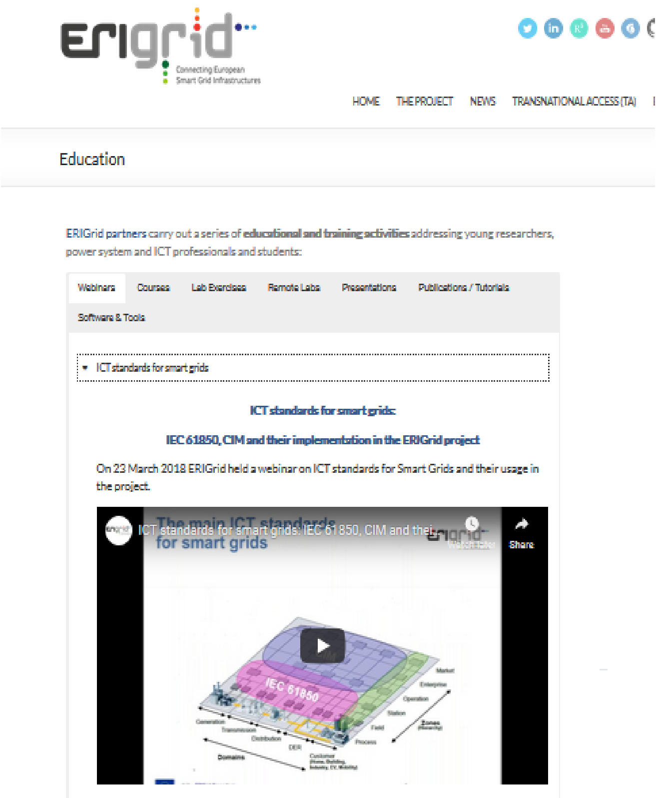
- Technological advancements can revolutionize education by providing a variety of tools for education.

- **i) E-learning tools**:
  - Webinars
  - Massive Open Online Courses (MOOCs)
  - Interactive notebooks (e.g. Jupyter)
  - Animations
  - Virtual labs
  - Remote labs

- **ii) Laboratory education**:
  - Scaled down hardware models
  - Hardware in the Loop simulation
  - Co-simulation (e.g. ICT and power system)
  - Augmented/virtual reality

- **iii) Classroom education**
  - Can be enhanced with e-learning tools (e.g. remote connection to lab to show some experiments, students use smart phones etc)
  - The boundaries between classroom and laboratory education can become more flexible

Overview of ERIGrid H2020 project educational/training activities

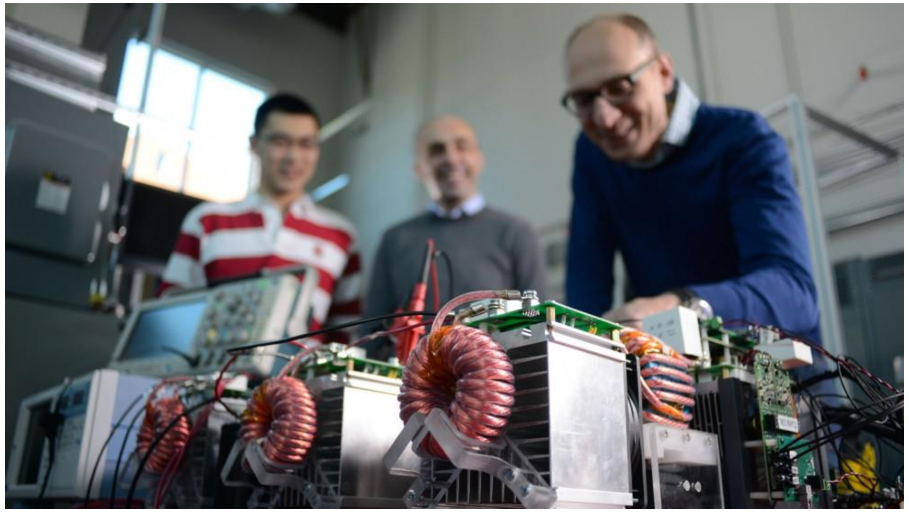


- 4 Webinars: **220 participants** (1200 views on Youtube)
- 5 Summer Schools at ERIGrid partner universities
- 10 Workshops and 3 Tutorials**: 400 participants**.
- 7 Educational tools: virtual/remote labs, interactive notebooks, co-simulation tools etc
- Advanced laboratory exercises
- **450 students** have benefited from ERIGrid exercises, tools and other resources in their Bachelor, Master or PhD studies
- Online resource center at the ERIGrid website:

https://erigrid.eu/education-training/

Hardware in the Loop (HIL) simulation for Laboratory Education

- Lab education on electric machines and power electronics: Hands-on with hardware equipment
- Laboratory education in the power systems domain is usually performed with software simulations and more rarely with small hardware setups with specific capabilities
- The students have limited familiarity with real hardware power systems
- Hardware in the Loop (HIL) simulation: Connection of hardware equipment (e.g. relays, inverters) to a power system simulated in a digital real-time simulator
- HIL simulation can provide to students hands-on experience with real hardware, while maintaining the advantages of the digital simulation (flexibility etc)

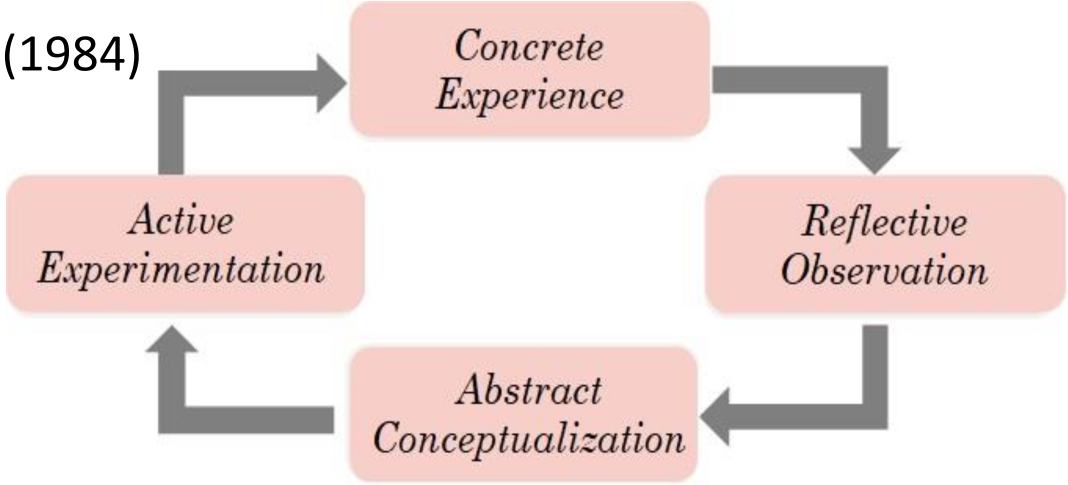


Hardware in the Loop (HIL) simulation for Laboratory Education

- Advantages of HIL simulation for education/training:
  - Real Time system in front of the students: monitor and control
  - Connection of real hardware: actual measurements and equipment control
  - Implementation of demanding tests, such as faults. The students can change the position/type of the fault etc.
- Controller HIL (CHIL) simulation: connection of hardware controllers (relay, EMS etc):
  - CHIL has been used several times for the education of engineers (e.g. control systems, electric machine drives, power system protection etc.)
- Power HIL (PHIL) simulation: connection of hardware power equipment (inverter, motor etc)
  - The use of the PHIL method for education hadn’t been investigated yet in a systematic way

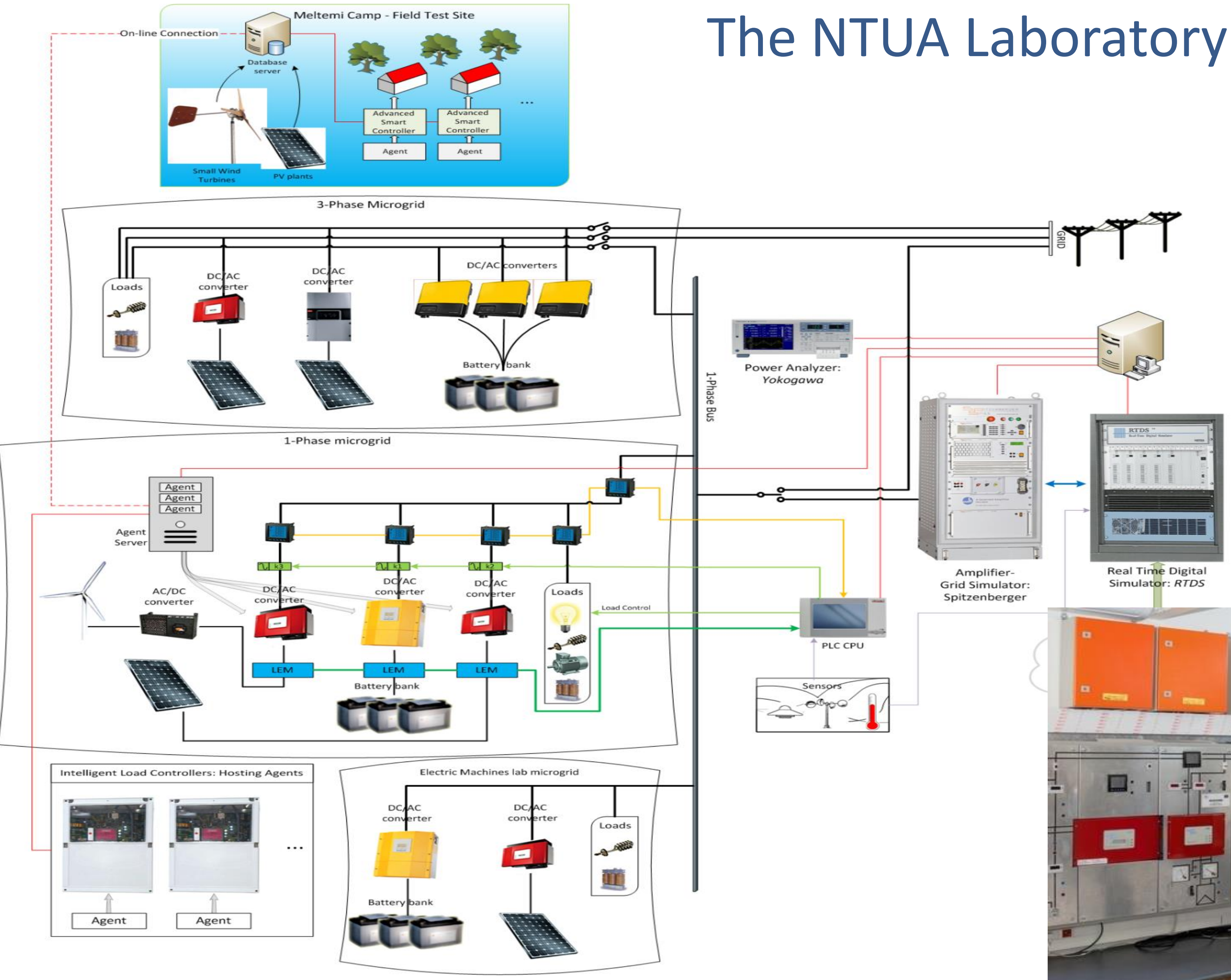
Educational approach and methodology used

- **Experiential education**: educators engage their students directly to the object of knowledge and later on to a focused reflection relative to that experience
- Experiential education has been applied several times for the education of engineers
- Kolb's four-stage learning cycle (1984)

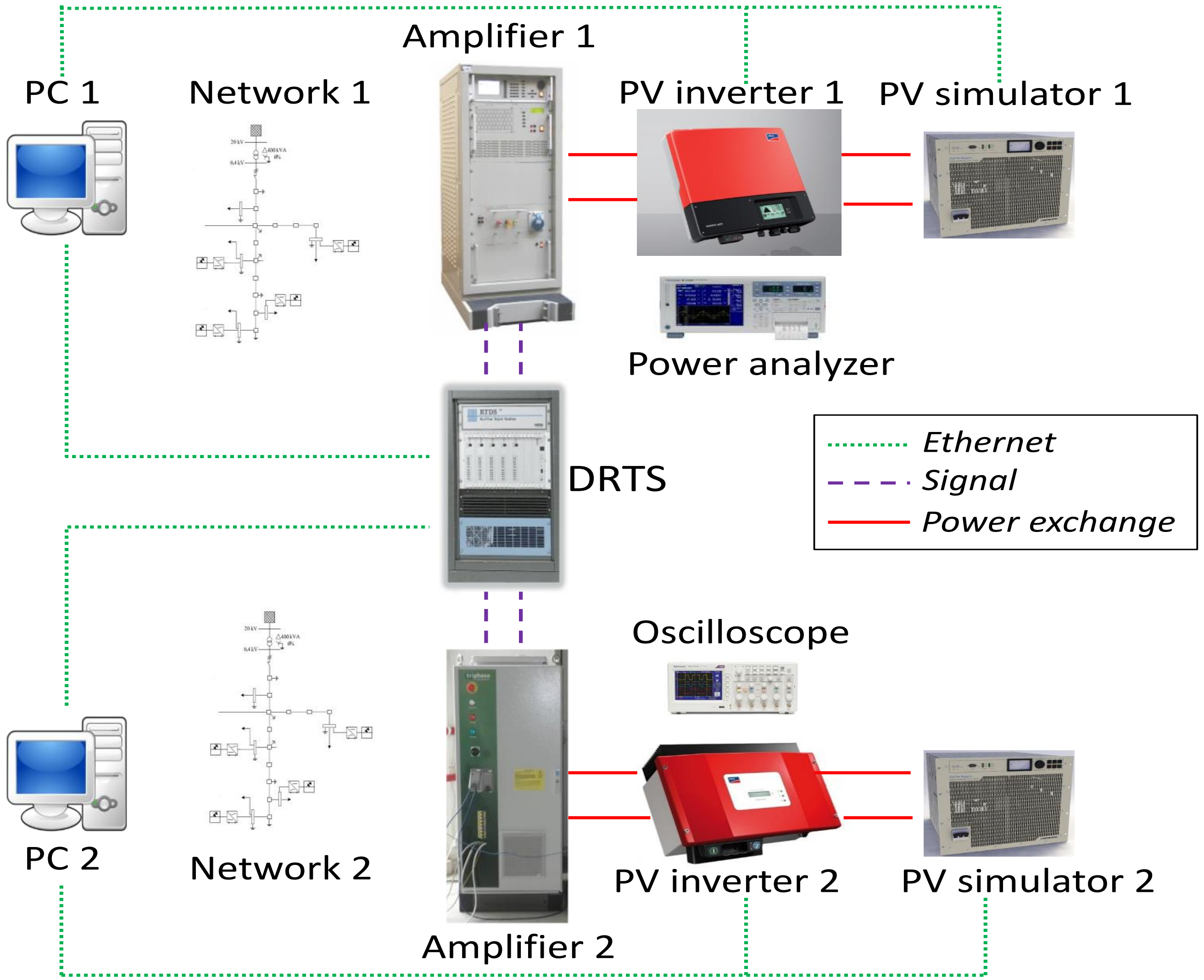


- Aim to bring the students “back to the hardware lab”
- Double PHIL configuration (small groups of students). Equipment that was not available was simulated
- 4 laboratory exercises, unified in 2 sessions: 50 minutes each session
- 8 groups: 5-6 students at each group

The NTUA Laboratory



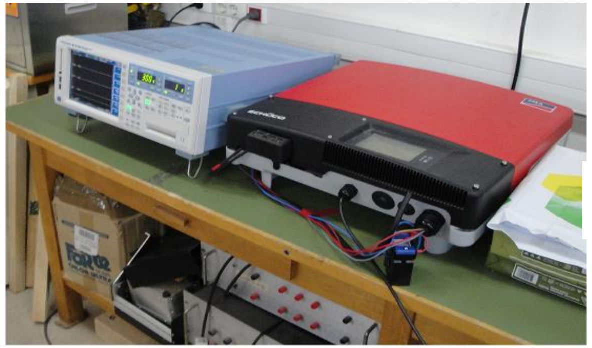
Double PHIL configuration



2 independent PHIL setups → 2 workbenches

P. Kotsampopoulos, V. Kleftakis, N. Hatziargyriou, "Laboratory Education of Modern Power Systems using PHIL Simulation", IEEE Transactions on Power Systems, December 2016

Equipment in operation



Workbench 1

Workbench 2

Voltage control in distribution networks with distributed generation

- Conventional voltage control:

On-load tap changer (OLTC), capacitors etc

$$\Delta V \approx \frac{P_{load} \cdot R + Q_{load} \cdot X}{V}$$

- Kolb's experiential learning cycle:

i) Increase of PV's active power :

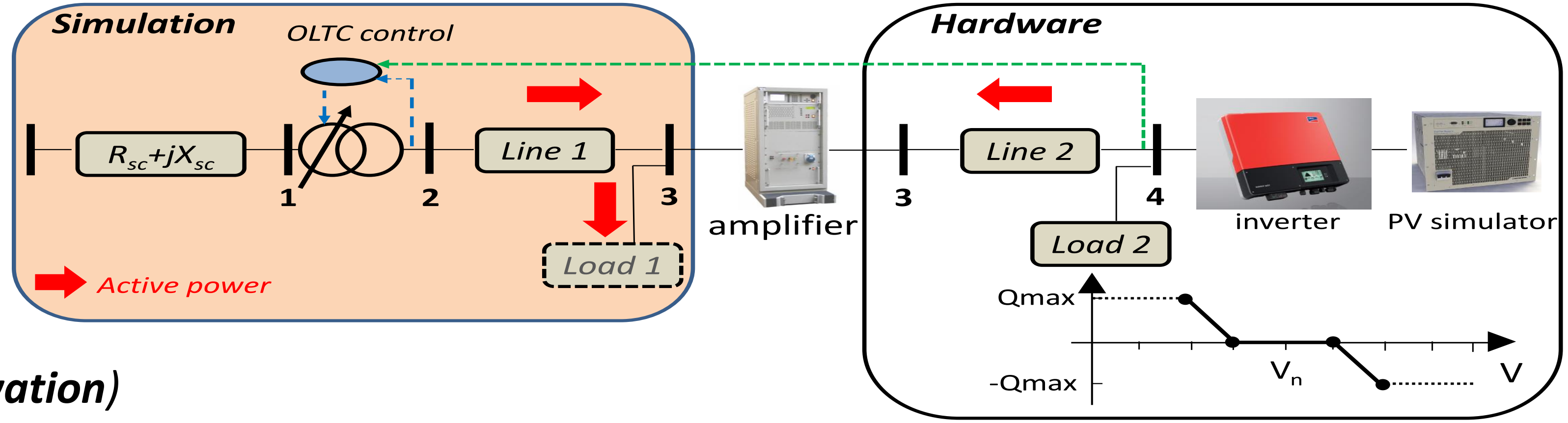
*voltage rise (**concrete experience**)*

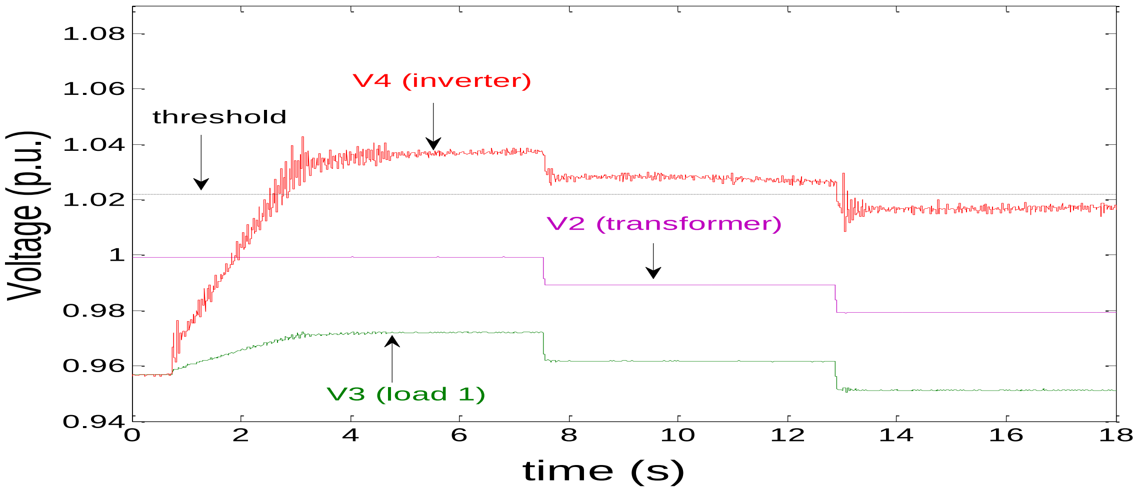
*ii) Understand the problem (**reflective observation**)*

iii) Extend the ΔV equation.

*Solution: reactive power absorption (**abstract conceptualization**)*

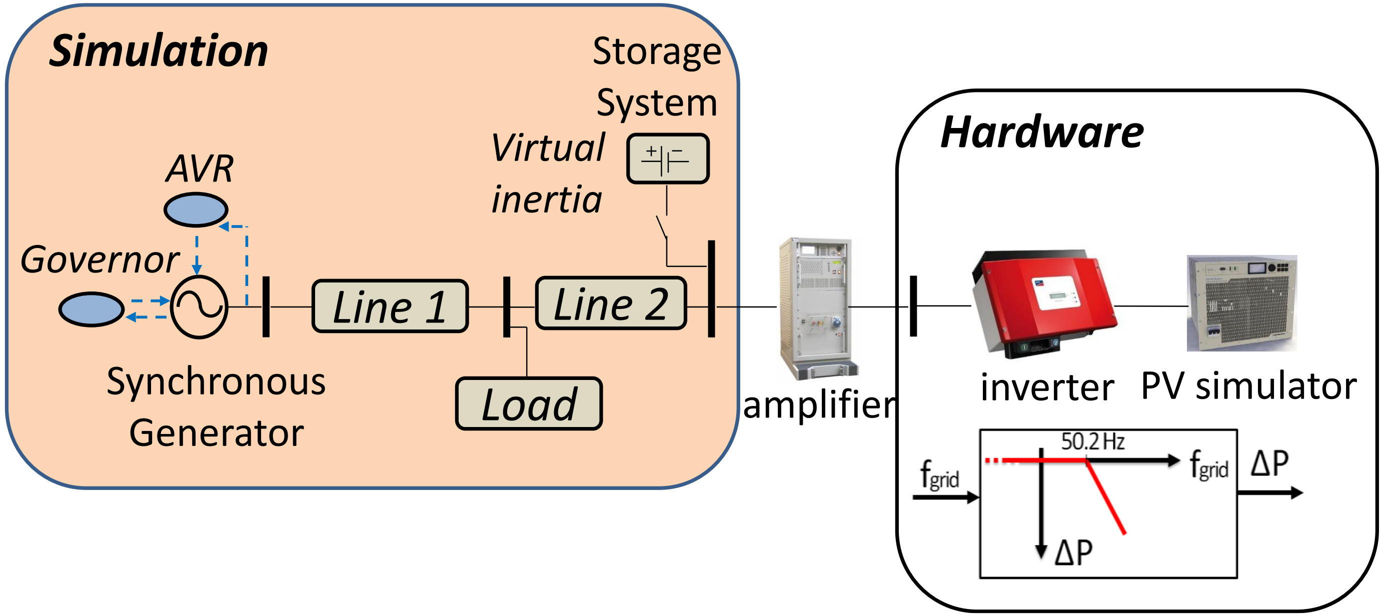
*iv) Send reactive power setpoints (**active experimentation**)*



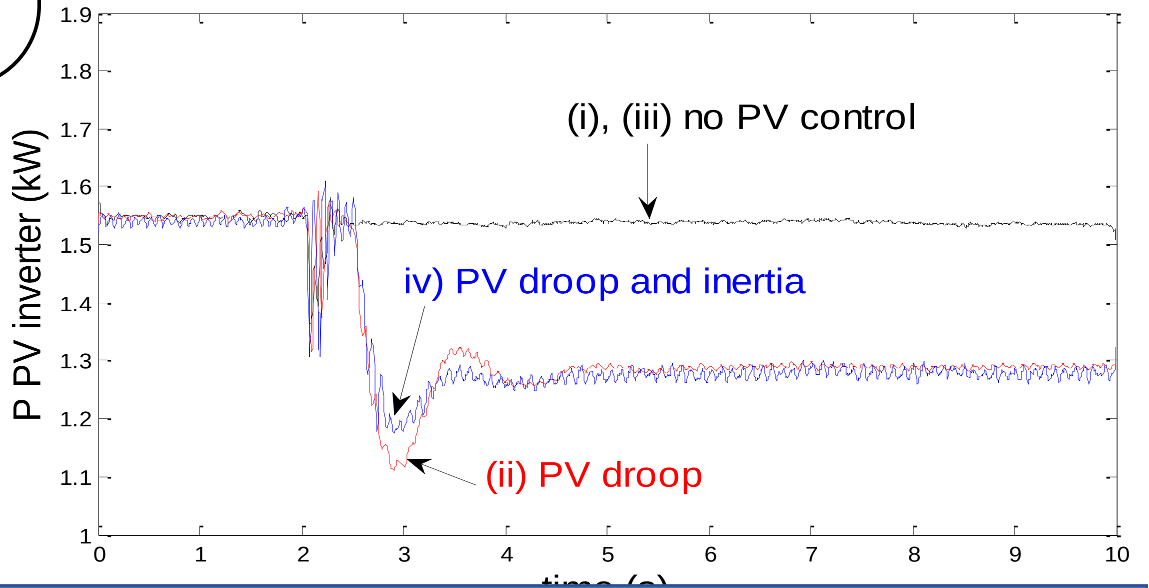


- OLTC: reduces the voltage rise at the PV inverter's node but further decreases the voltage of the load → need for coordinated control

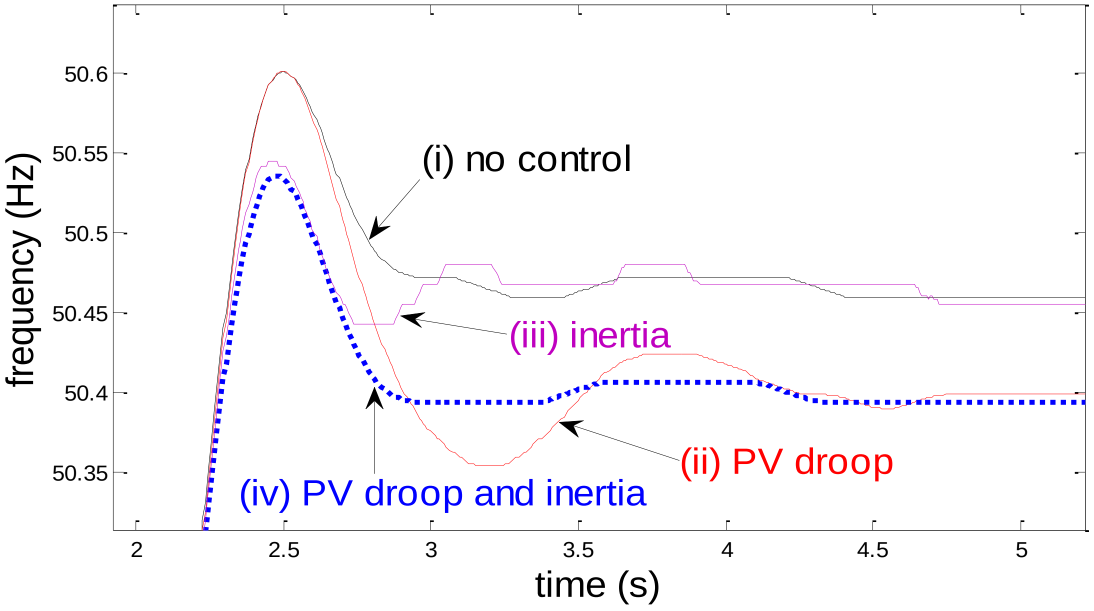
Parallel operation of synchronous generators and distributed generation

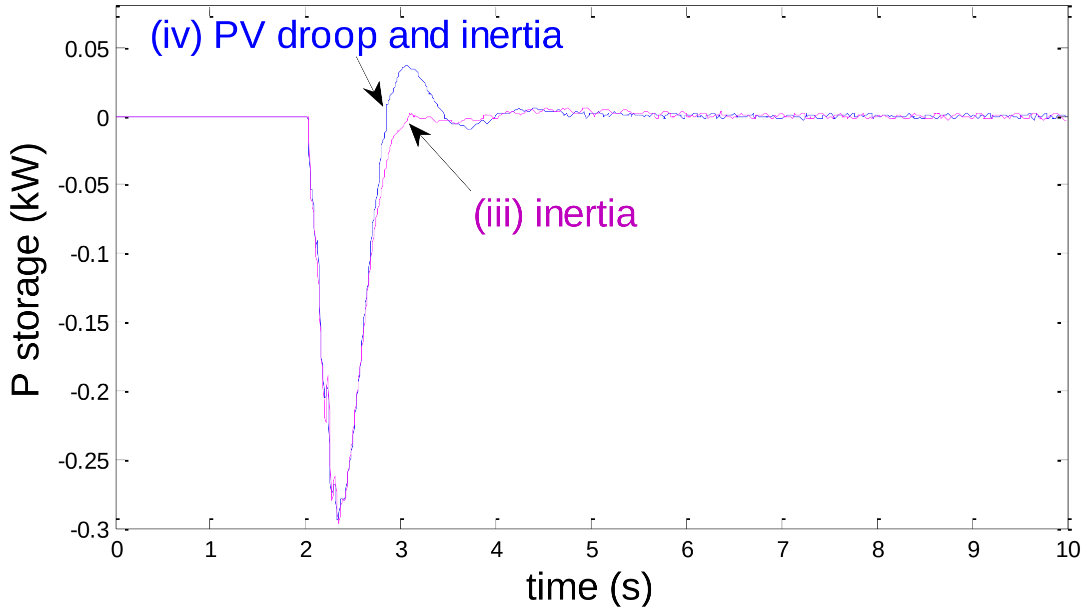


- Conventional Generation
- Hardware inverter operating with P(f) droop control
- Simulated storage system providing virtual inertia



Parallel operation of synchronous generators and distributed generation

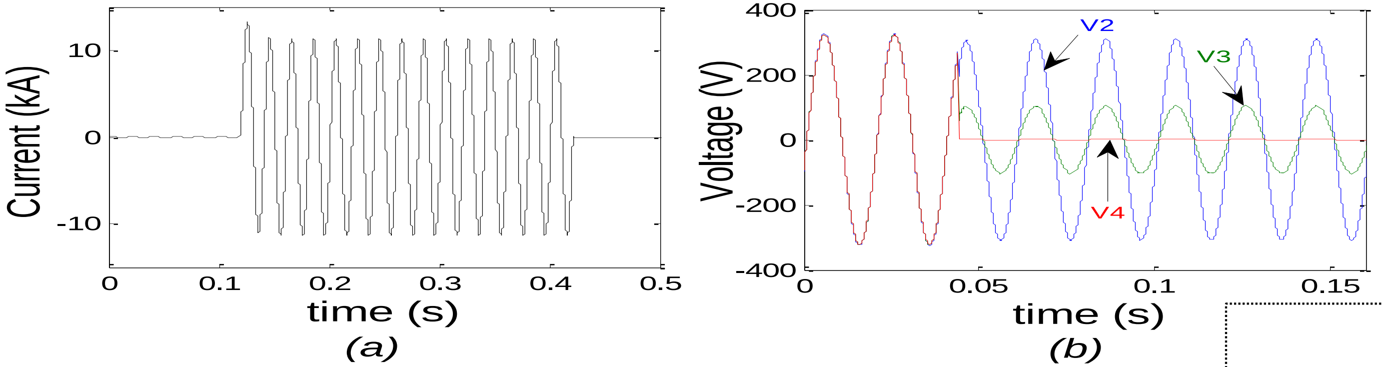


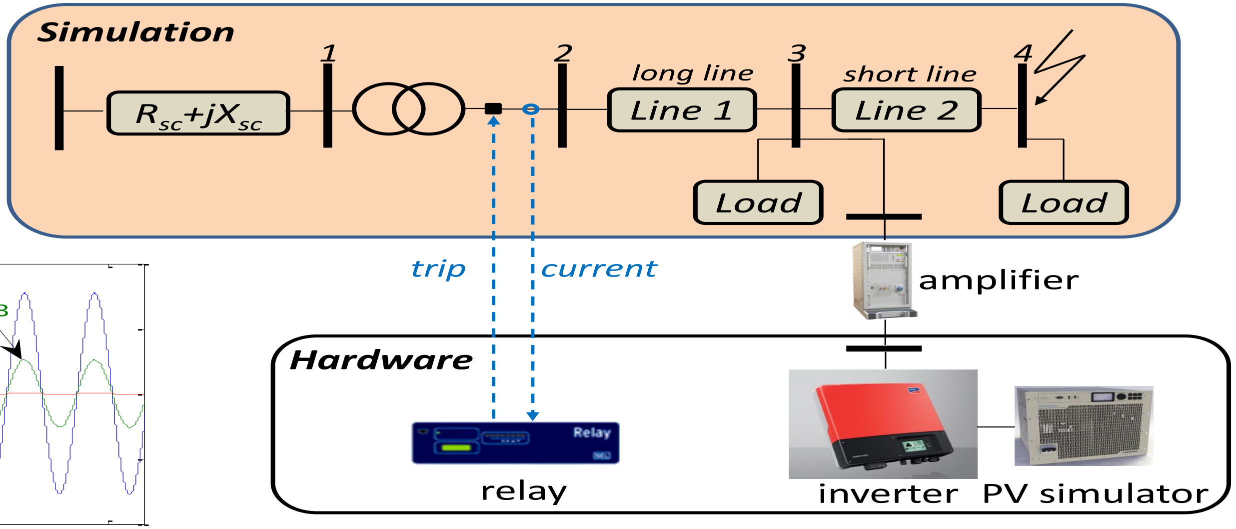


- Droop control improves only the steady state (slow controller in this inverter). The combined operation performs better
- Virtual inertia improves the dynamic response

Short-circuits: digital relays and behaviour of PV inverters

- Location of the fault moves away from the transformer, short circuit current is decreased and the trip time of the relay is increased

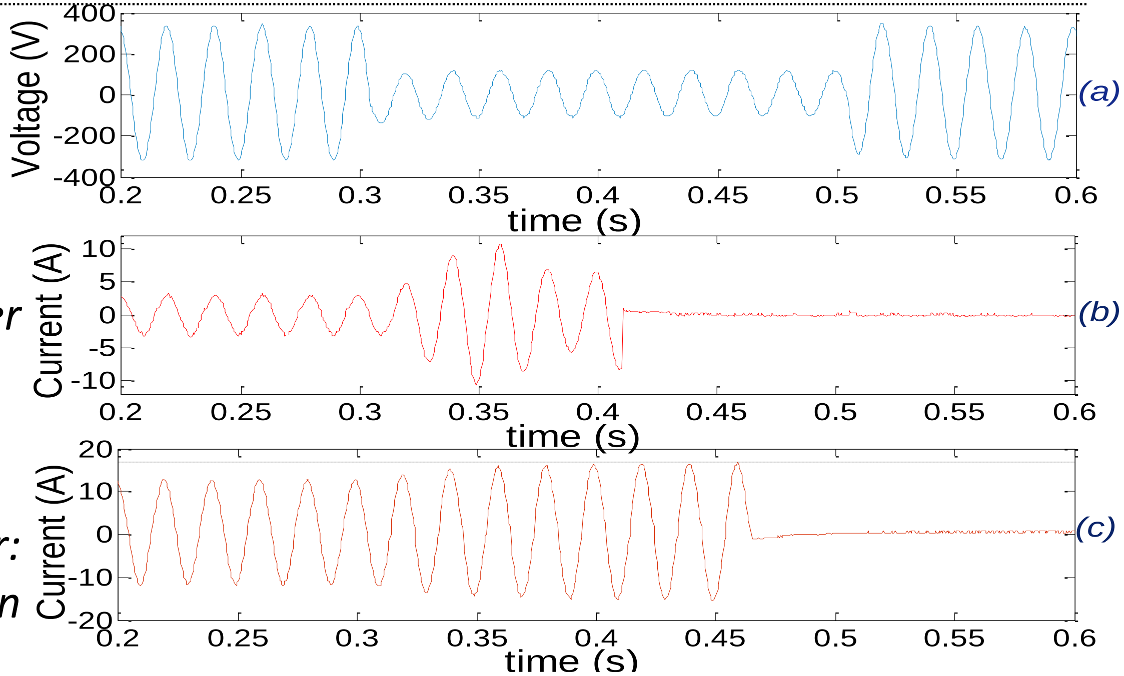




- Voltage drop at 1/3 due to the short-circuit
- Limitation on the current of the inverter when operating at nominal power

low power

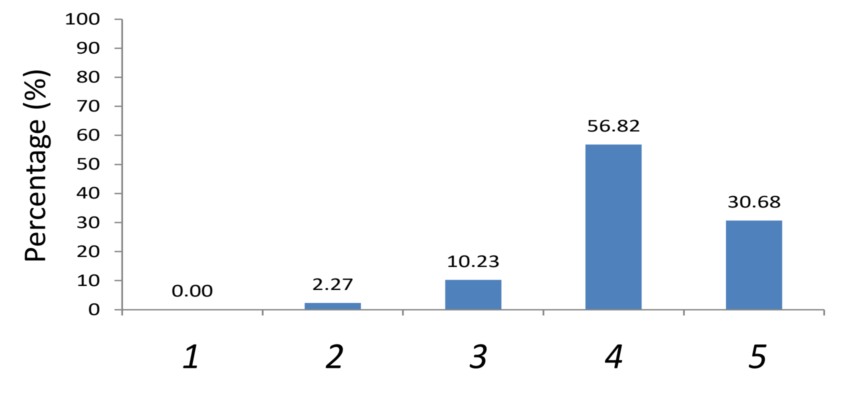
nominal power:
current limitation



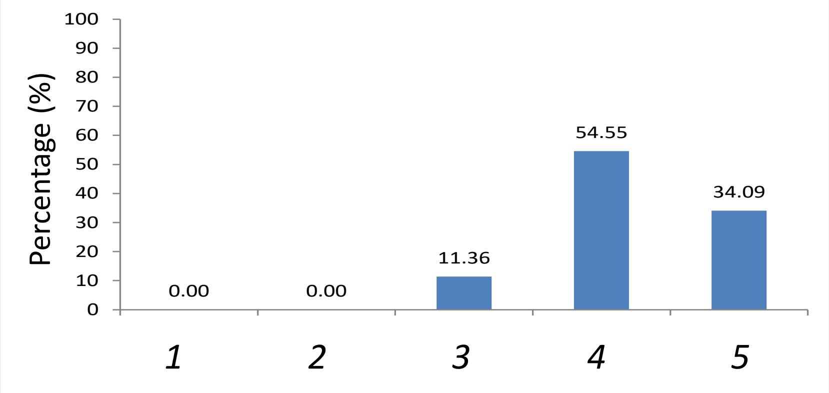
Evaluation of the laboratory exercises by the students

- 10 questions, 95 questionnaires received

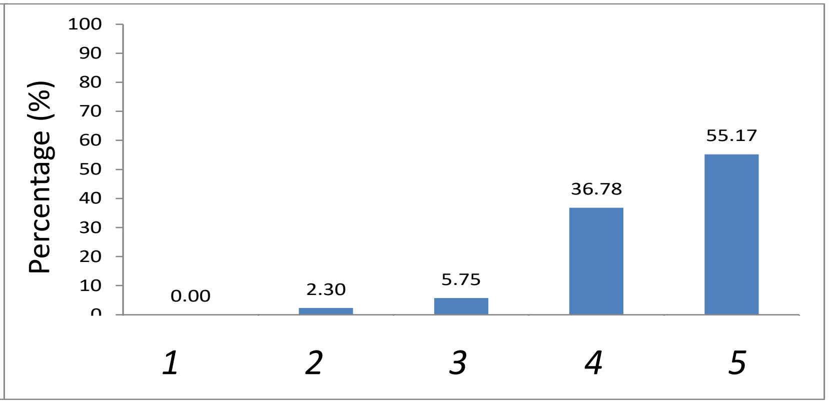
The laboratory exercise has helped me understand the operation of modern power systems with distributed generation



The laboratory exercise is interesting (in overall)



Real-time simulation is a useful educational tool



- ***1*: I strongly disagree, *2*: I disagree, *3*: I am neutral, *4*: I agree, *5*: I strongly agree**
- They highly appreciated the use of real-time simulation for educational purposes (*37% I agree, 55% I strongly agree*)
- They prefer hands-on approaches compared to demonstrations (*51% I strongly agree)*
- They find the introduction of modern topics motivating (*51% I strongly agree)*

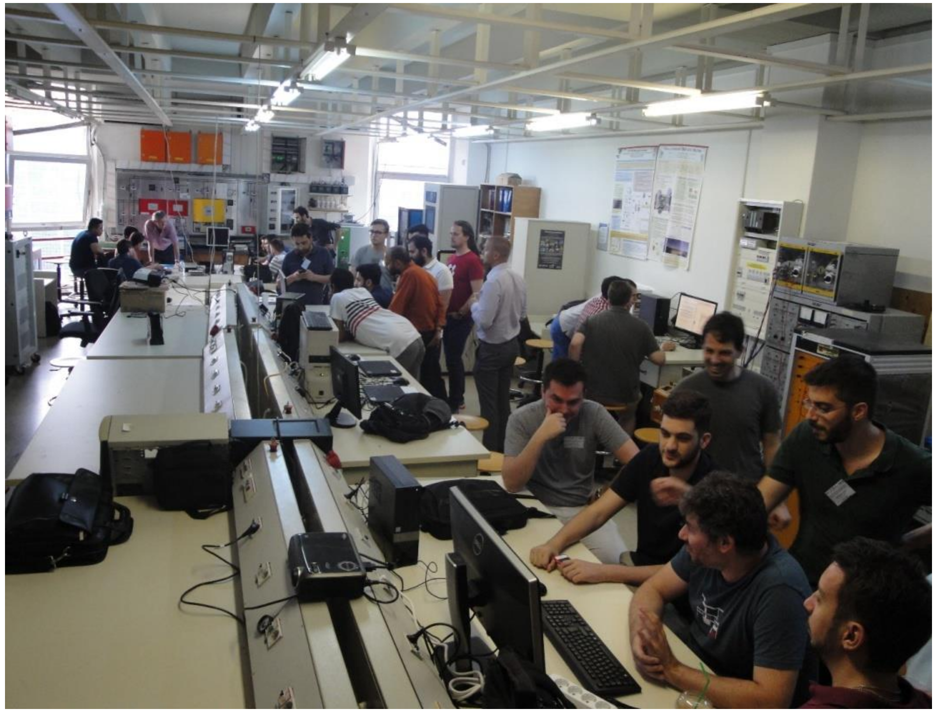
- **Questionnaires to graduates :** highly appreciated the use of real-time simulation **at their diploma thesis**: 8 publications

Experiences from the ERIGrid Summer School: “Advanced operation and control of active distribution networks” in Athens, June 2019

- 5 day event co-organized by: ERIGrid project partners ICCS-NTUA and HEDNO together with RTDS Technologies
- Well-balanced set of lectures, hands-on laboratory work, visits to cutting-edge installations and industry insights
- 32 participants from academia and industry from 14 countries that provided excellent feedback

Laboratory sessions at the ERIGrid Summer School

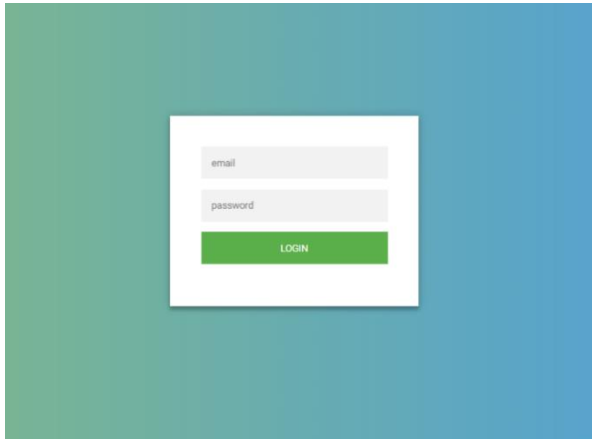
- **Individual work:** use the software of RTDS Technologies in order to execute real-time simulations
- **Team work:** CHIL experiments of DER inverter controls: fine tune control parameters
- **Live demonstrations** of several CHIL and PHIL experiments

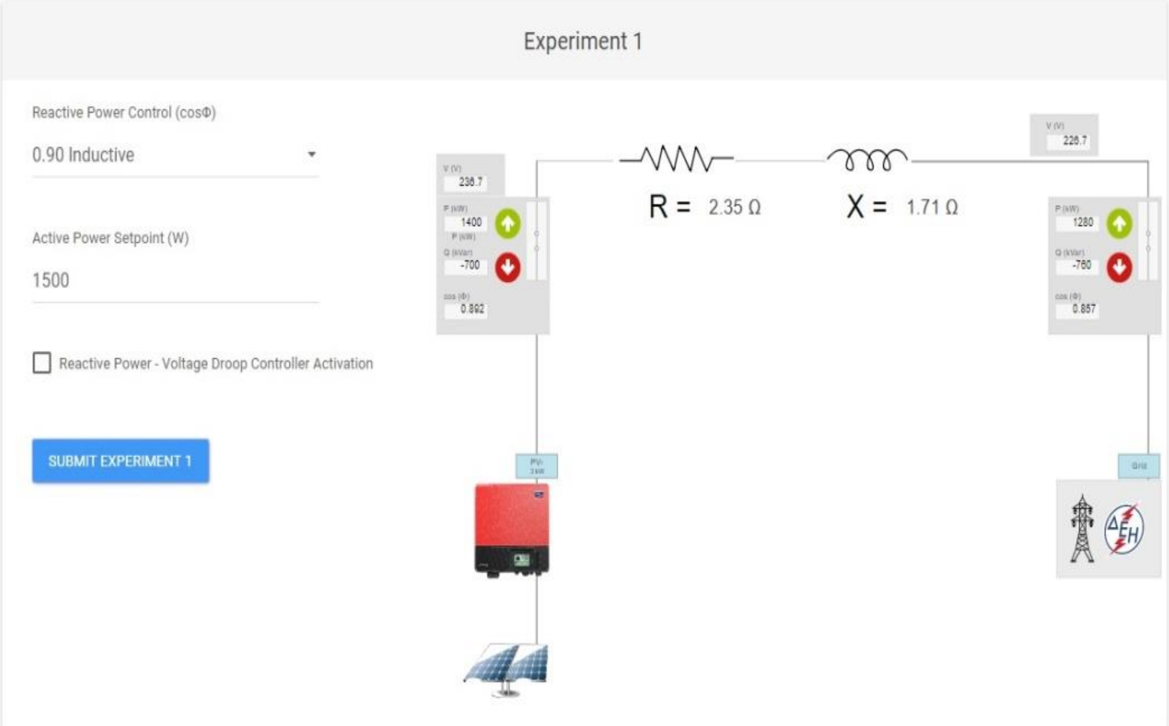


Virtual Lab and Remote Lab of NTUA

- *Virtual lab*: Mathematical representation of the lab. Graphical User Interface (GUI). *Web-based tool*.

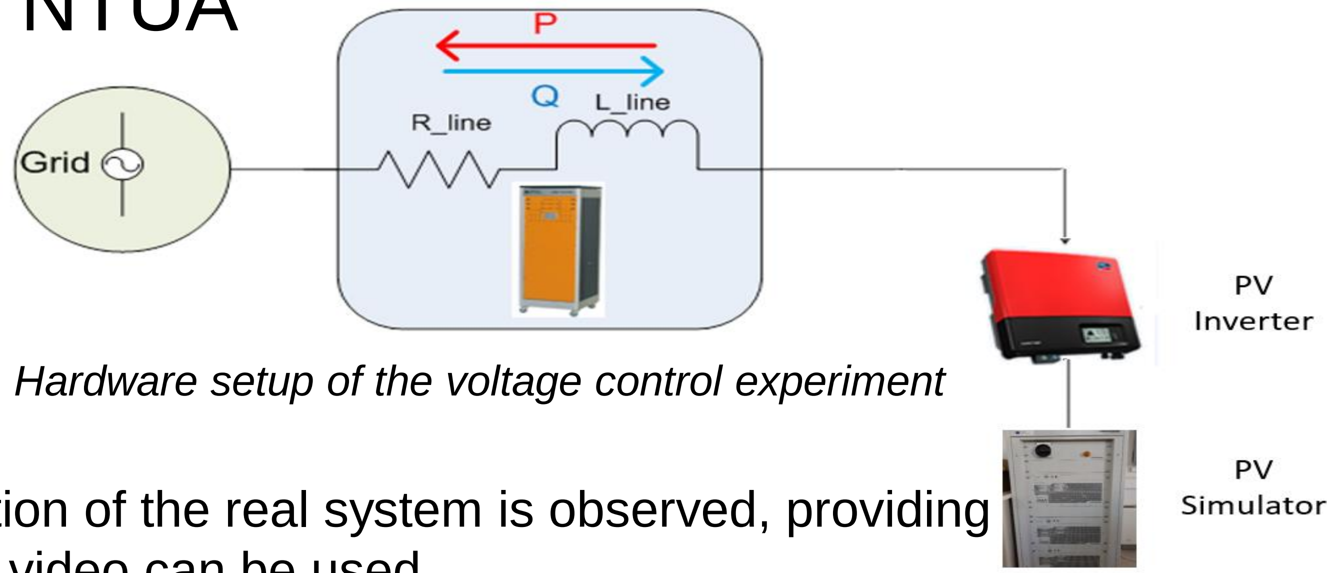
https://virtuallabntua.herokuapp.com/login





- *Remote lab: Allows remote measurement and control of actual equipment. Web-based tool:* access to the SCADA of the actual laboratory of NTUA

Virtual Lab and Remote Lab of NTUA



Hardware setup of the voltage control experiment

Two test cases:

- Voltage control with DER
- Microgrid operation

<u>Advantages</u> of the Remote Lab:

- More realistic than the Virtual Lab as the operation of the real system is observed, providing a more meaningful experience to the user. Also video can be used
- Noise, equipment inaccuracies, communication delays, etc are taken into account

<u>Disadvantages</u> of the Remote Lab:

- Only 1 user can typically have access at a time → more difficult to offer to a wide audience.
- Safety reasons: laboratory staff monitors the process of the experiment and if necessary communicates with the user.
- The test setup has to be actually implemented in the laboratory, requiring additional effort.

Conclusions

- A need for new skills and competences. New technical tools but also educational methodologies
- The role of laboratory education/training is important in the new complex era
- PHIL simulation is an efficient educational tool: hands-on experience with hardware devices, while maintaining the flexibility and modeling capabilities of simulation
- Feedback from students was really encouraging
- Remote/virtual labs can support the educational process. Remote Lab offers important advantages, but its actual implementation is more challenging.

Thank you for your attention!

https://erigrid.eu/education-training/

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