PHIL and CHIL simulation for education, research and testing

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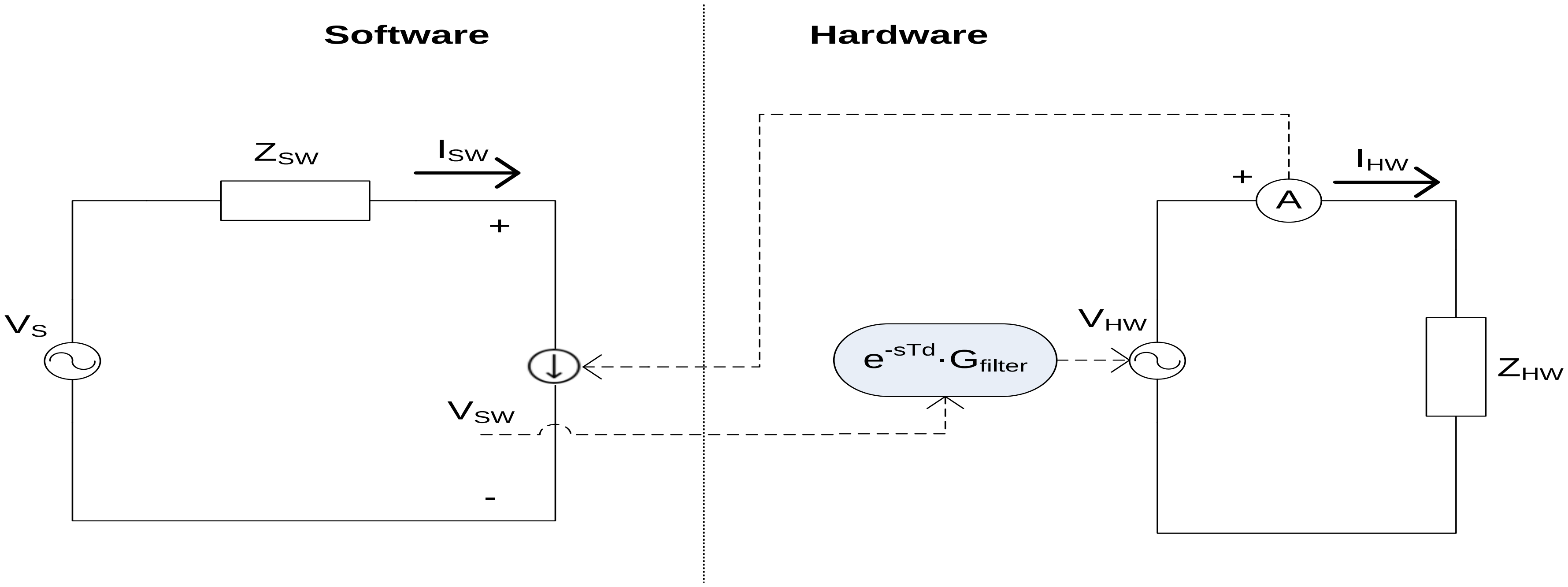
Overview

- PHIL stability analysis using the Bode stability criterion
- HIL for laboratory education
- Testing chain: combined CHIL/PHIL simulation
- Remote real-time co-simulation
- Additional activities

PHIL STABILITY ANALYSIS

Stability of PHIL simulation

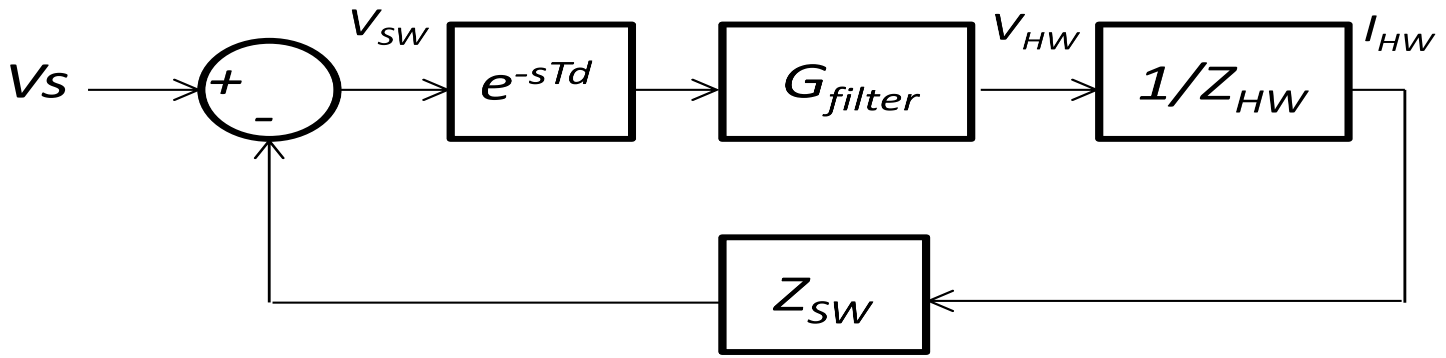


$$V_{HW} = V_{SW} \cdot e^{-sTd} \cdot G_{filter}$$

$$I_{HW} = \frac{V_{HW}}{Z_{HW}}$$

$$I_{SW} = I_{HW}$$

$$V_{SW} = Vs - I_{SW} \cdot Z_{SW}$$



$$G_{OL}(s) = \frac{Z_{SW}(s)}{Z_{HW}(s)} e^{-sTd} \cdot G_{filter}(s)$$

- Nyquist plot, Routh criterion (e.g. Pade approximation), Root Locus, Dynamic simulation etc

Stability analysis of PHIL simulation: Bode Stability Criterion

Bode Stability Criterion (Definition):

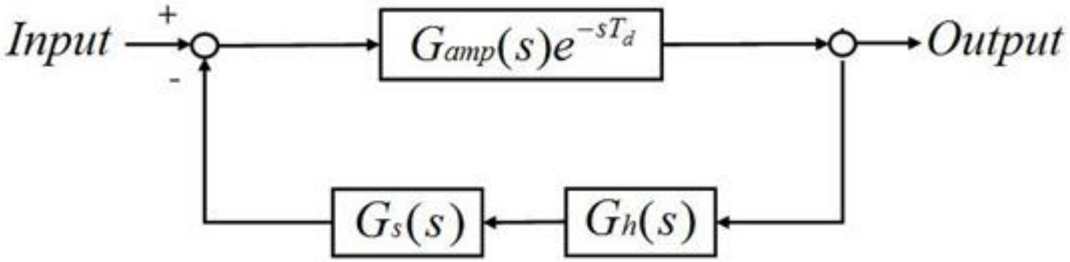
Consider the open loop transfer function G(s) of the system. If at the phase crossover frequency w_{pc} (namely, where the phase of G(s) is equal to -180), the corresponding magnitude of G(iw_{pc}) is less than 0 dB, then the feedback system is stable.

According to Bode stability criterion for a stable PHIL simulation the following conditions should be satisfied:

$$\left|G_s(s)G_{amp}(s)e^{-sT_d}G_h(s)\right| \leq 1$$

and

$$\angle G_s(s) + \angle G_{amp}(s) + \angle G_h(s) - \omega T_d = \pi$$



A. Markou, V. Kleftakis, P. Kotsampopoulos, N. Hatziargyriou, "Improving existing methods for stable and more accurate Power Hardware-in-the-Loop experiments", IEEE ISIE 2017 conference, Edinburgh, June 2017

Stability analysis of PHIL simulation: Bode Stability Criterion

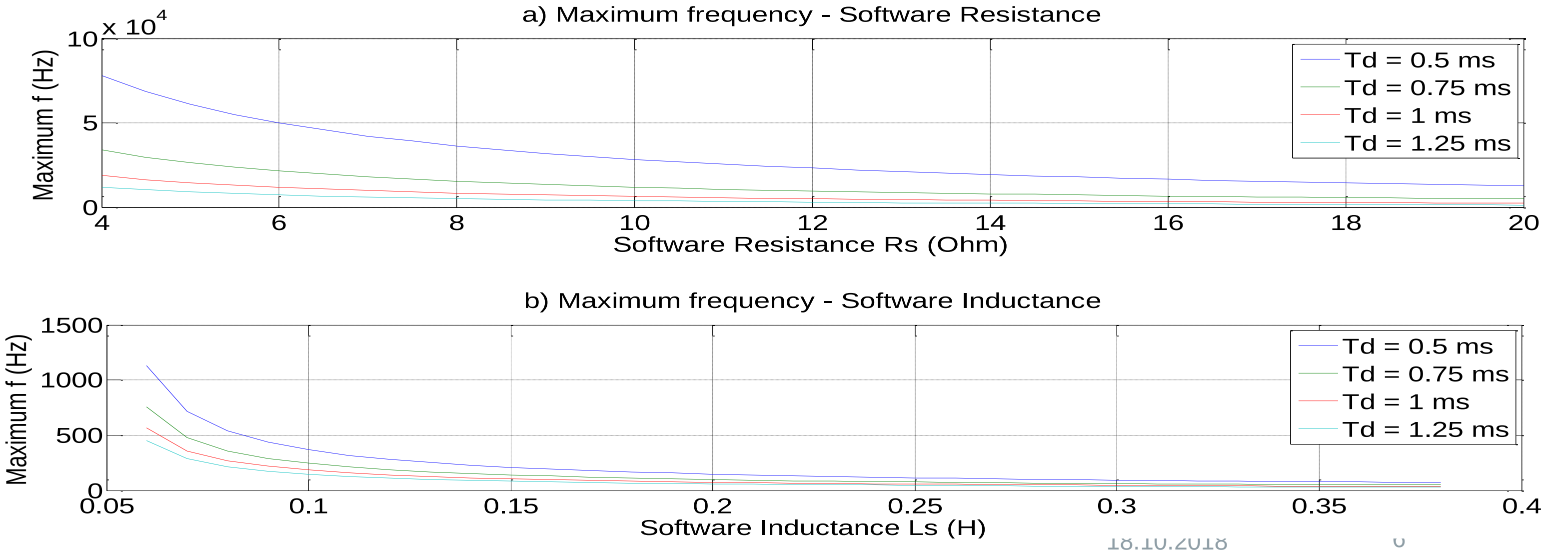
In the simple example of a voltage divider the conditions that should be satisfied is the following:

$$\sqrt{\frac{{R_s}^2 + {L_s}^2\omega^2}{{R_h}^2 + {L_h}^2\omega^2}} \leq 1 \qquad \arctan\left(\frac{\omega L_s}{R_s}\right) - \arctan\left(\frac{\omega L_h}{R_h}\right) - \omega T_d = \pi$$

Stability conditions using the Feedback Filter Method are the following:

$$\sqrt{\frac{{R_s}^2 + {L_s}^2\omega^2}{({R_h}^2 + {L_h}^2\omega^2)(1+\omega^2\mathrm{T}^2)}} \leq 1 \qquad \arctan\left(\frac{\omega L_s}{R_s}\right) - \arctan\left(\frac{\omega L_h}{R_h}\right) - \arctan(\omega T) - \omega T_d = \pi$$

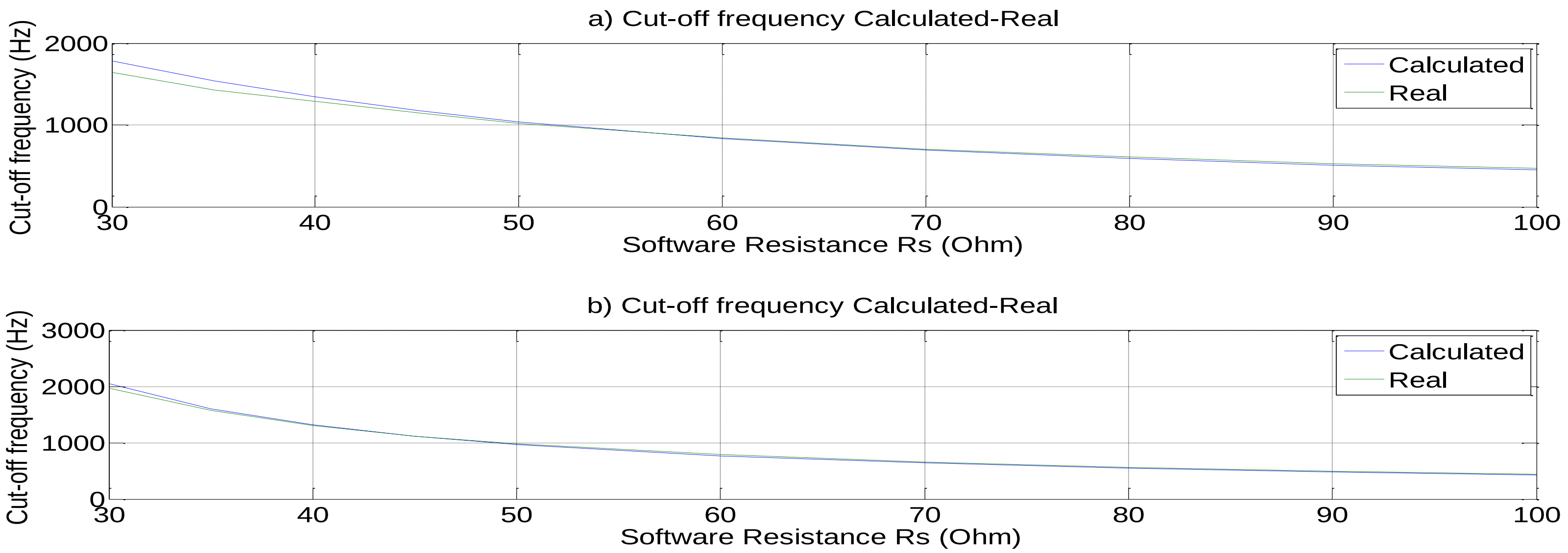
Solving the above pair of equations the marginal values of the cut-off frequency of the feedback filter can be found.
In principle, the higher the cut-off frequency the better.



Experimental Results: Proposed analysis applied on existing methods – Feedback Filter

Load: Rh 15.9 Ohms.
Software Inductance 0.1 and 1 mH.
Different Software resistances

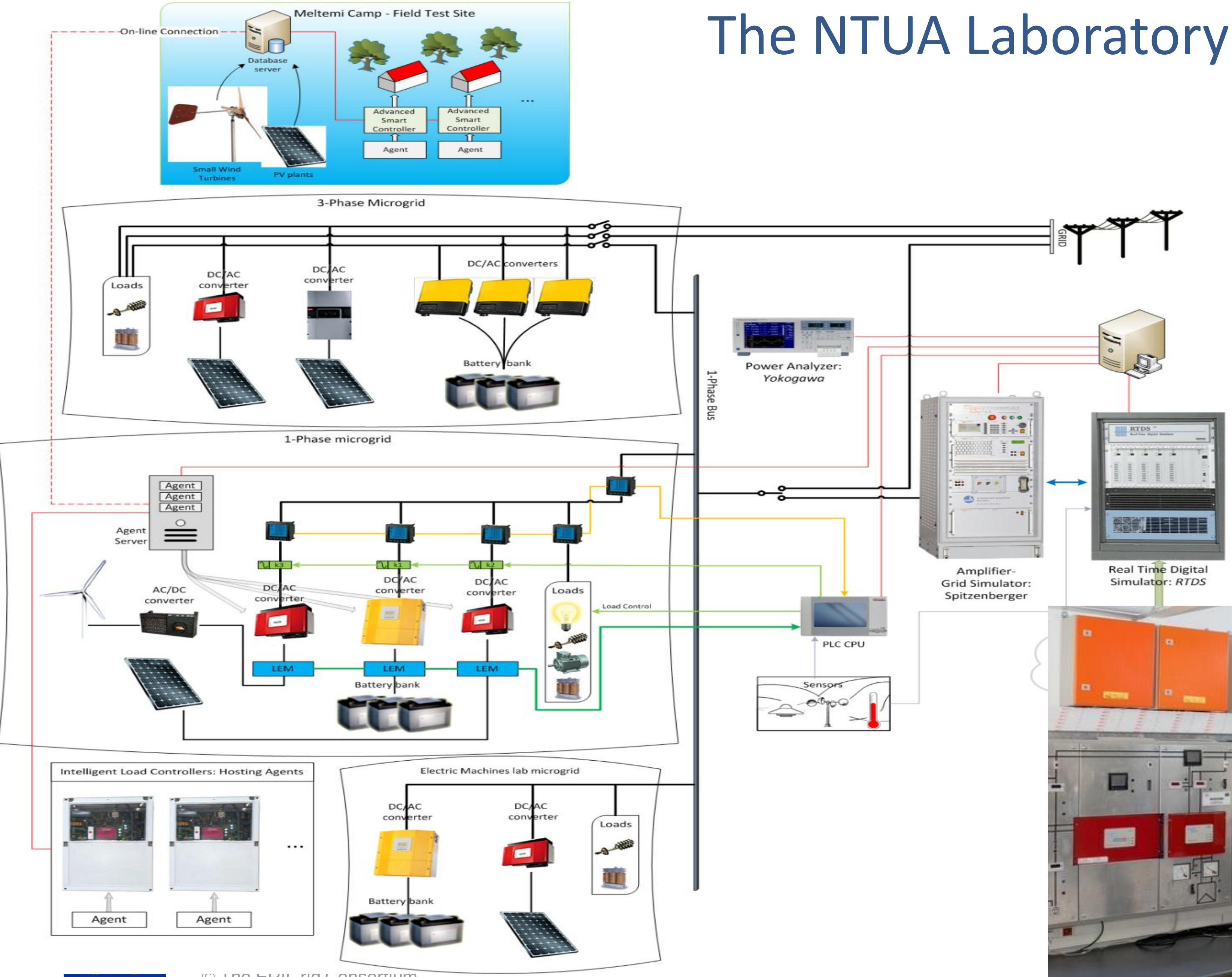
Less than 5% error



- An accurate method to determine the marginal parameters of a PHIL experiment **without using approximations for the time delay.**
- The proposed analysis was applied to existing methods (i.e. feedback current filter, shifting impedance method) to achieve stability and the accurate selection of parameters is made possible

HIL FOR LABORATORY EDUCATION

The NTUA Laboratory

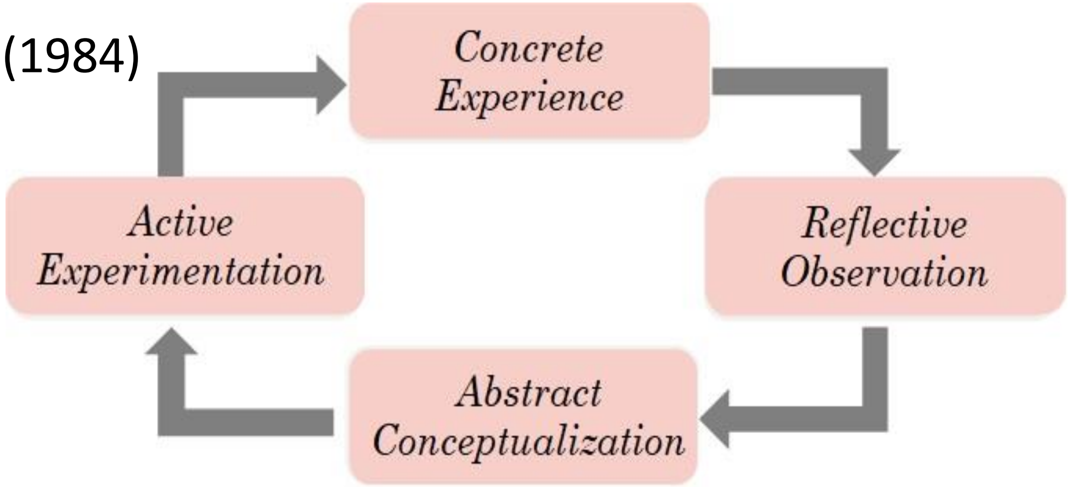


HIL for Laboratory Education

- Laboratory education in the power systems domain is usually performed with software simulations and more rarely with small hardware setups with limited capabilities (contrary to other domains e.g. electric machines)
- The students have limited familiarity with real hardware power systems
- PHIL simulation can provide to students hands-on experience with real hardware, while maintaining the advantages of the digital simulation (flexibility etc)
  - 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.
- CHIL simulation has already been used in the education of engineers (e.g. control systems, electric machine drives, power system protection etc.)
- The use of the PHIL method for education hadn't been investigated yet in a systematic way

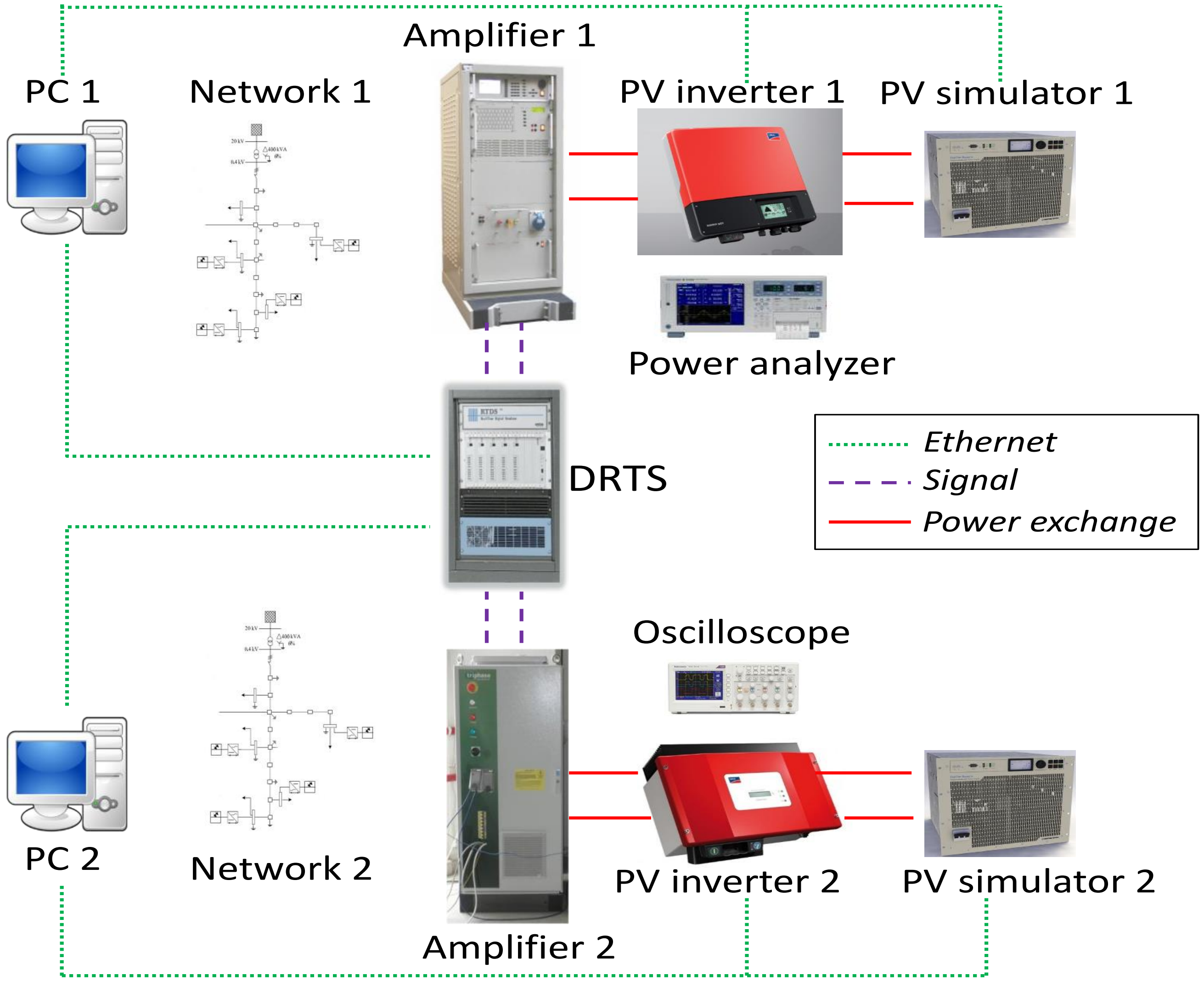
Educational approach and methodology used

- 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)



- Aims 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

Double PHIL configuration



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

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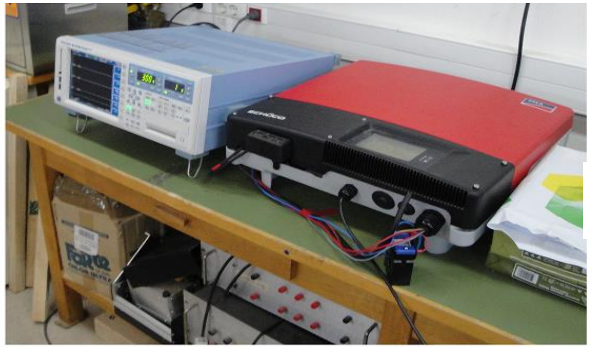


Workbench 1

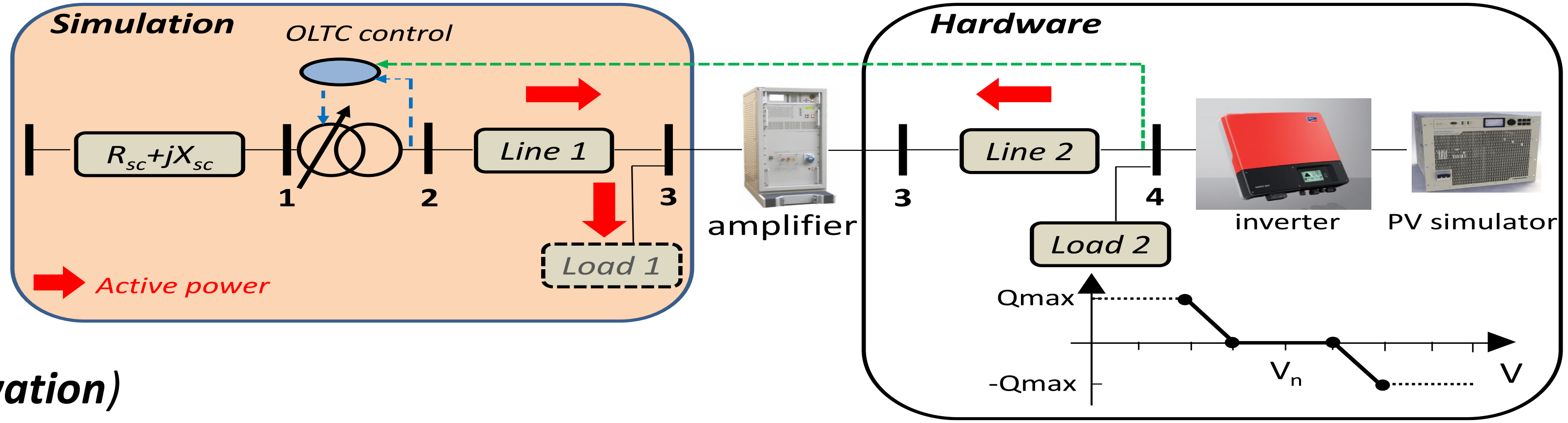
Workbench 2

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 :

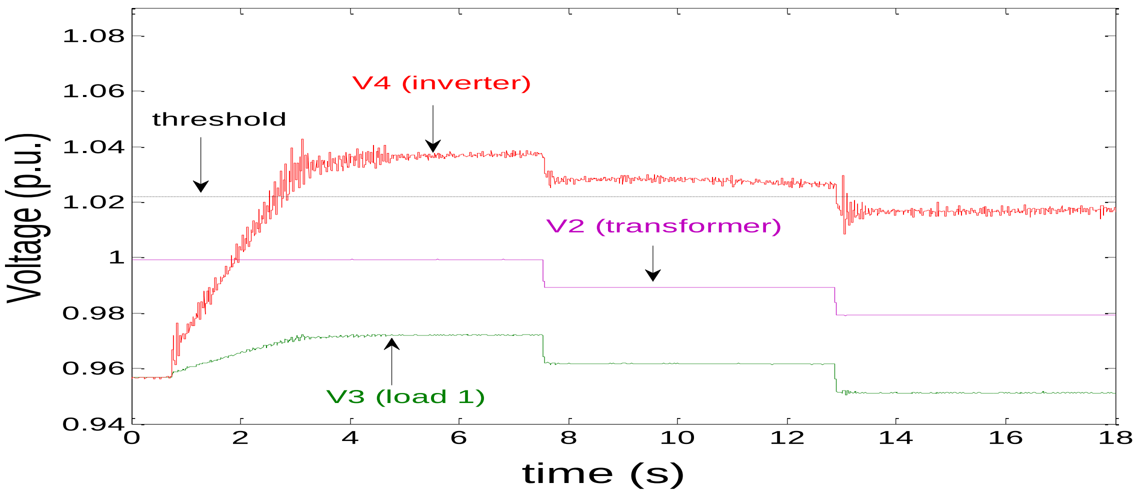
*voltage rise (**concrete experience**)*

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

iii) Extend the ΔV equation.

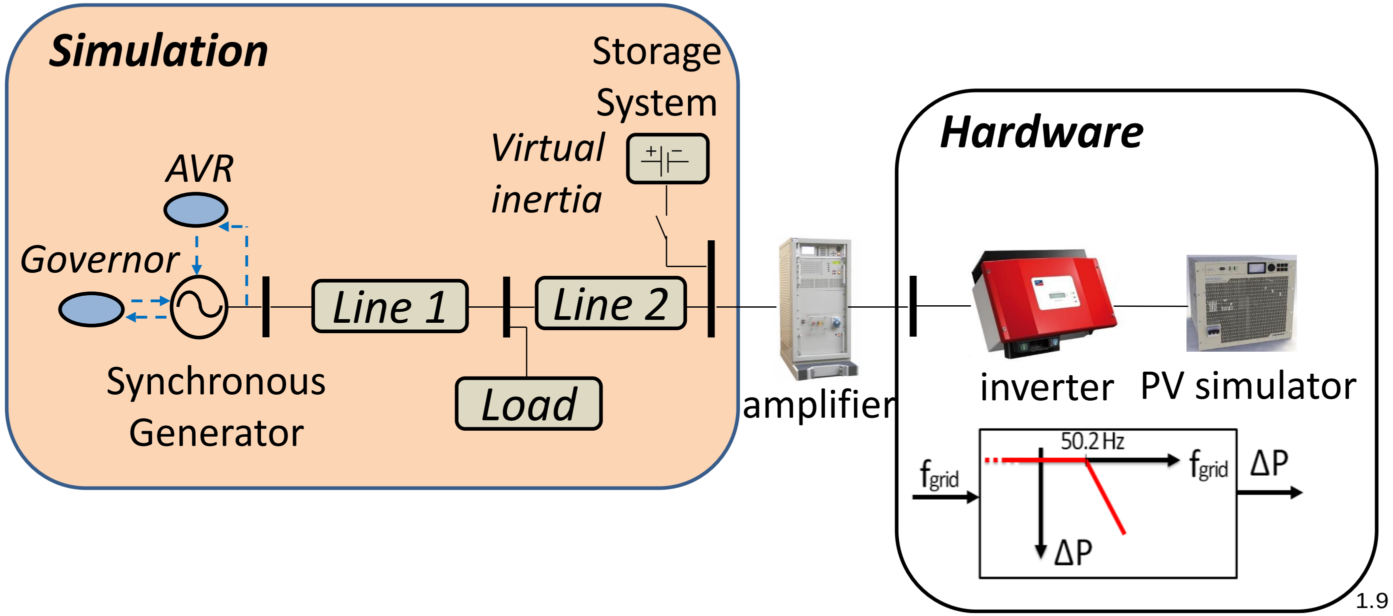
*Solution: reactive power absorption (**abstract conceptualization**)*

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

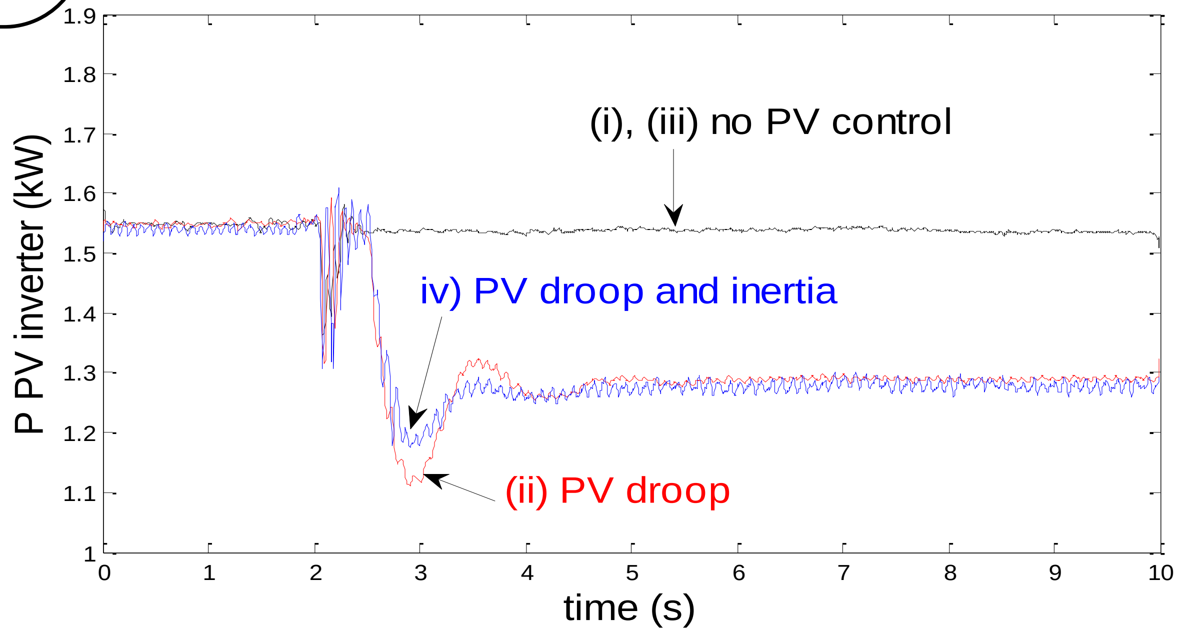


- OLTC: reduces the voltage rise at the PV inverter's node but further decreases the voltage of the load → need for coordinated control

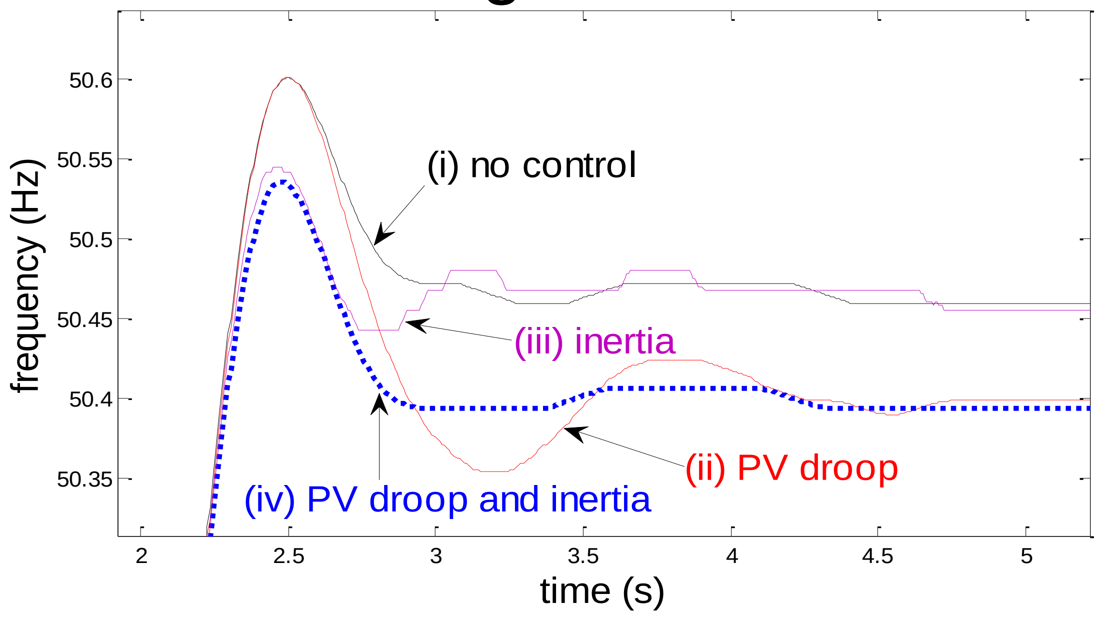
Parallel operation of synchronous generators and distributed generation

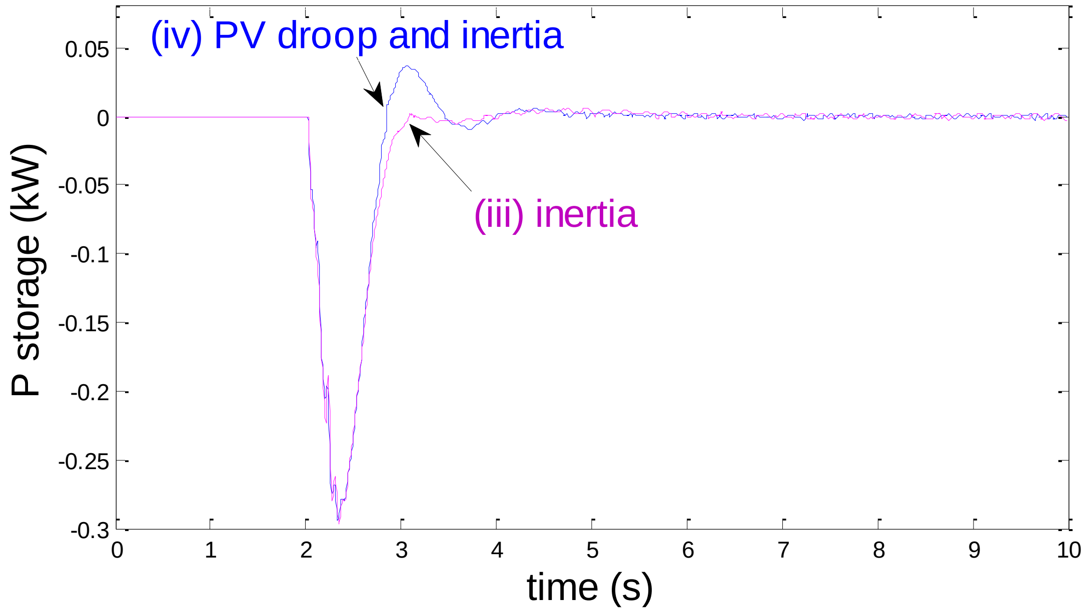


- Conventional Generation
- Hardware inverter operating with P(f) droop control
- Simulated storage system providing virtual inertia
- No communication between the components



Parallel operation of synchronous generators and distributed generation

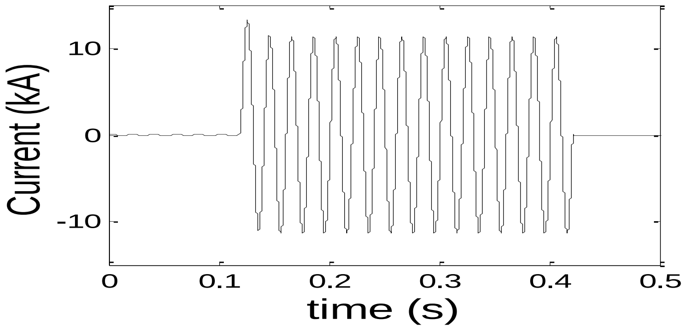




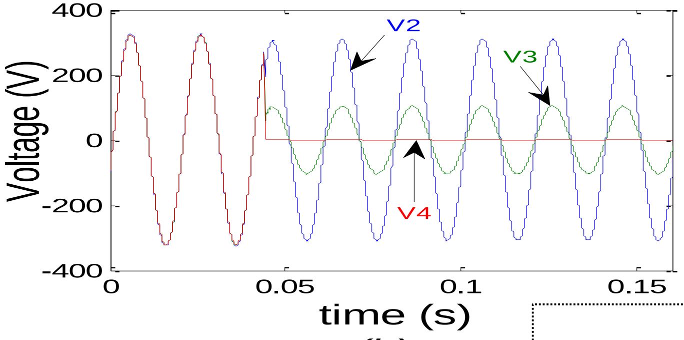
- Droop control improves only the steady state (slow controller in this inverter). The combined operation performs better
- Virtual inertia improves the dynamic response
- **System level testing (not only the inverter is tested but also its impact on the system).**

Short-circuits: digital relays and behaviour of PV inverters

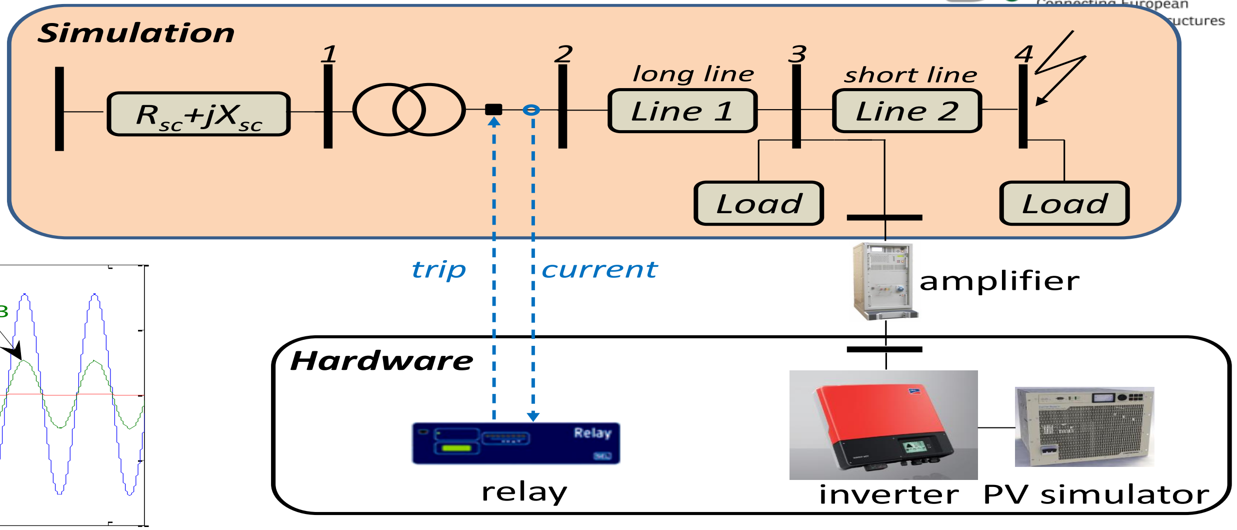
- location of the fault moves away from the transformer, short circuit current is decreased and the trip time of the relay is increased

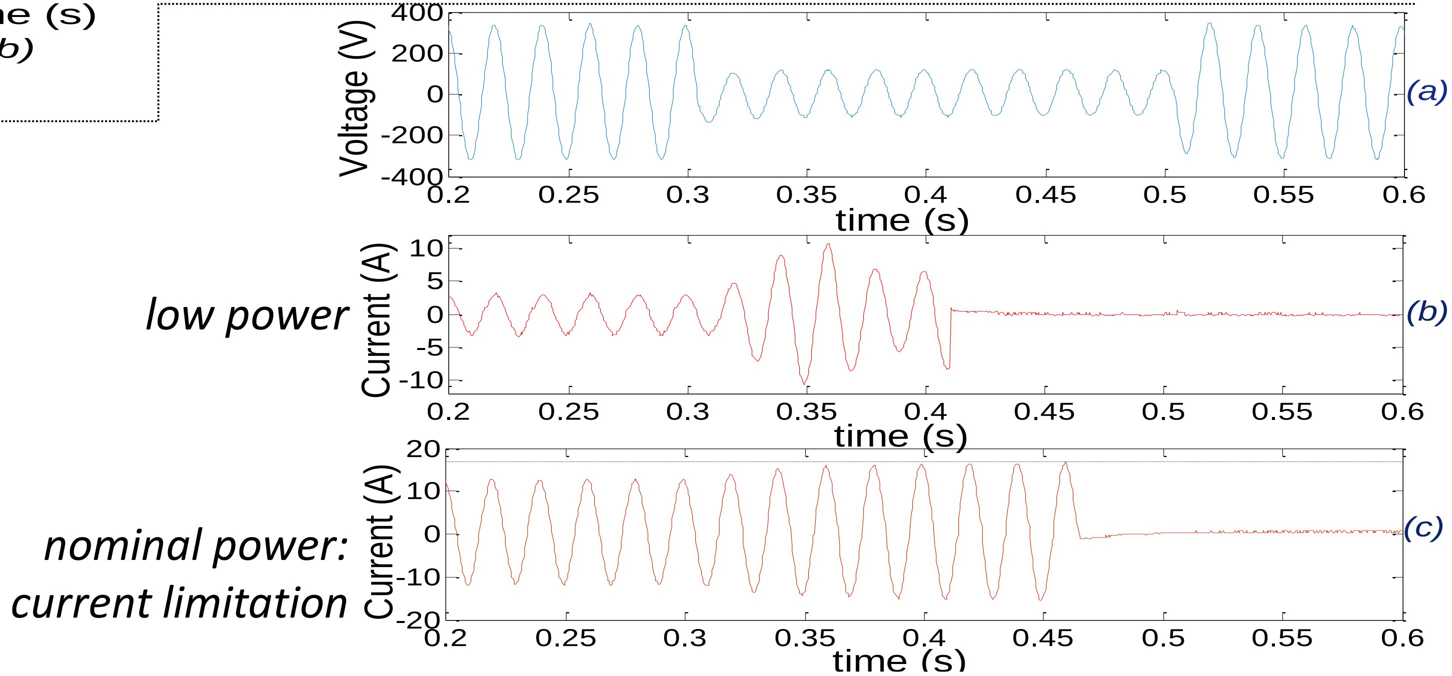


(a)



(b)



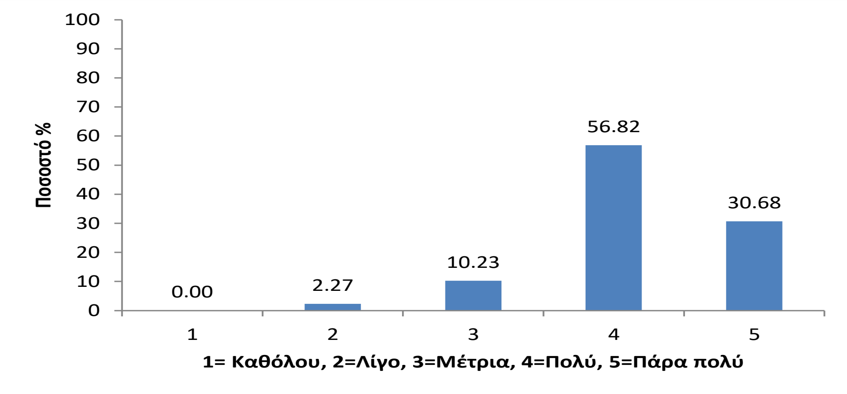


- Voltage drop at 1/3 due to the short-circuit
- Limitation on the current of the inverter when operating at nominal power

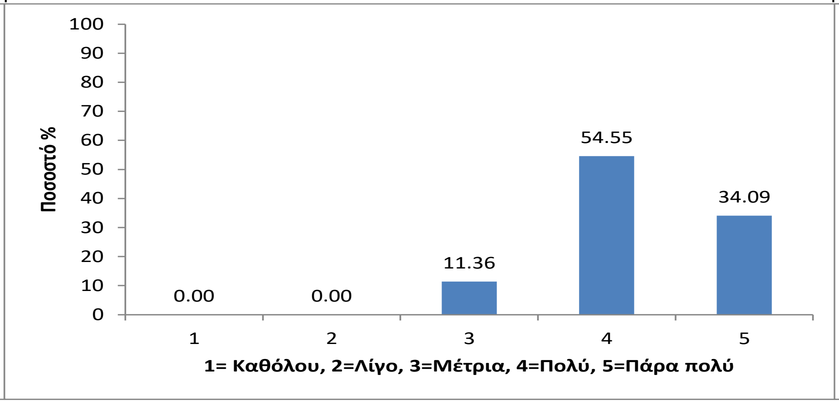
Evaluation of the laboratory exercises by the students

- 10 questions, 95 questionnaires received
- ***1***: I strongly disagree, ***2***: I disagree, ***3***: I am neutral, ***4***: I agree, ***5***: I strongly agree

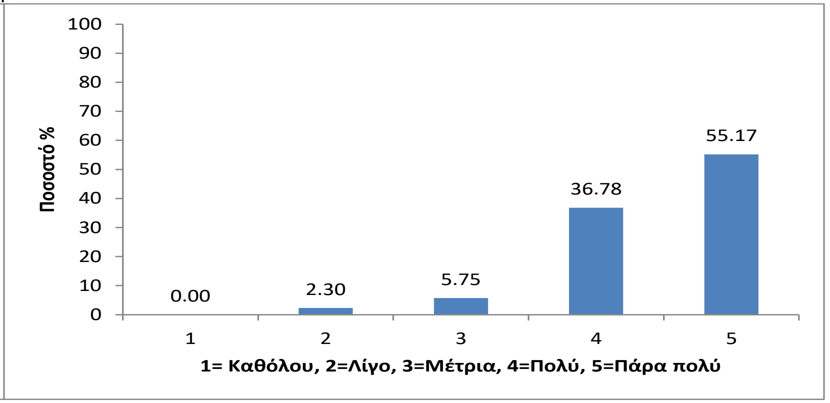
The laboratory exercise has helped me understand the operation of modern power systems with distributed generation



The laboratory exercise is interesting (in overall)



Real-time simulation is a useful educational tool

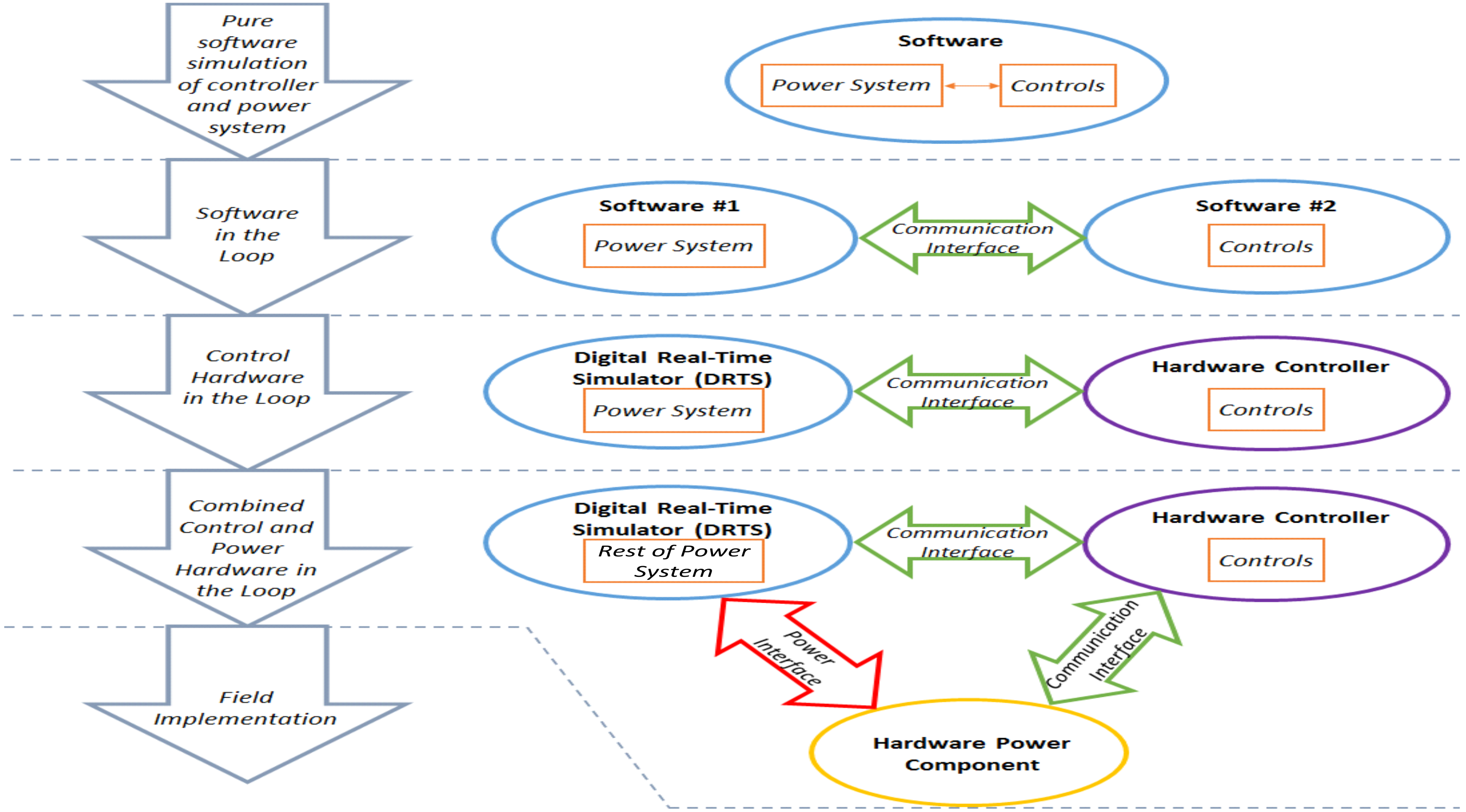


- They highly appreciated the use of real-time simulation for educational purposes (*37% I agree, 55% I strongly agree*)
- They prefer hands-on approaches compared to demonstrations *(51% I strongly agree)*
- They find the introduction of modern topics motivating (*51% I strongly agree)*

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

TESTING CHAIN: COMBINED CHIL/PHIL SIMULATION AND REMOTE REAL-TIME CO-SIMULATION

Supervisory Controller testing: EMS/DMS Proposed testing chain of Smart Grid control algorithms

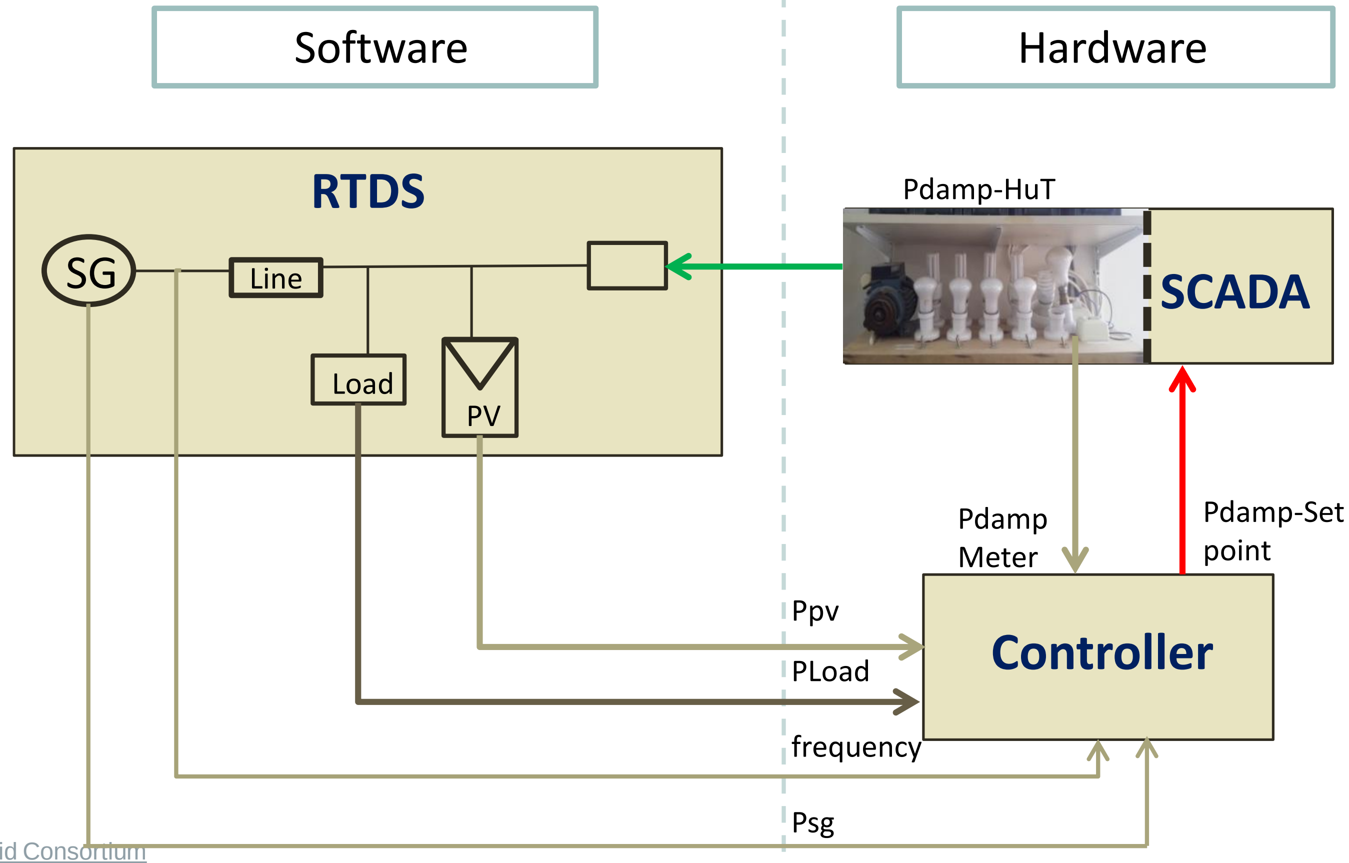


The combination of CHIL and PHIL simulation allows to test a controller in a CHIL configuration, while critical power components are incorporated as physical devices (PHIL simulation) allowing to analyze more realistic real-world based conditions.

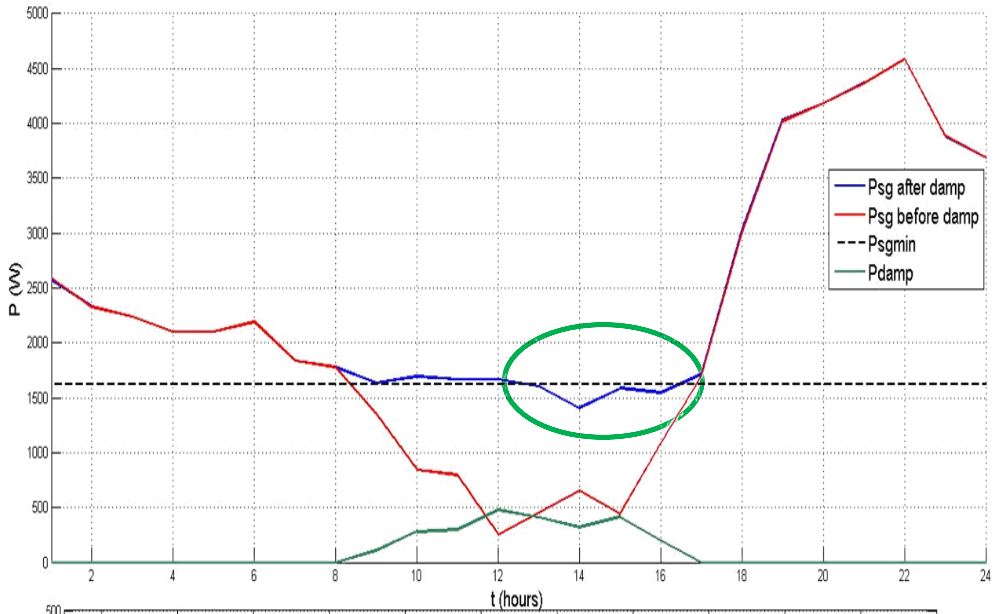
M. Maniatopoulos, D. Lagos, P. Kotsampopoulos, N. Hatziargyriou, "Combined Control and Power Hardware-in-the-Loop simulation for testing Smart grid control algorithms", IET Generation, Transmission & Distribution, Early Access, March 2017

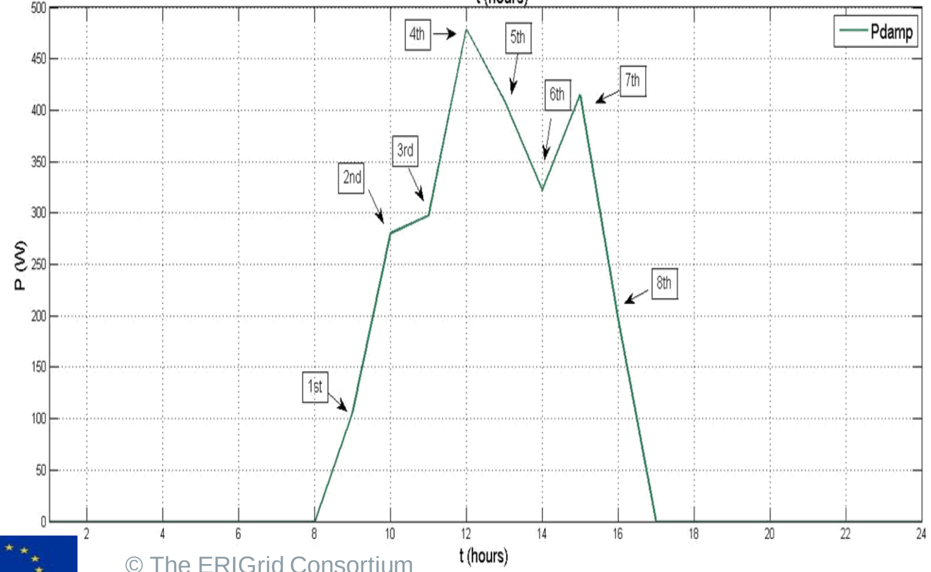
Supervisory Controller testing: EMS/DMS - CHIL/PHIL testing of off-grid microgrid controller

- Testing of central controller of off-grid systems (Diesel Generator-PV-loads)
- The controller activates damp loads in order to respect the minimum load ratio (30% of nominal power) of the Diesel generator, due to high PV penetration

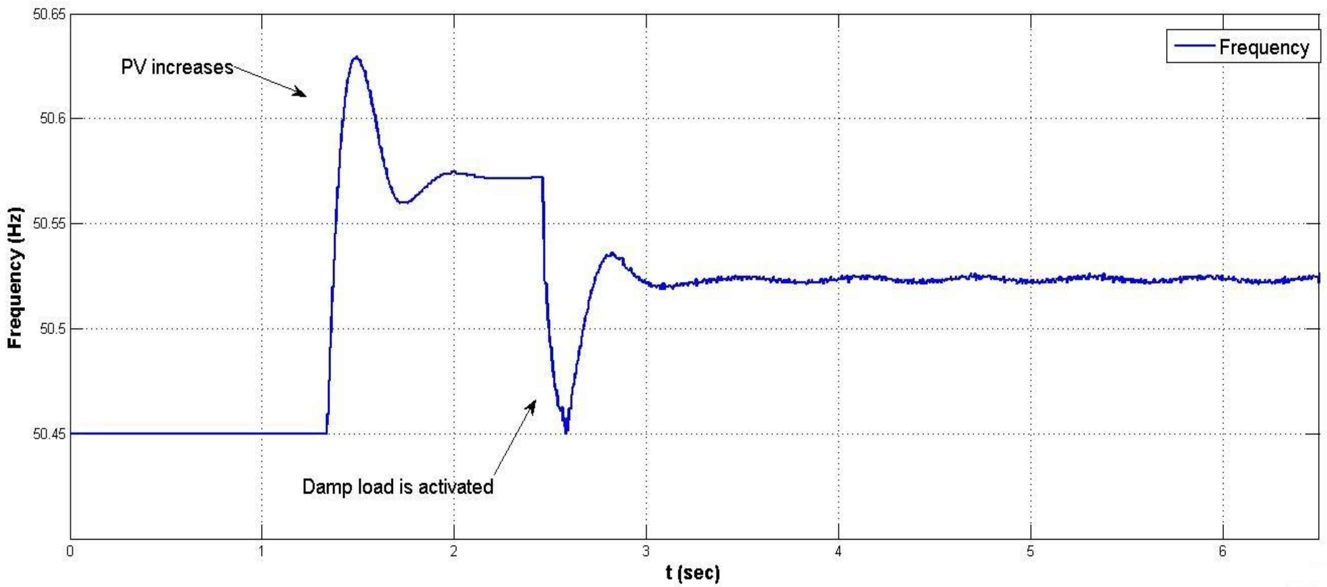


Supervisory Controller testing: EMS/DMS - CHIL/PHIL
testing of off-grid microgrid controller



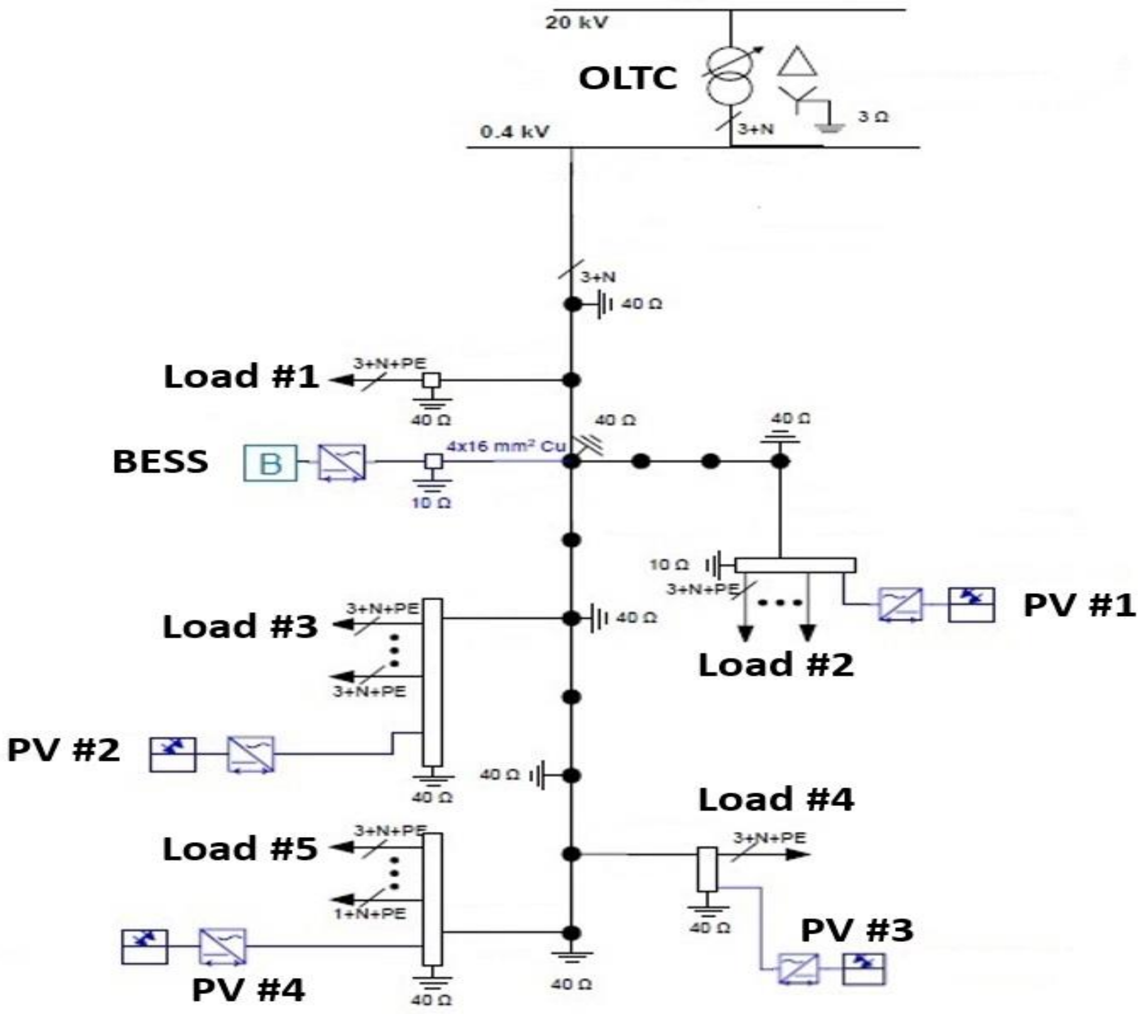


- **The non ideal operation of the damp load shows the benefit of using the CHIL/PHIL approach**



Coordinated Voltage Controller (CVC) Testing

Modified CIGRE Benchmark Low Voltage Microgrid



Coordinated Voltage Control algorithm

$$\min_{x} f(x) = w_1 * \sum_{i=1}^{12}\sum_{j=1}^{12} P_{losses,ij} + w_2 * \sum_{k=1}^{6} (V_k - 1)^2 + w_3 * |tap_{new} - tap_{current}|$$

$$x = [V_1 \quad \dots \quad V_{12} \quad \delta_1 \quad \dots \quad \delta_{12} \quad P_{bat} \quad Q_{bat} \quad Q_{pv,1} \quad Q_{pv,2} \quad Q_{pv,3} \quad Q_{pv,4} \quad tap_{changes}]$$

where:

$$P_{losses,ij} = -G_{ij} * [V_i^2 + V_j^2 - 2V_iV_j \cos\delta_{ij}]$$

$$tap_{changes} = \text{deviation from the nominal tap position (integer variable)}$$

$$tap_{new} = nominal\ tap\ position + tap_{changes}$$

$$tap_{current} = current\ tap\ position$$

$$w_1, w_2, w_3 = \text{weights for the objective function terms}$$

subject to:

Voltage Constraints

$$V_1 = 1$$
$$\delta_1 = 0$$
$$0.9 \le V_i \le 1.1$$
$$0^\circ \le \delta_i < 360^\circ$$

OLTC Constraints

$$-8 \le Tap\_changes \le 8$$

BESS Constraints

$$P_{discharge} \le P_{bat} \le P_{charge}$$
$$-S_{bat,nom} \le Q_{bat} \le S_{bat,nom}$$
$$P_{bat}^2 + Q_{bat}^2 \le S_{bat,nom}^2$$

Power Flow Constraints

$$P_{Gen,i} - P_{load,i} = V_i \sum_{j=1}^{n} V_j [G_{ij}\cos\delta_{ij} + B_{ij}\sin\delta_{ij}]$$

$$Q_{Gen,i} - Q_{load,i} = V_i \sum_{j=1}^{n} V_j [G_{ij}\sin\delta_{ij} - B_{ij}\cos\delta_{ij}]$$

PV Inverter Constraints

$$|Q_{pv,i}| \le P_{pv,i} * \tan(\cos^{-1}(0.8))$$
$$P_{pv,i}^2 + Q_{pv,i}^2 \le S_{pv,nom,i}^2$$

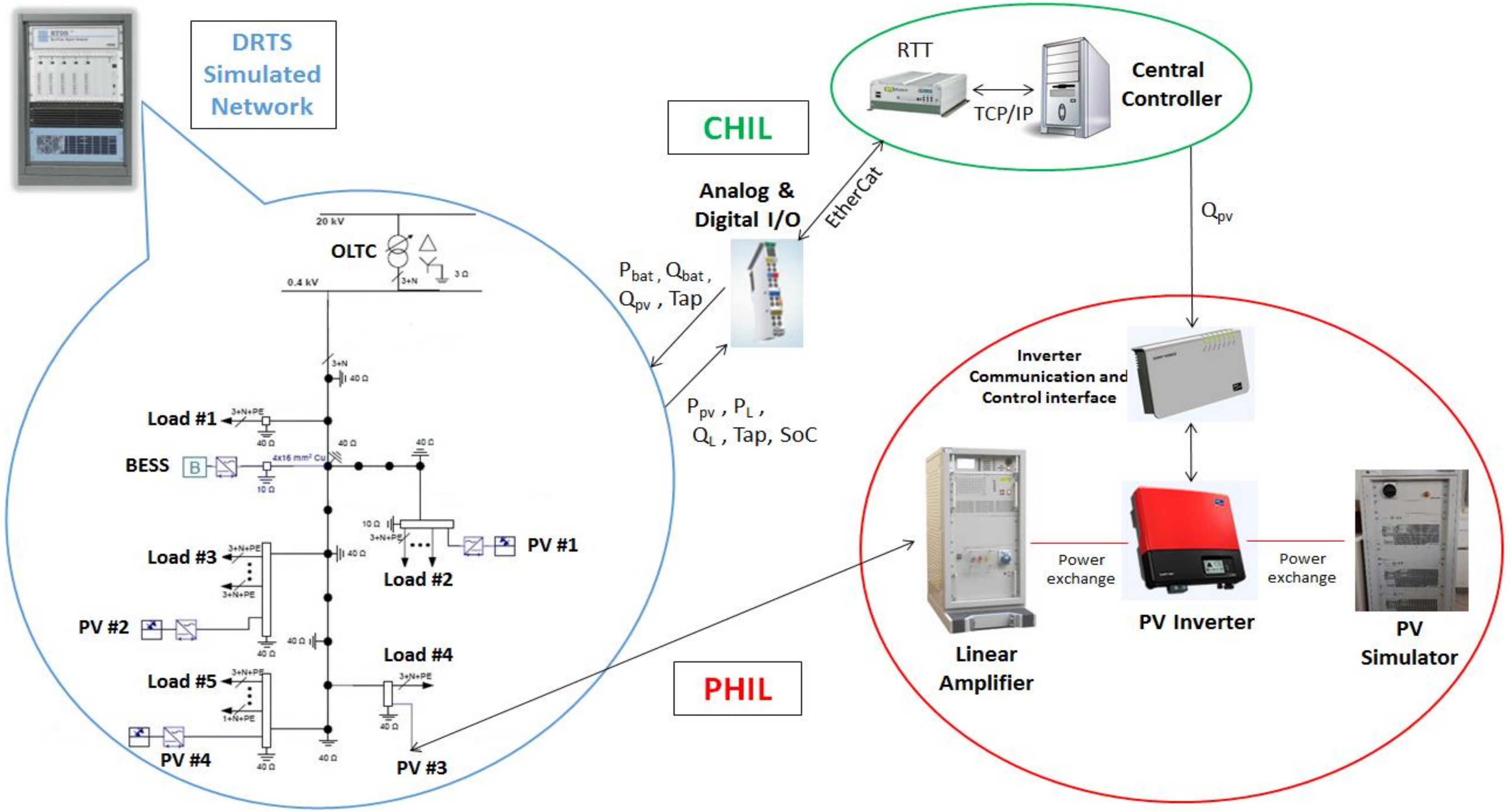
Line Current Constraints

$$Y_{ij} * (\widetilde{V_i} - \widetilde{V_j}) \le I_{ij,limit}$$

Coordinated Voltage Controller Testing: combined CHIL and PHIL

Connecting European Smart Grid Infrastructures

- The CVC algorithm was tested in pure simulation, Software in Loop (SIL), CHIL and finally combined CHIL and PHIL
- The controller was tested in realistic conditions (real time communication) in the CHIL setup
- The combined CHIL and PHIL setup also provided:
  - Insight on communication issues between the controller and the real hardware
  - Validation of the CVC with real power hardware behaviour



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Coordinated Voltage Controller Testing

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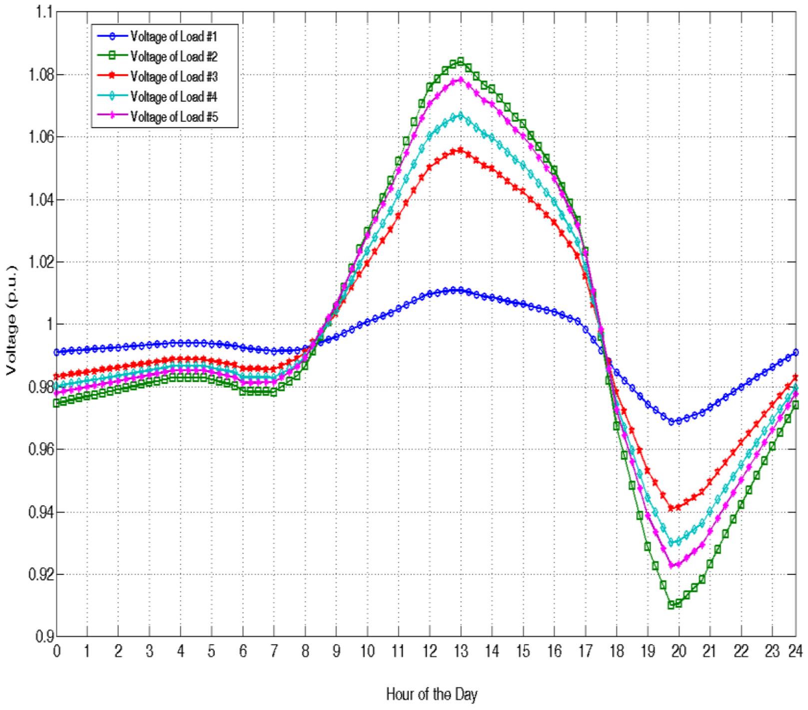
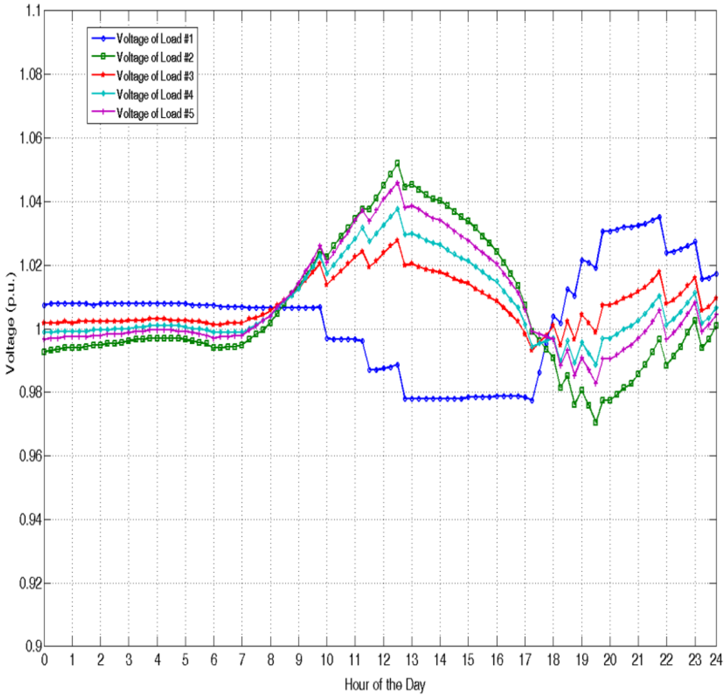
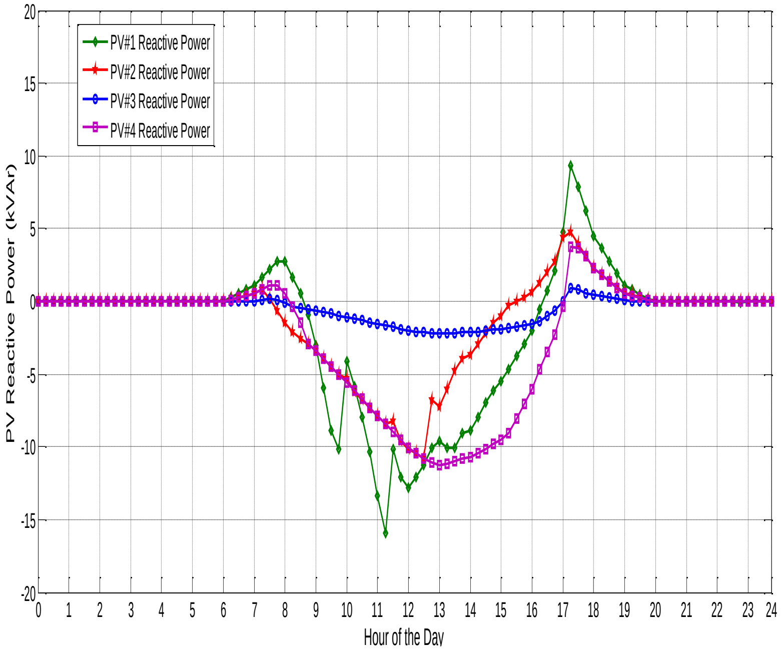


Voltage of all nodes without voltage control



Voltage of all nodes with CVC

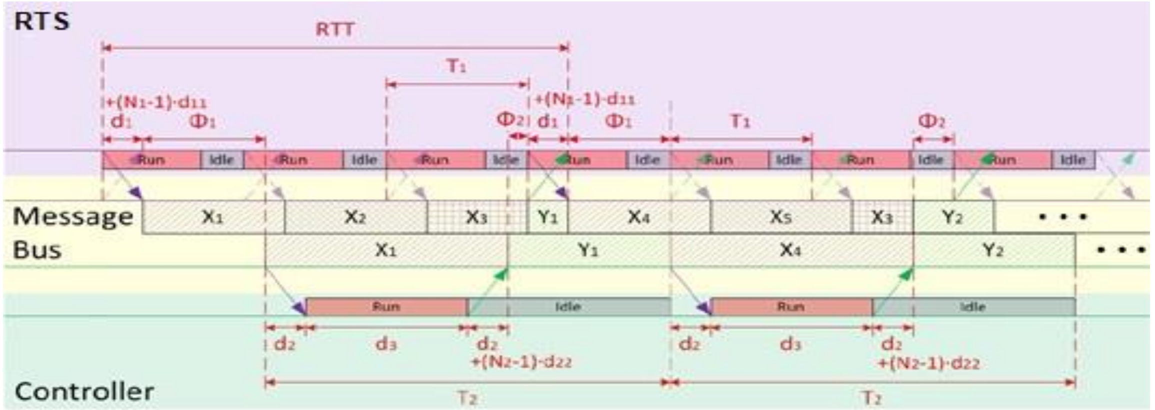


PV reactive power

Real-time co-simulation via OPSim

Joint work with Fraunhofer IEE

- **OPSim tool**: developed by Fraunhofer IEE
- Interconnect two geographically distributed simulators via the co-simulation environment OPSim to assess delay impact on Real-Time Simulation and to understand the boundaries in the co-simulation environment OPSim.
- Determine a holistic performance of a Coordinated Voltage Control (CVC) algorithm through the co-simulation environment.

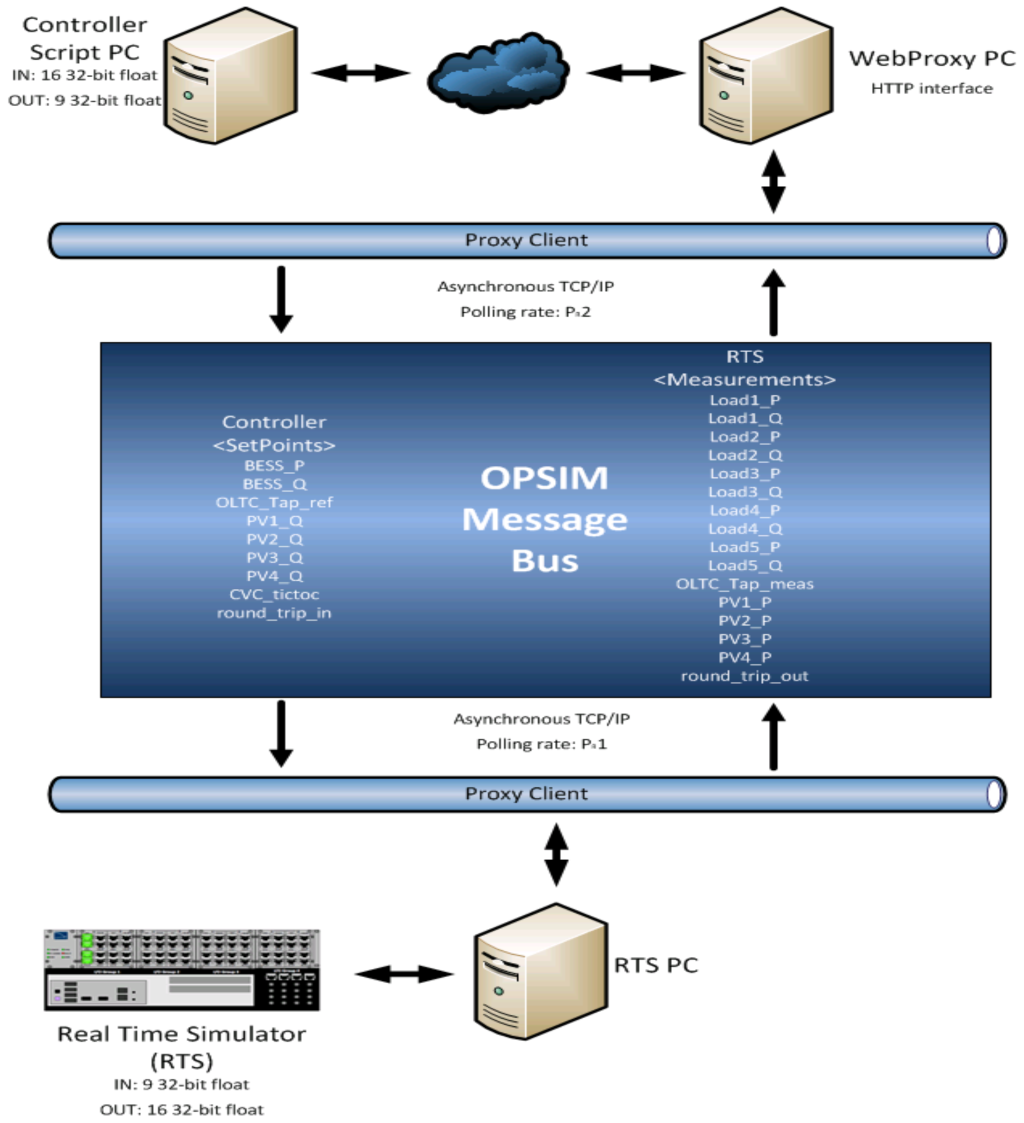


J. Montoya, R. Brandl, M. Vogt, F. Marten, A. Fabian, M. Maniatopoulos, "Asynchronous Integration of a Real-Time Simulator to a Geographically Distributed Controller through a Co-Simulation Environment", accepted for presentation at IECON 2018

Remote real-time simulation: CVC response

Joint work with Fraunhofer IEE

- The main purpose is to determine the response of the Real Time Simulator models to the reference set-points provided by the CVC controller.
- CVC results are compared to a reference simulation scenario.
- The convergence of the OPF in the CVC controller is analyzed to determine the limit of the refresh rate to publish data in the OpSim Message Bus and avoid data losses.



Remote real-time simulation: Test results

Joint work with Fraunhofer IEE

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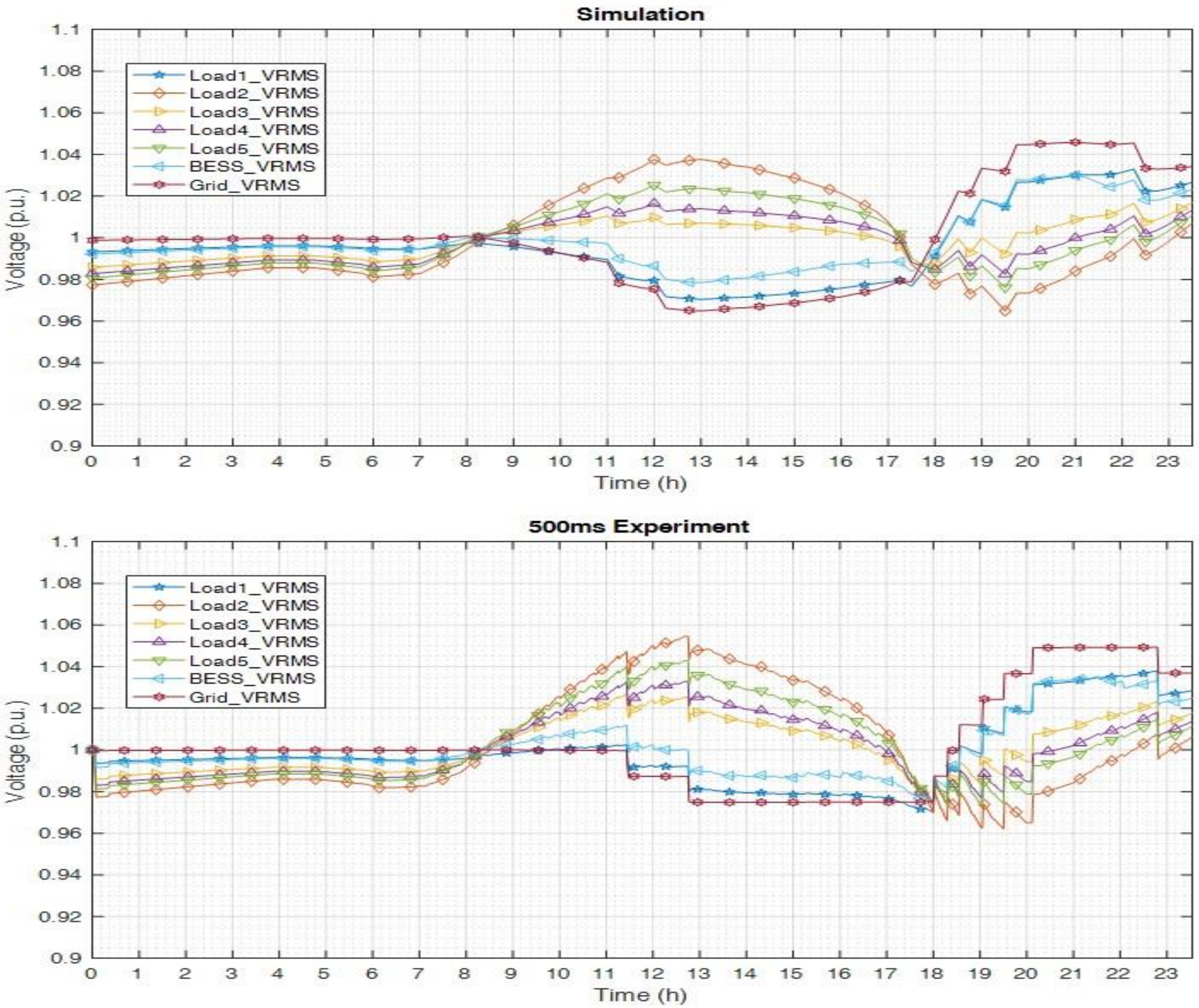
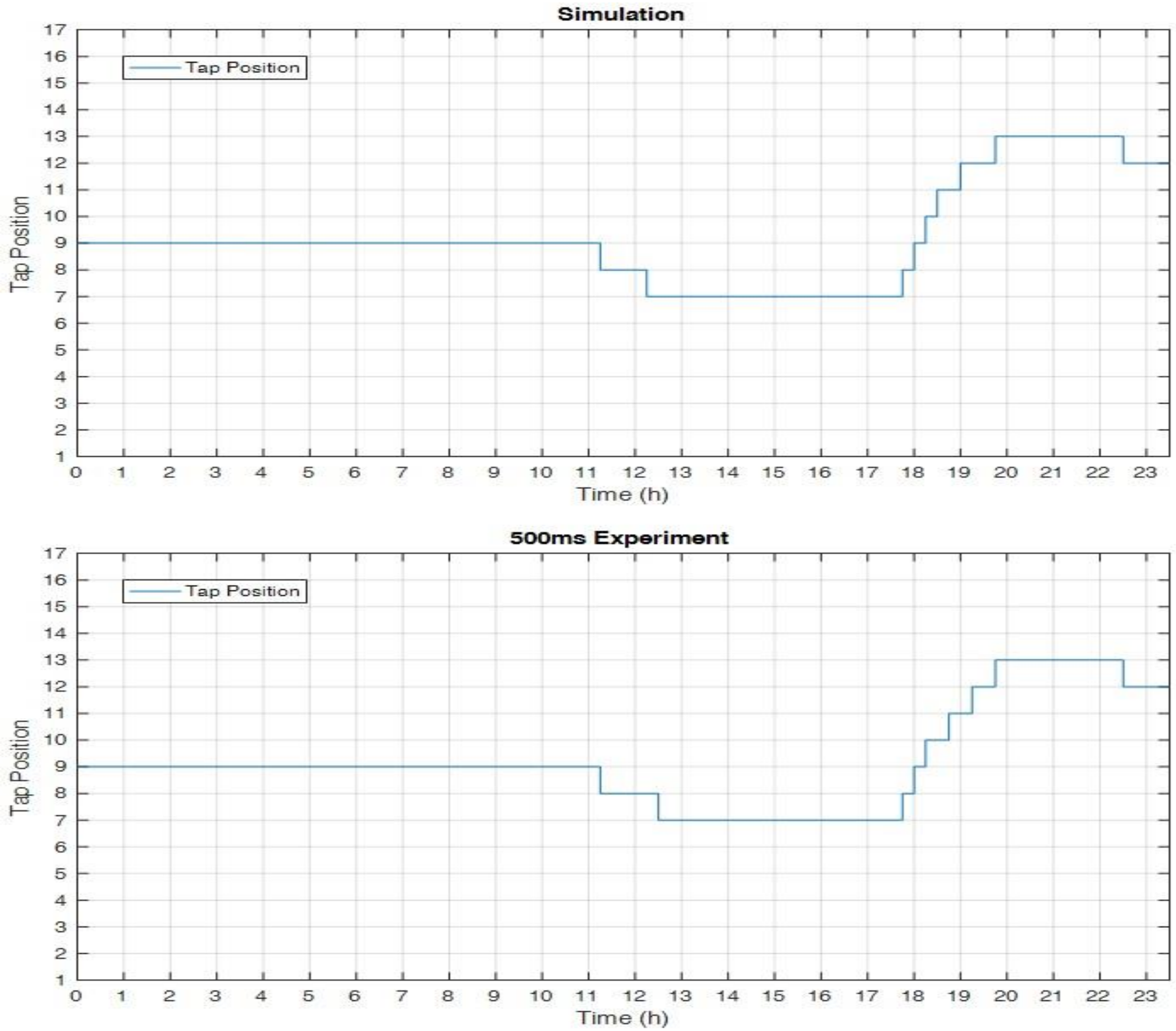
Bus Voltage



OLTC - Tap Position



ADDITIONAL ACTIVITIES

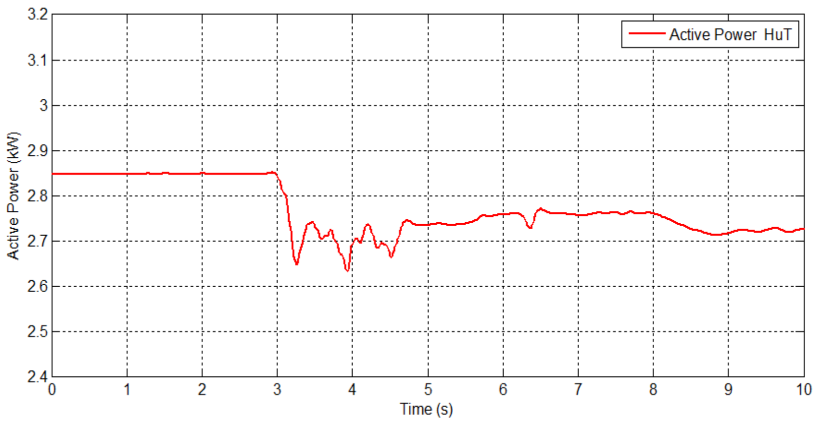
Benchmark System for HIL testing of DER

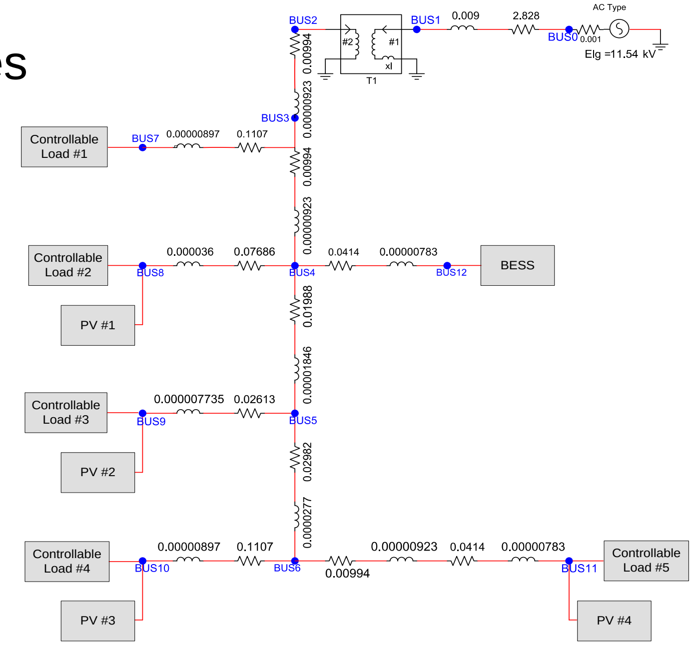
- Developed by the *IEEE PES Task Force on Real-Time Simulation of Power and Energy Systems*
- *P. Kotsampopoulos, D. Lagos, N. Hatziargyriou, M.O. Faruque et al. “A Benchmark System for Hardware-in-the-Loop Testing of Distributed Energy Resources”, IEEE Power and Energy Technology Systems Journal, Sept. 2018*

Proposes:

- Benchmark network for RT-HIL (simplification of CIGRE LV benchmark)
- Reference laboratory CHIL and PHIL test procedures

CHIL/PHIL test results substantiate the approach





Step	Preparation of the experiment
I) Test case development	▪ Test case development (power system configuration, characteristics of the network). . ▪ Modeling phase (implementation of real-time models and control algorithms on the DRTS, verification of real-time capability). ▪ Providing sufficient level of protection by observing experimental quantities to bring the PHIL experiment to a safe state if unexpected behavior (HUT failure, instability, etc.) occurs
II) Stability and accuracy evaluation	There are mainly two straightforward methods for evaluating the stability of a PHIL simulation system: ▪ Application of the Nyquist criterion on the open-loop transfer function of the closed-loop system derived from the block diagram representing the quasi-continuous model of the PHIL control system. ▪ Dynamic simulation as a virtual emulation of the PHIL system, which contains all the parts and interactions of the PHIL experiment (real-time model, HUT, I/O, interface algorithm (IA)). Accuracy evaluation is recommended based on methods described in [29][30] and the aforementioned virtual emulation of PHIL systems.
III) Checking protection and compensation blocks	▪ In case a HUT (or power interface) is not known in certain detail, stability evaluation according to II) cannot ensure safe PHIL simulation operation. Therefore, the incorporation of protection schemes on the software side (safety routines in the DRTS) and on the hardware side (current, voltage, power, temperature, or control protection) is of key importance. Before the implementation of each PHIL test, the effective operation of the protection schemes should be fully verified. ▪ In many occasions, stability-accuracy analysis has shown the need to use interface compensation measures [31], such as filtering on the feedback signals [32], in order to guarantee system stability of the PHIL test and/or improve accuracy. It is important to verify that the selected functions are enabled for the execution of the PHIL experiment.
Step	**Execution of the experiment**
IV) Execution of the DRTS model	The simulated system modeled in the software of the DRTS is compiled and executed in the following. While the model runs, it produces a low-voltage reference signal for the power interface that drives the PHIL simulation.
V) Power interface (PI) start-up	The PI produces an AC (or DC) voltage (or current) according to the set-point provided by the DRTS. It is recommended to check in advance the waveform and RMS value of the reference signal. Depending on the amplifier the start-up can be straightforward or may require several steps (e.g. connection to the utility grid, loading the DC bus, etc).
VI) Connection of the HUT with the power interface	The AC voltage produced by the power interface is applied to the HUT. The HUT can be connected with the power interface via a relay controlled by power interface software, thus power connection to the HUT is established.

IEEE **WG P2004:** Recommended Practice for Hardware-in-the-Loop (HIL) Simulation Based Testing of Electric Power Apparatus and Controls

- No standard exists that provides guidance and recommends best practices for the application of HIL simulation

IEEE **WG P2004:**

- Brings together all the relevant stakeholders
- Serves as a platform to further promote HIL
- Will establish practices for real-time simulation model development
- Will provide guidance on requirements for power amplifiers, DRTS, HIL interface algorithms for classes of HIL testing needs
- etc

Chair: Mischa Steurer (CAPS-FSU)

Co-chair: Georg Lauss (AIT)

Secretary: Blake Lundstrom (NREL)

Get involved

Conclusions

- A method to analyze PHIL stability and determine marginal parameters without using approximations for the time delay
- PHIL simulation is an efficient educational tool: hands-on experience with hardware devices while maintaining the flexibility and modeling capabilities of simulation
- A testing chain for system controllers (DMS/EMS) was proposed: combined CHIL and PHIL approach provides more realistic results.
- Remote real-time co-simulation test: the delays can impact the operation of the control algorithm
- HIL simulation is/must/will be considered for future standardized testing

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Thank you for your attention!

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