GRID INTEGRATION OF DER SUPPORTED BY PHIL AND CHIL SIMULATION: NTUA EXPERIENCES

PANOS KOTSAMPOPOULOS,

D. LAGOS, V. KLEFTAKIS, A. VASILAKIS, A. KONTOU, V. PAPASPILIOTOPOULOS, I. KOUVELIOTIS-LYSIKATOS, A. CHRONIS, G. KORRES, N. HATZIARGYRIOU

SMART GRIDS RESEARCH UNIT – SMART RUE

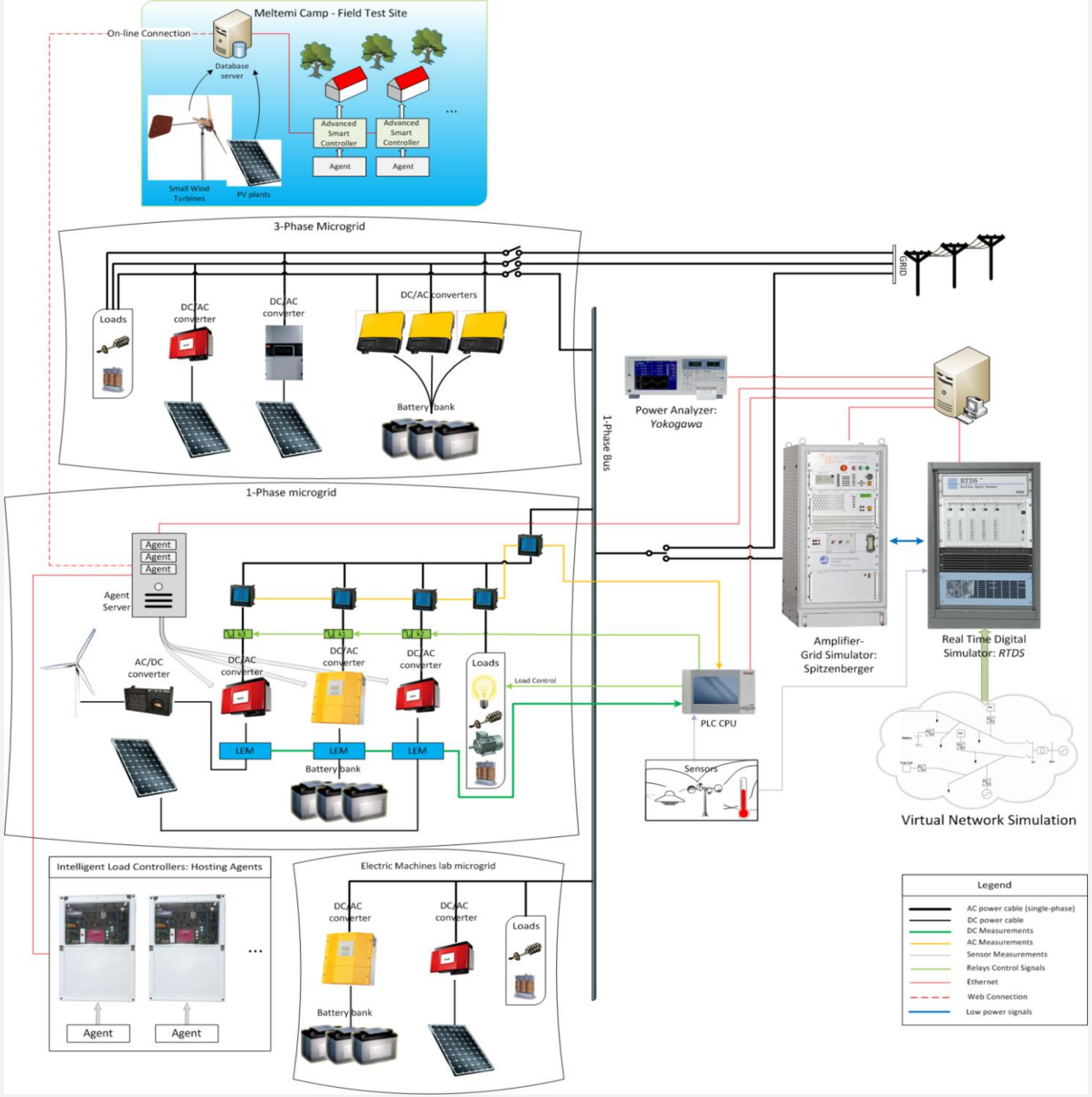
NATIONAL TECHNICAL UNIVERSITY OF ATHENS

USER SPOTLIGHT SERIES BY RTDS Technologies

OVERVIEW

- HIL testing of **power electronic converters**
    1) Inverter development and testing
    2) FACTS testing
    3) Microgrid primary control
    4) DER and OLTC interactions
- HIL testing of **smart grid controllers**
    5) Coordinated voltage controller
    6) Adaptive protection of distribution networks
    7) Distributed control of loads and DER (Multi-Agent System)
- HIL for Laboratory Education

ELECTRIC ENERGY SYSTEMS LABORATORY OF NTUA



USER SPOTLIGHT SERIES BY RTDS Technologies

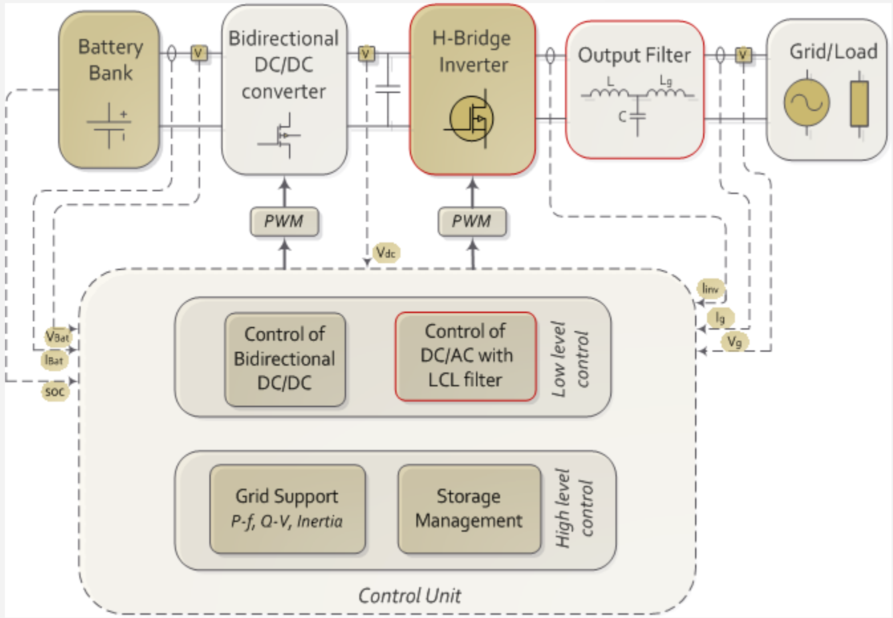
1) DER INVERTER DEVELOPMENT AND TESTING (CHIL AND PHIL TESTS)

DEVELOPMENT OVERVIEW OF BATTERY INVERTER AND TEST PROCEDURE

Design

☐ **Requirements**

- ○ Grid connected Operation
- ○ Islanded Operation
- ○ Bidirectional Power flow
- ○ Grid Support Functions



Testing

☐ **Simulation Validation**

- PI SRRF Voltage Control
- PR Voltage Control
- H-Infinity Control
- PI SF Voltage Control
- Virtual Resistance
- 2-DoF

☐ **CHIL Tests**

- ○ Islanded operation
- ○ Grid connected operation
- ○ Grid support functionalities

☐ **Hardware tests**

- ○ Islanded operation
  - PI SRRF Voltage Control
  - PR Voltage Control
  - H-Infinity Control
- ○ Grid connected operation
  - PI SF Voltage Control
  - Virtual Resistance
  - 2-DoF

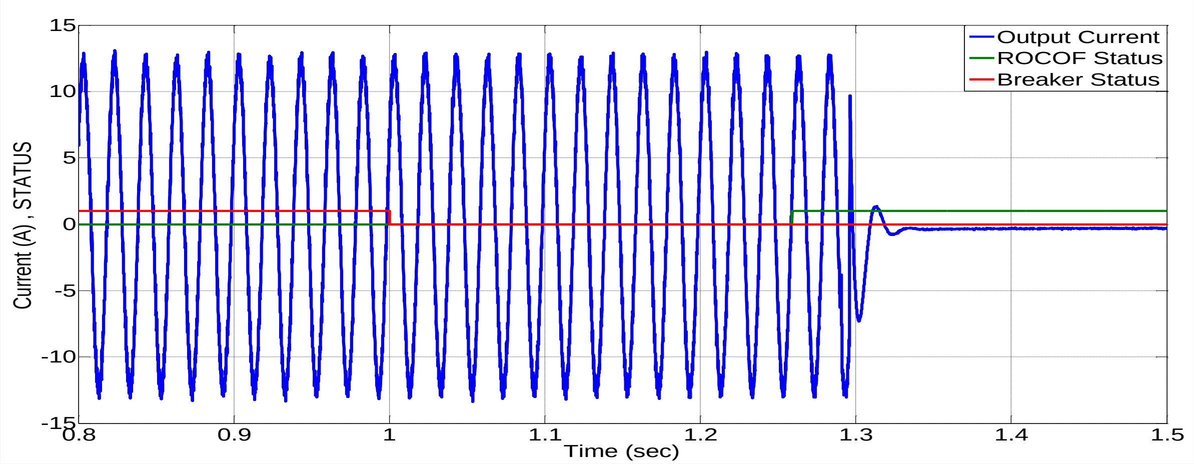
☐ **Power-Hardware-in-the Loop Tests**

- ○ Grid support functionalities
- ○ Integrated protection
- ○ Communication interface

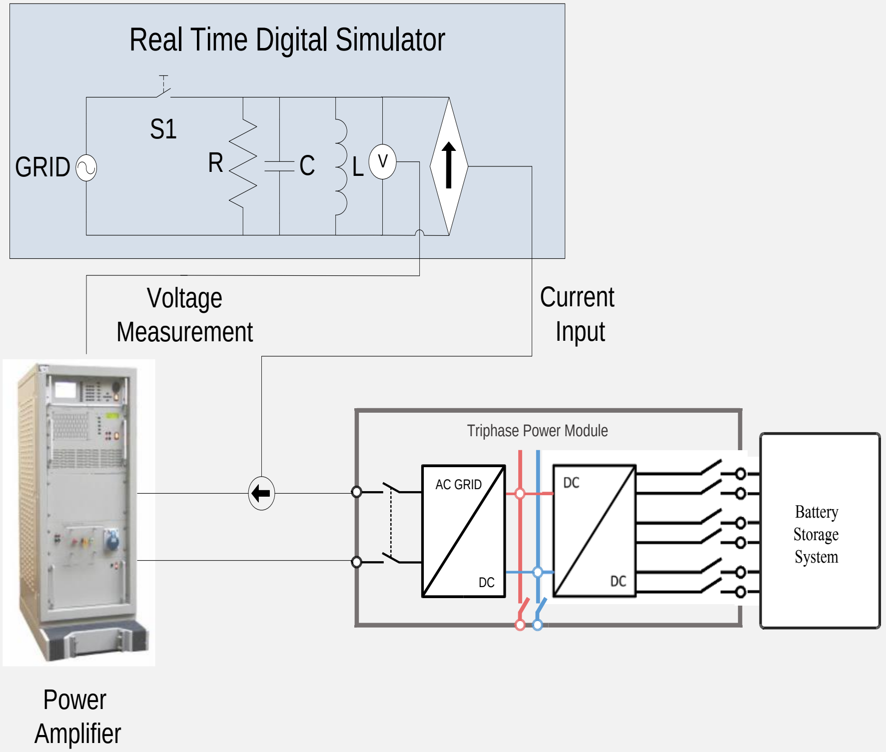
PHIL TESTING OF DER INVERTER ANTI-ISLANDING PROTECTION

Islanding Detection Algorithms testing with PHIL setup

- Same setup as the IEEE 1547.1 standard
- Easy modification of the load bank to the different RLC values required by the standard in the PHIL setup
- Check if the islanded is detected in adequate time (<2s)
- **More flexible than conventional hardware test**
- Evaluation of different strategies (ROCOF etc)

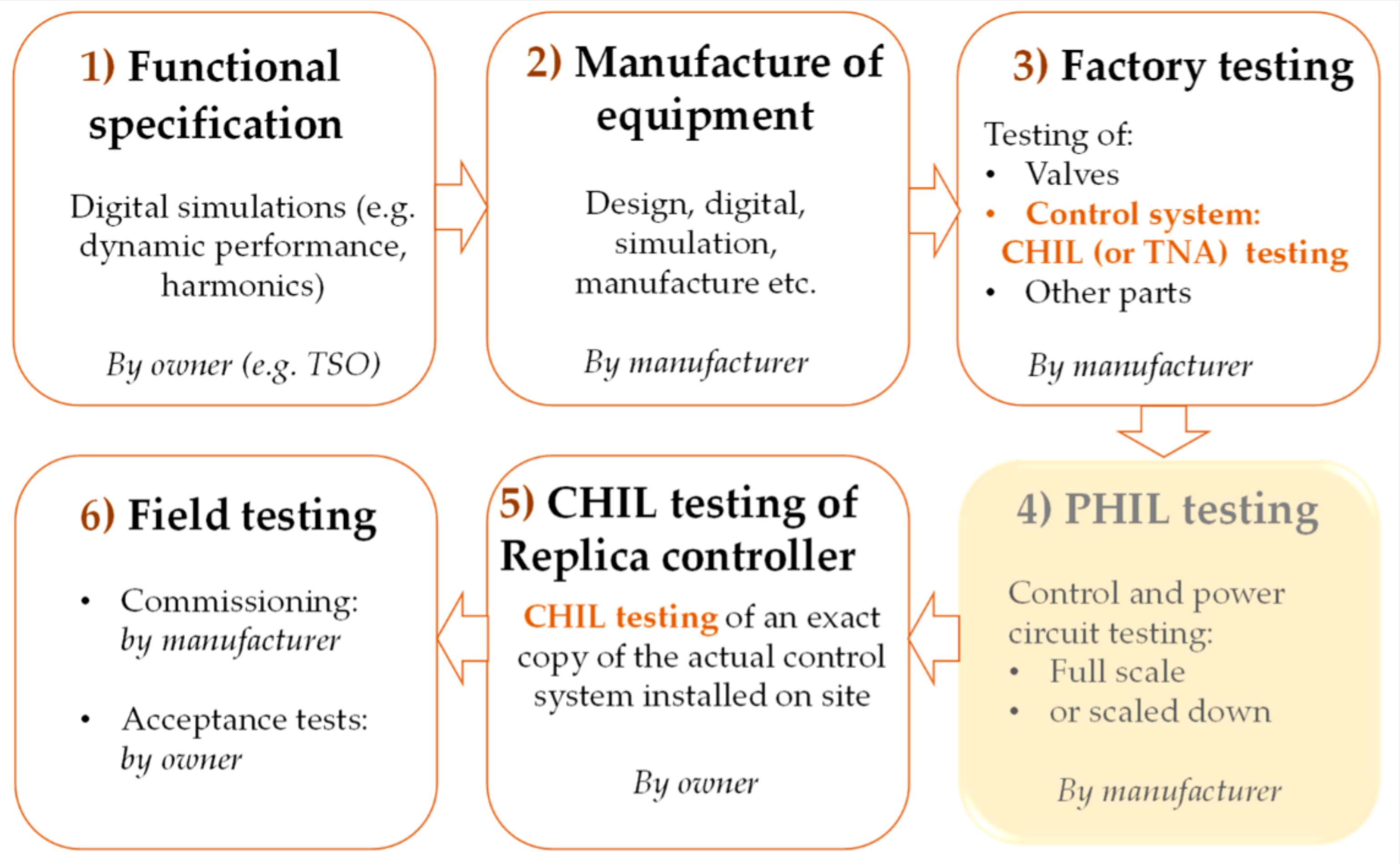


PHIL setup for Islanding detection tests



2) FACTS TESTING

DEVELOPMENT AND TESTING STAGES OF FACTS



1) Functional specification

Digital simulations (e.g. dynamic performance, harmonics)

By owner (e.g. TSO)

2) Manufacture of equipment

Design, digital, simulation, manufacture etc.

By manufacturer

3) Factory testing

Testing of:

- Valves
- **Control system: CHIL (or TNA) testing**
- Other parts

By manufacturer

4) PHIL testing

Control and power circuit testing:

- Full scale
- or scaled down

By manufacturer

5) CHIL testing of Replica controller

CHIL testing of an exact copy of the actual control system installed on site

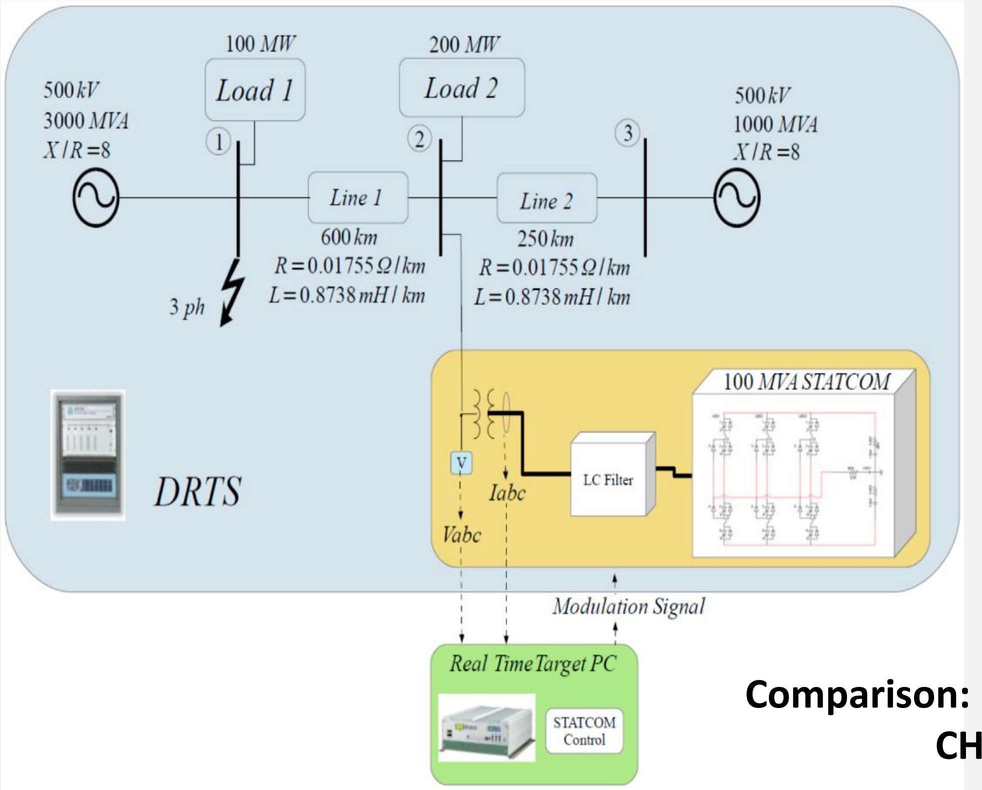
By owner

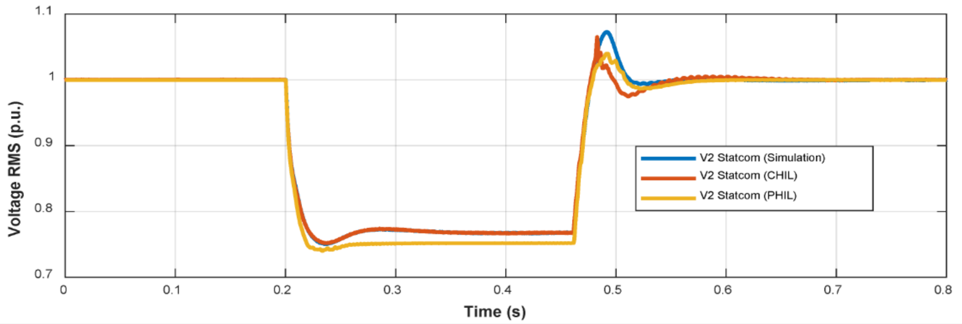
6) Field testing

- Commissioning: *by manufacturer*
- Acceptance tests: *by owner*

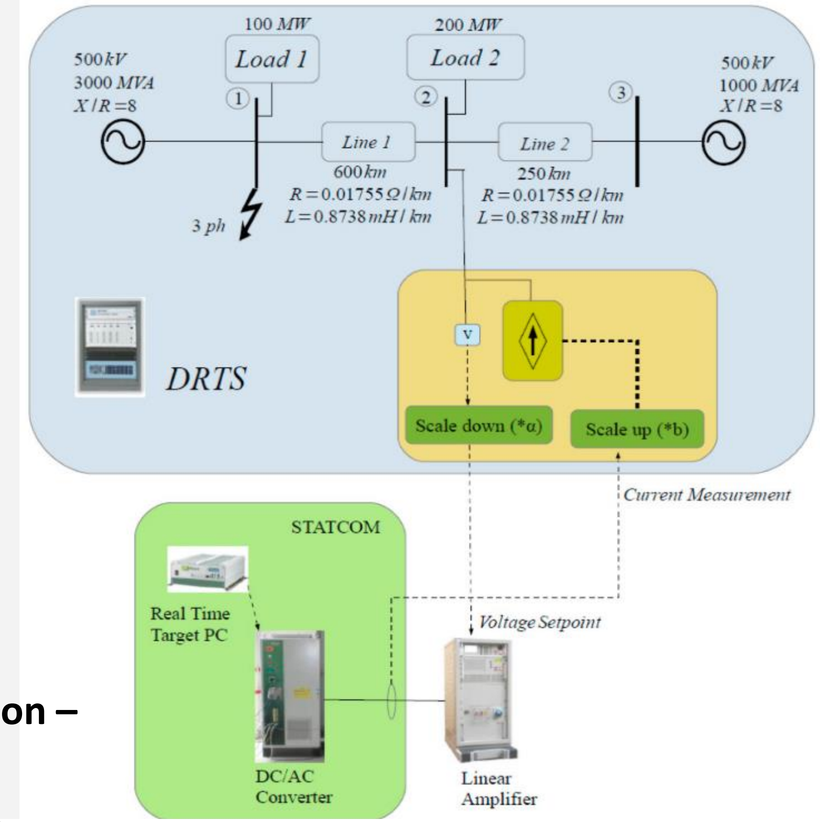
Kotsampopoulos, P.; Georgilakis, P.; Lagos, D.T.; Kleftakis, V.; Hatziargyriou, N. FACTS Providing Grid Services: Applications and Testing. Energies 2019, 12, 2554.

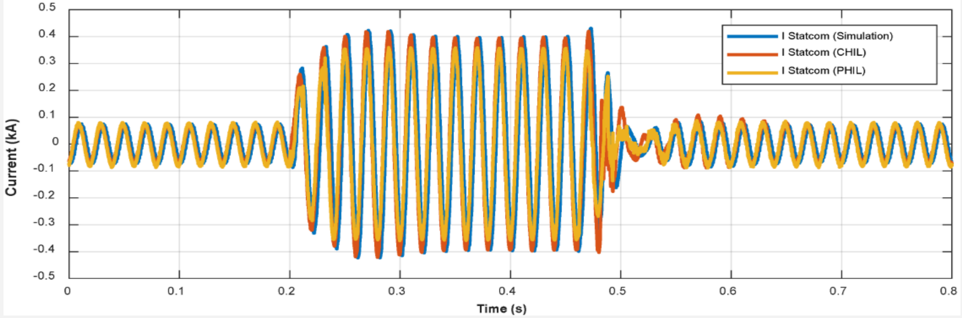
DEVELOPMENT AND TESTING STAGES OF FACTS





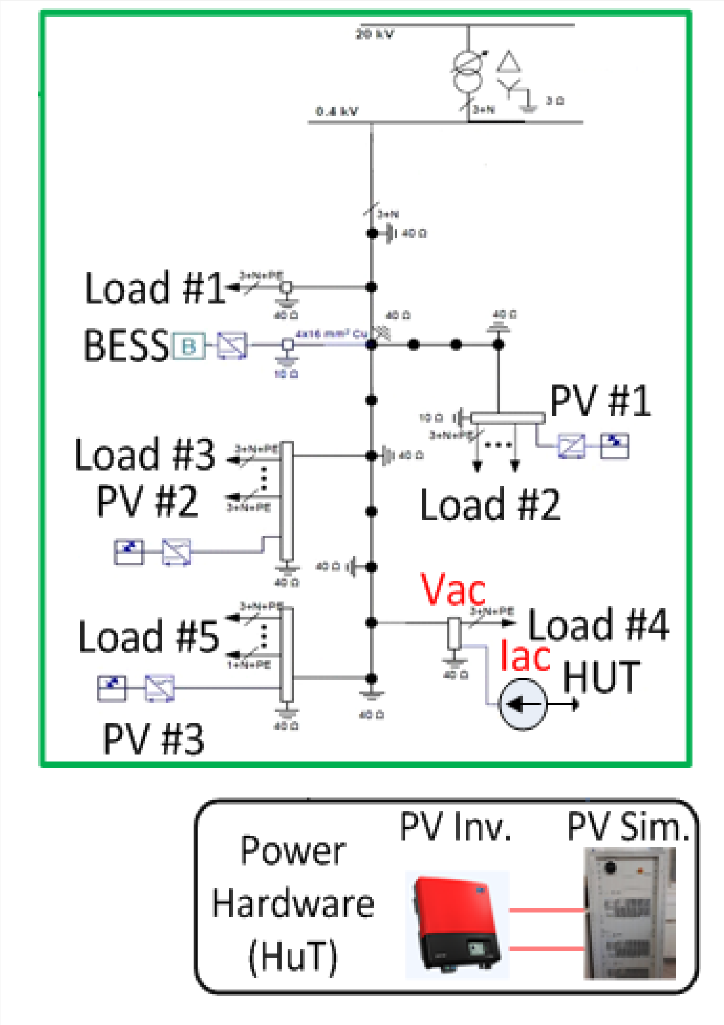
Comparison: Digital Simulation – CHIL – PHIL





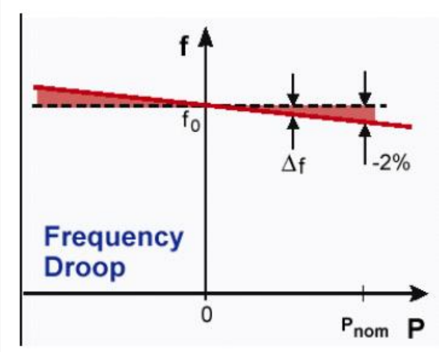
3) MICROGRID PRIMARY CONTROL (PHIL TESTS)

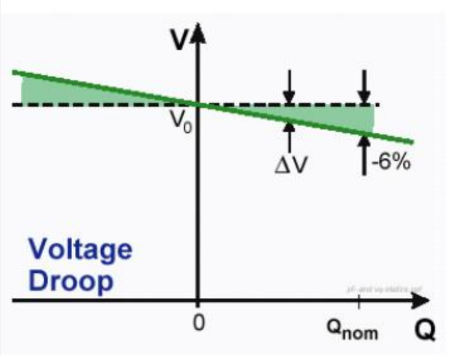
PHIL TEST AT THE CIGRE BENCHMARK LV MICROGRID



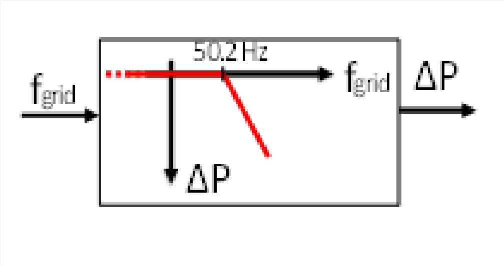
- Simulated storage system: *f (P)*, *V (Q)* droop curves in island mode
- DG units (simulated and hardware): *P (f)* and *Q (V)* droop curves according to standards (grid-connected)

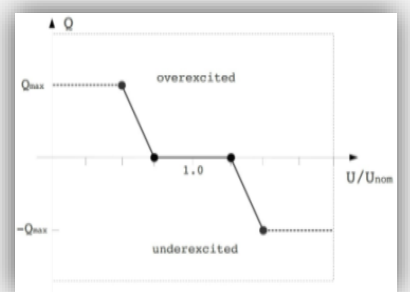
Grid forming – Battery Inverter





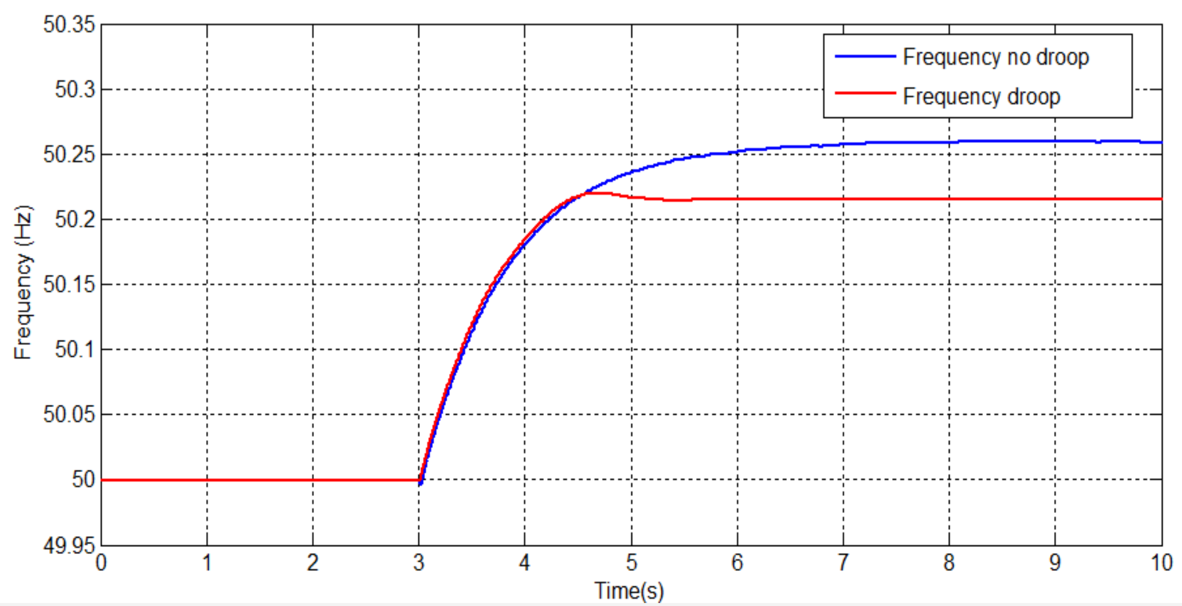
Grid following – PV Inverter

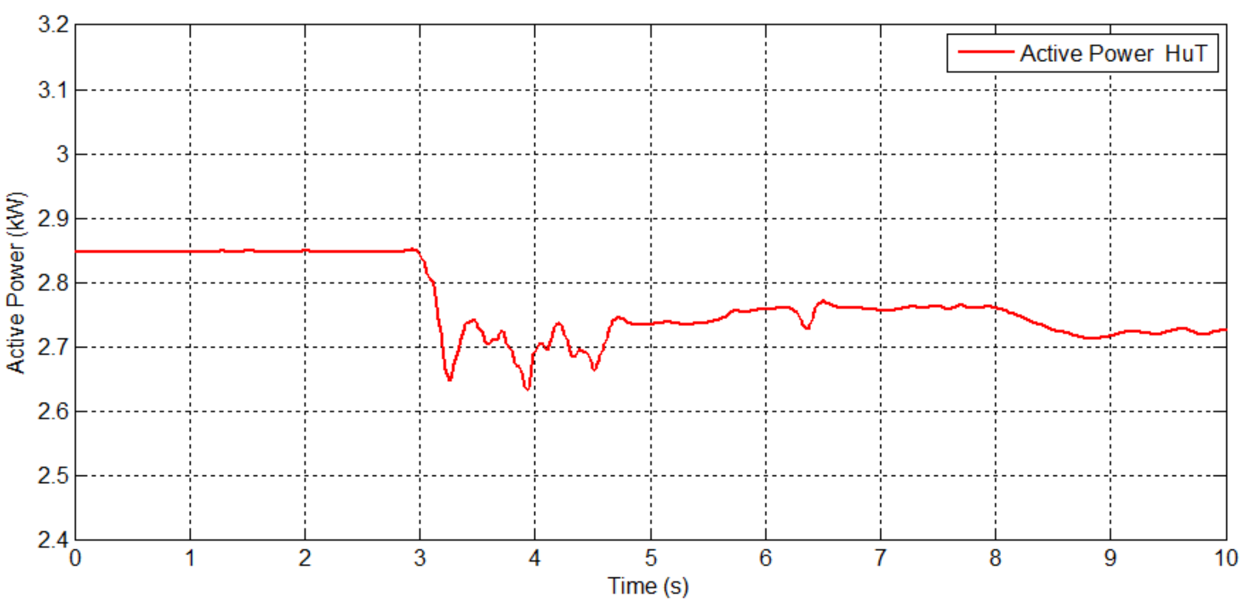




TRANSITION FROM GRID-CONNECTED TO ISLAND MODE – PHIL TESTING

- Excess of active power: frequency rises
- When the PV units operate with *P (f)* droop control, they decrease their active power, leading to improved frequency response

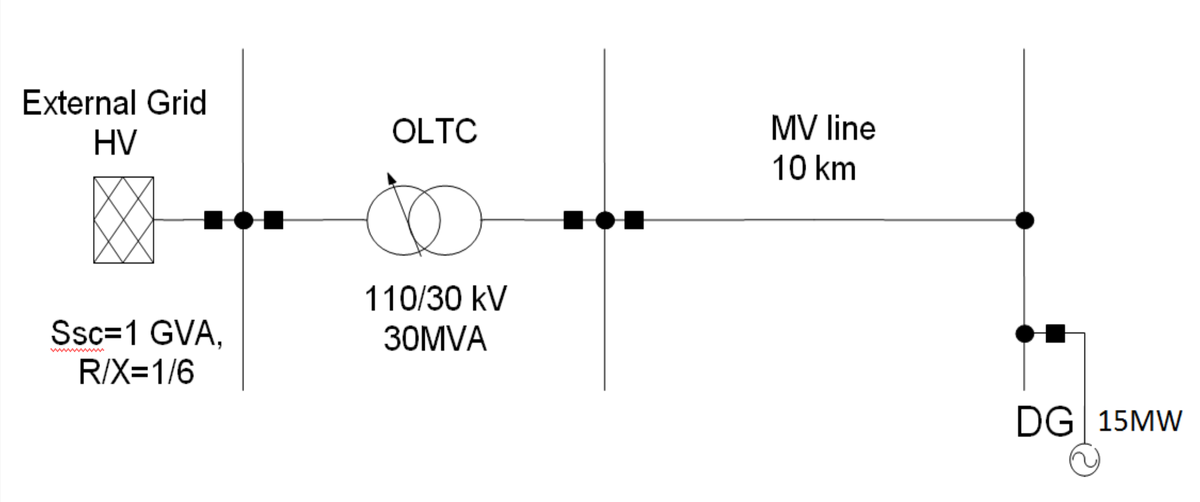




P. Kotsampopoulos, D. Lagos, N. Hatziargyriou, M.O. Faruque et al. "A Benchmark System for Hardware-in-the-Loop Testing of Distributed Energy Resources", IEEE Power and Energy Technology Systems Journal, 2018

4) DER AND OLTC INTERACTIONS (PHIL TESTS)

PHIL TESTS ON THE INTERACTION BETWEEN DER AND OLTC CONTROL



Joint work with the Austrian Institute of Technology - AIT

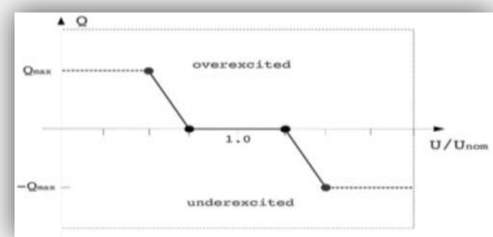
- Commercial PV inverter of lower nominal power with the same capabilities of voltage control: Q(V), cosφ(P)
- The nominal power of the inverter is virtually increased in the DRTS

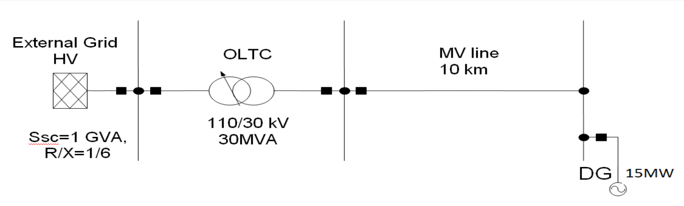
P. Kotsampopoulos, F. Lehfuss, G. Lauss, B. Bletterie, N. Hatziargyriou, "The limitations of digital simulation and the advantages of PHIL testing in studying Distributed Generation provision of ancillary services", IEEE Transactions on Industrial Electronics, 2015

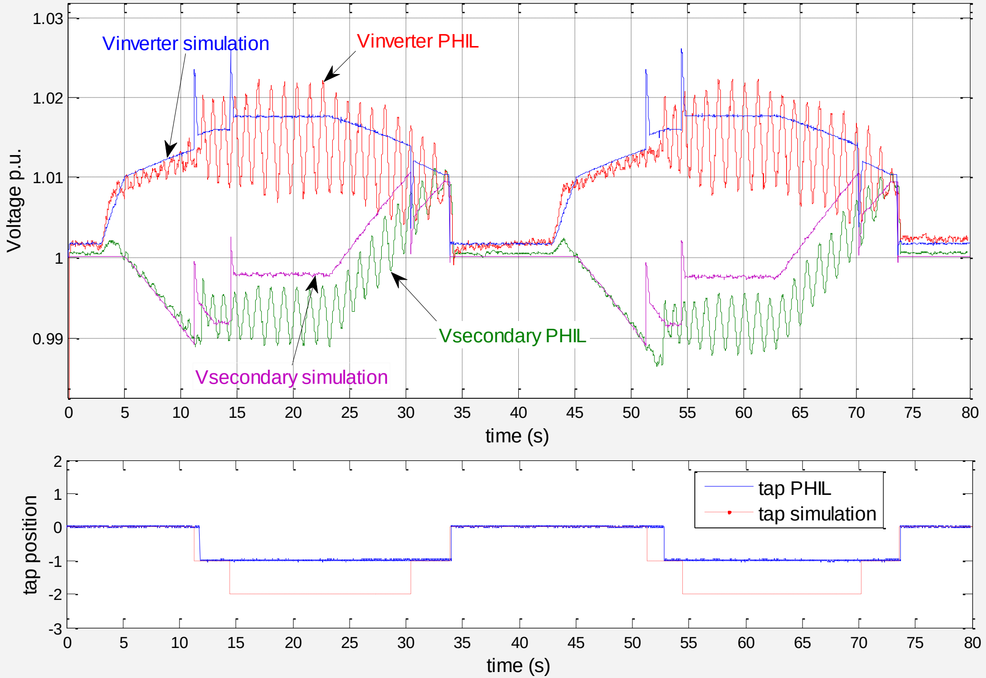
DER AND OLTC INTERACTIONS: Q(V) CONTROL

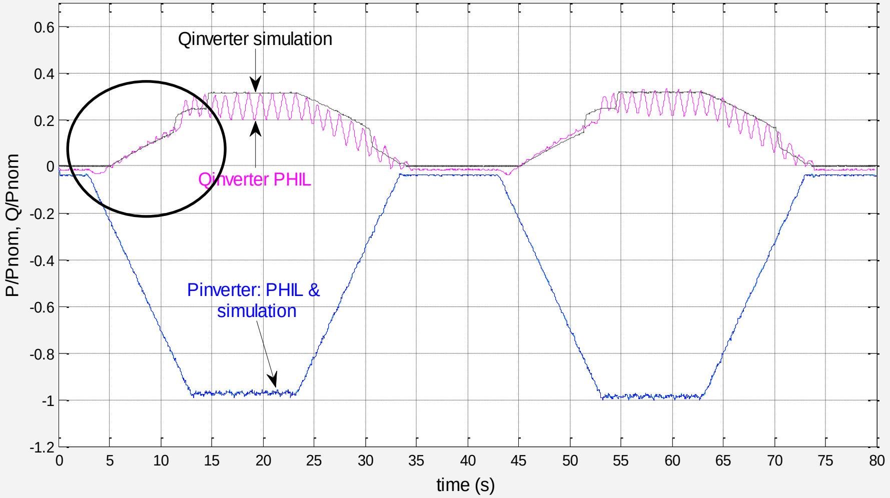
- Active power of the DER increases → **DER voltage increases** → reactive power absorption by the DER increases (Q(V)) → Voltage of the secondary of the **transformer decreases** → tap-change occurs
- Recurring tap-changes occur

- **Instability of the Q(V) controller (i.e. Oscillations): not visible at the pure digital simulation**





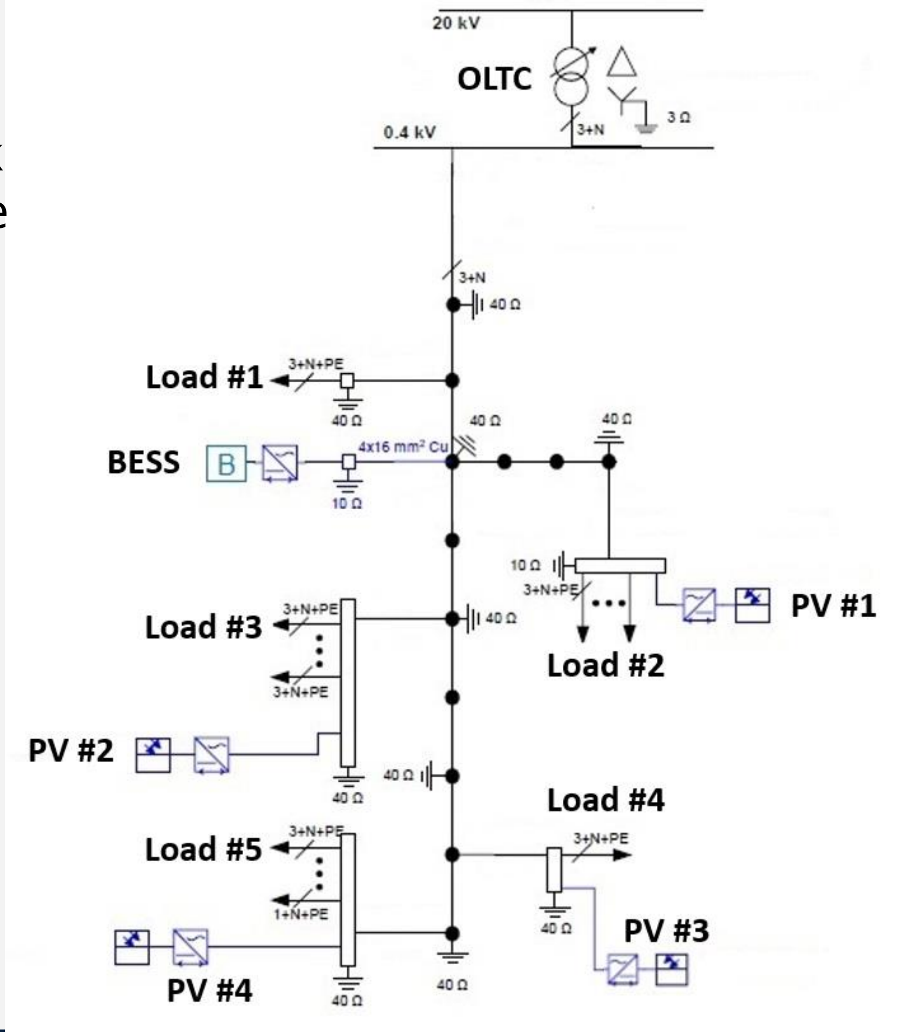




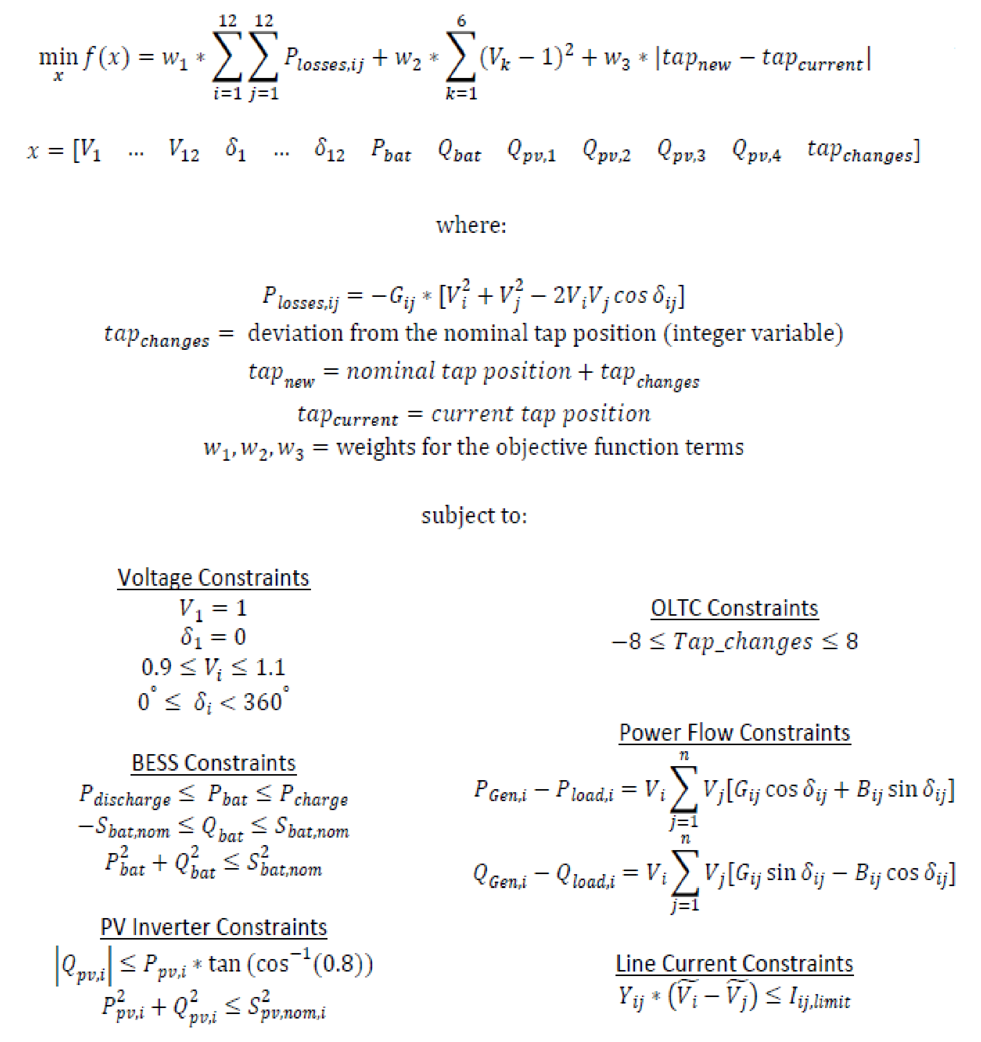
5) COORDINATED VOLTAGE CONTROLLER TESTING (COMBINED CHIL AND PHIL)

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:

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

$tap_{changes}$ = 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 = 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

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

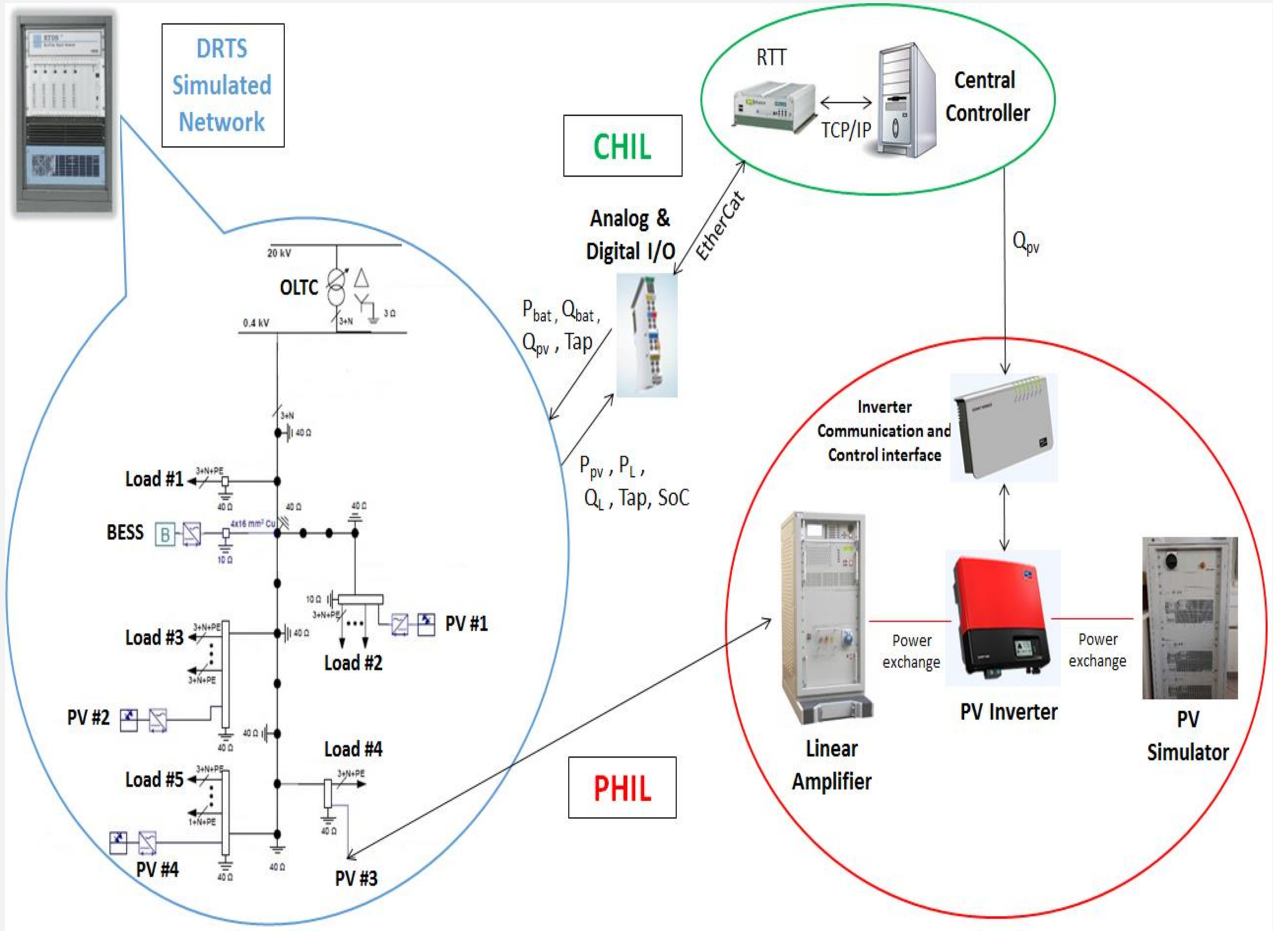
Line Current Constraints

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

COORDINATED VOLTAGE CONTROLLER TESTING: COMBINED CHIL AND PHIL

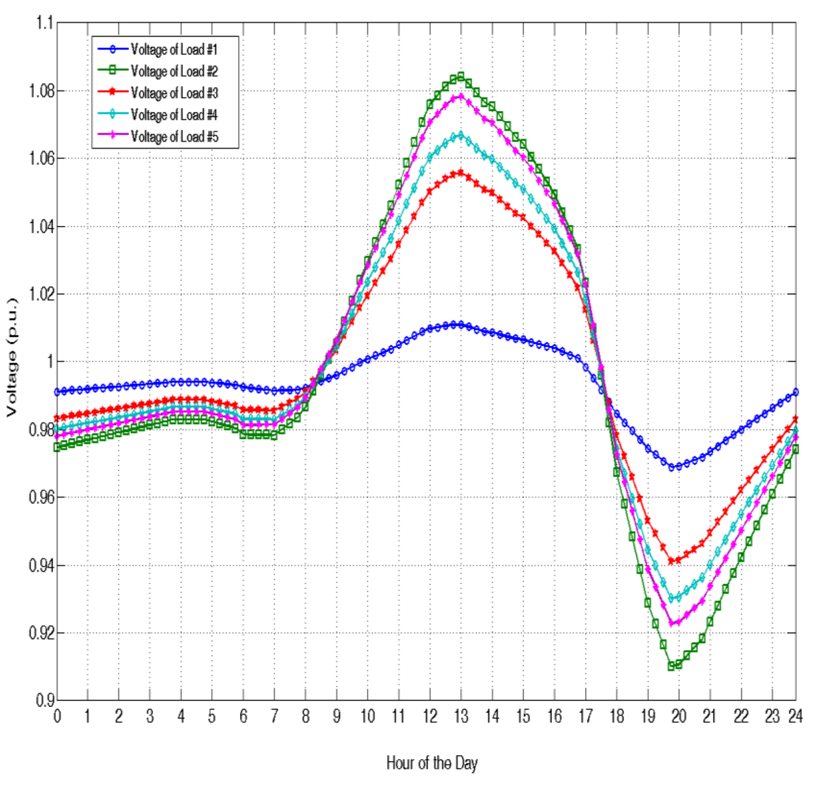
- Hardware controller (CHIL) and Hardware PV inverter (PHIL)

- The combined CHIL and PHIL setup also provided:
    - Insight on communication issues between the controller and the real hardware
    - Behaviour of the real PV inverter

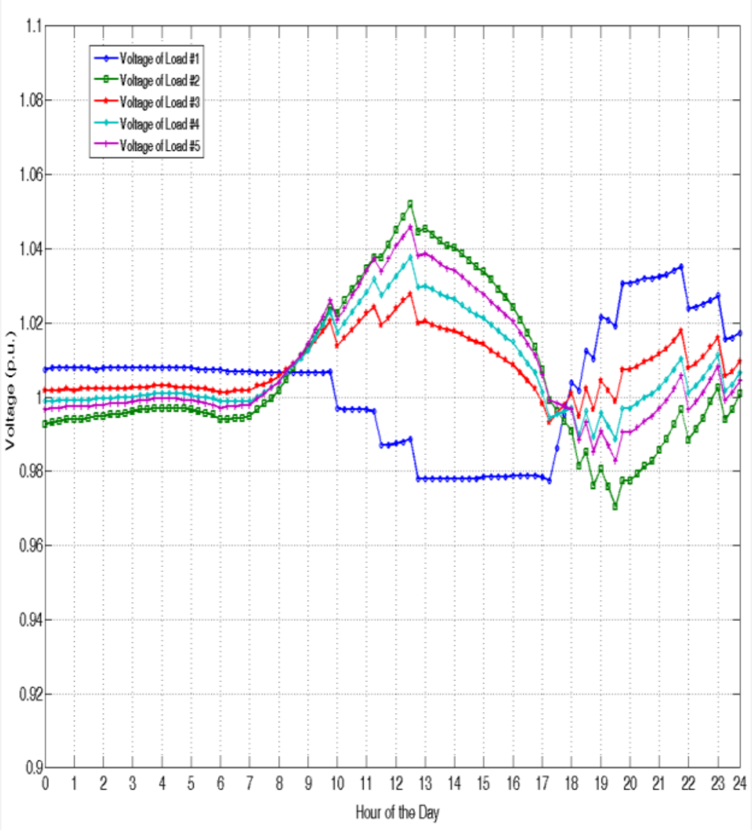


M. Maniatopoulos, D. Lagos, P. Kotsampopoulos, N. Hatziargyriou, "Combined Control and Power Hardware-in-the-Loop simulation for testing Smart grid control algorithms", IET Generation, Transmission & Distribution, 2017

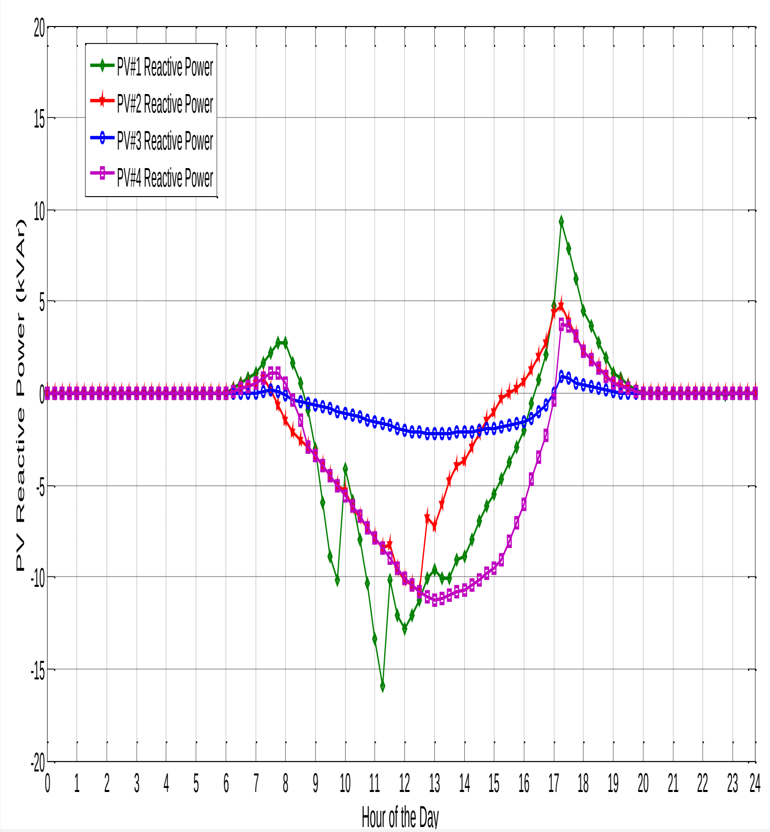
COORDINATED VOLTAGE CONTROLLER TESTING



Voltage of all nodes
without voltage control



Voltage of all nodes with
coordinated voltage control



PV reactive power

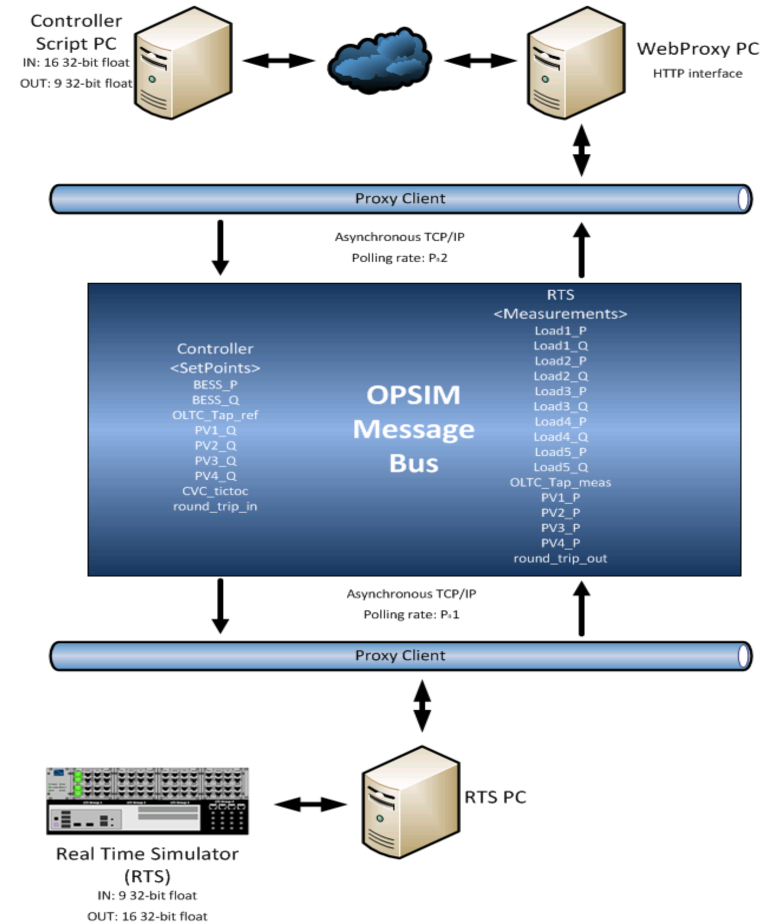
REMOTE REAL-TIME SIMULATION VIA OPSIM

- **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.

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", IECON 2018

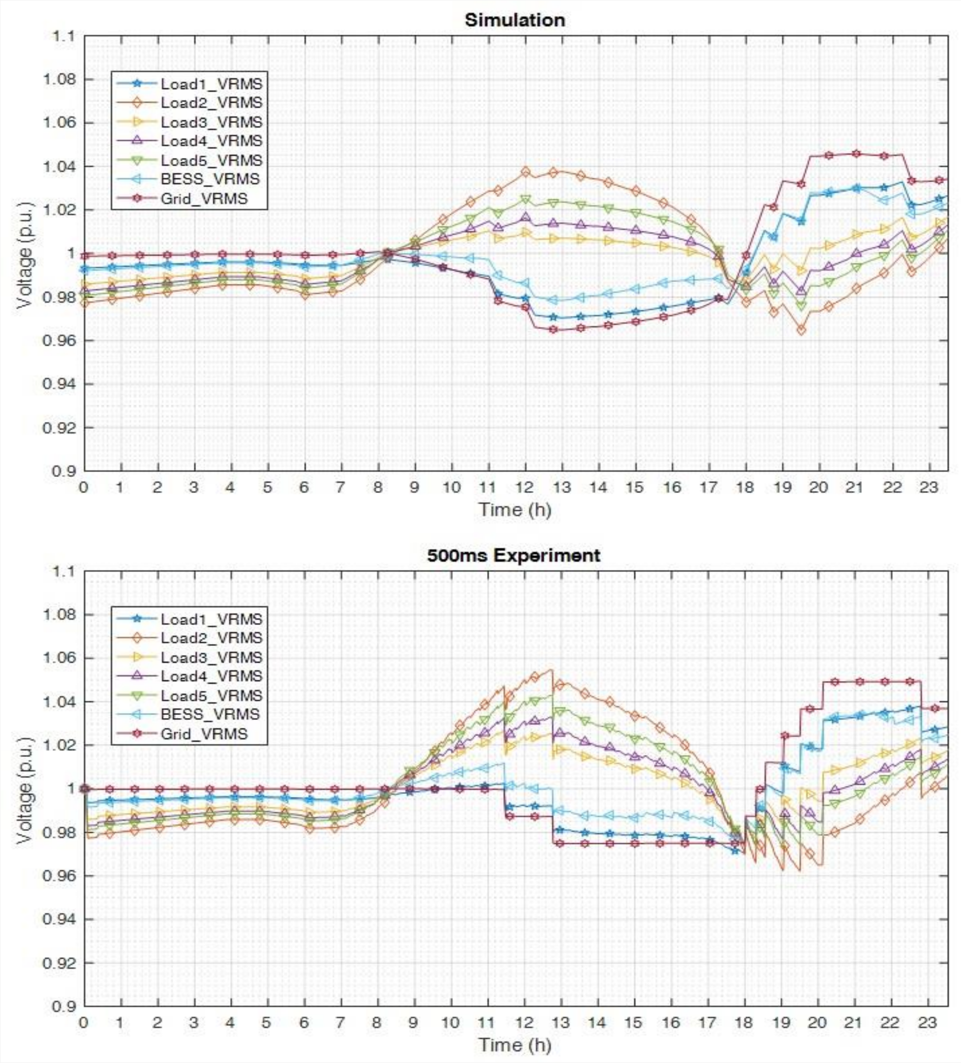
Joint work with Fraunhofer IEE

Fraunhofer IEE

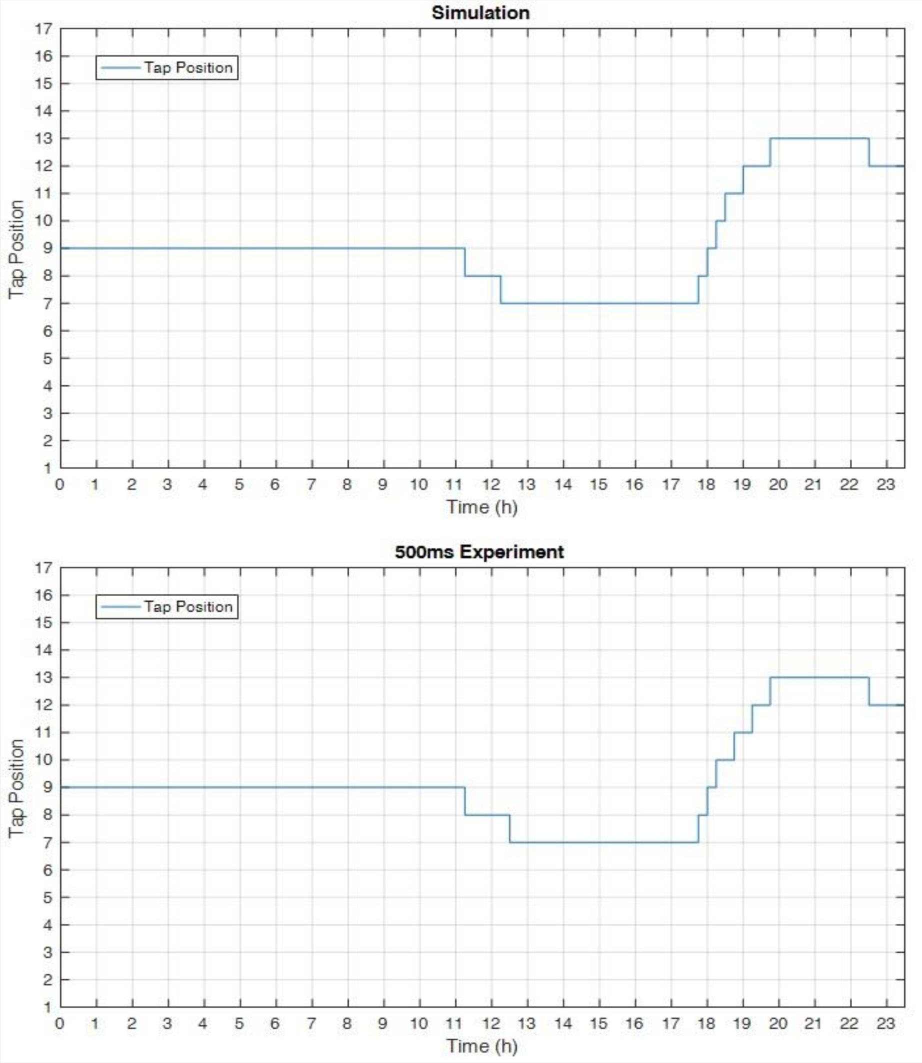


REMOTE REAL-TIME SIMULATION: TEST RESULTS

Bus Voltage



OLTC - Tap Position



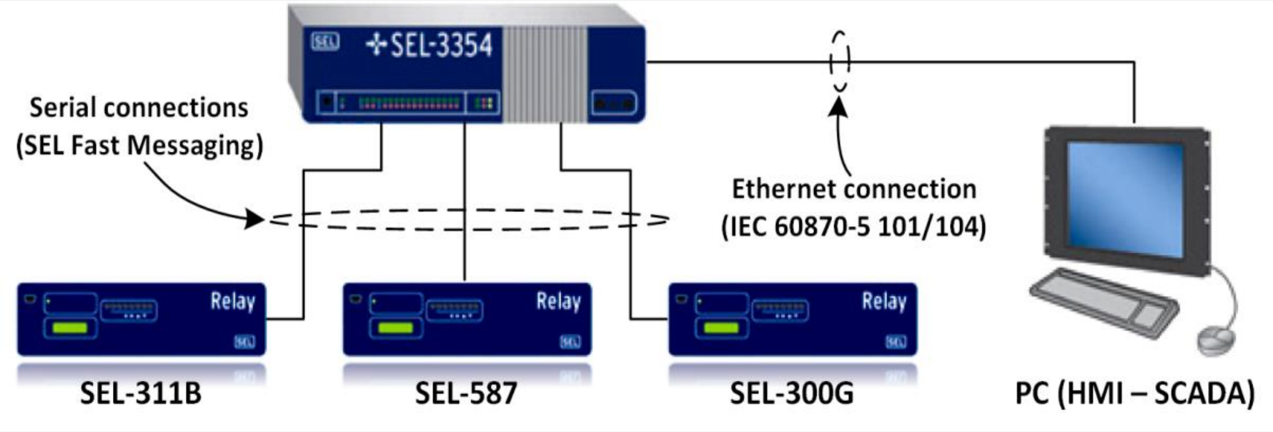
Fraunhofer
IEE

Joint work with Fraunhofer IEE

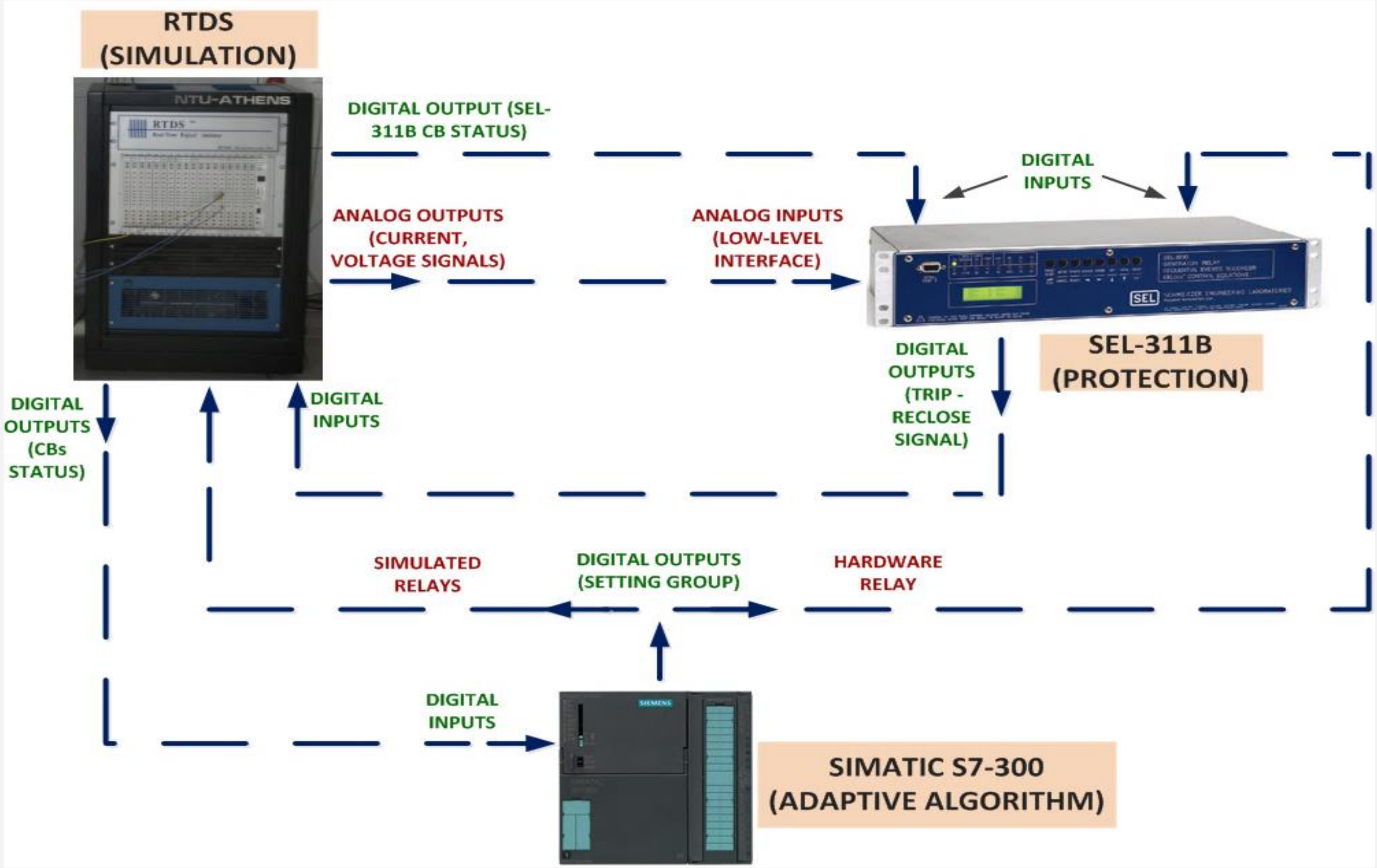
6) ADAPTIVE PROTECTION OF DISTRIBUTION NETWORKS (CHIL)

ADAPTIVE PROTECTION TESTING VIA HIL SIMULATION

- Adaptive protection systems are based on pre-calculated information where protection settings are updated periodically by the central controller with regard to the network’s operating state.
- A Programmable Logic Controller (PLC) receives the status of the circuit-breakers of the network and activates different setting groups at the digital relays

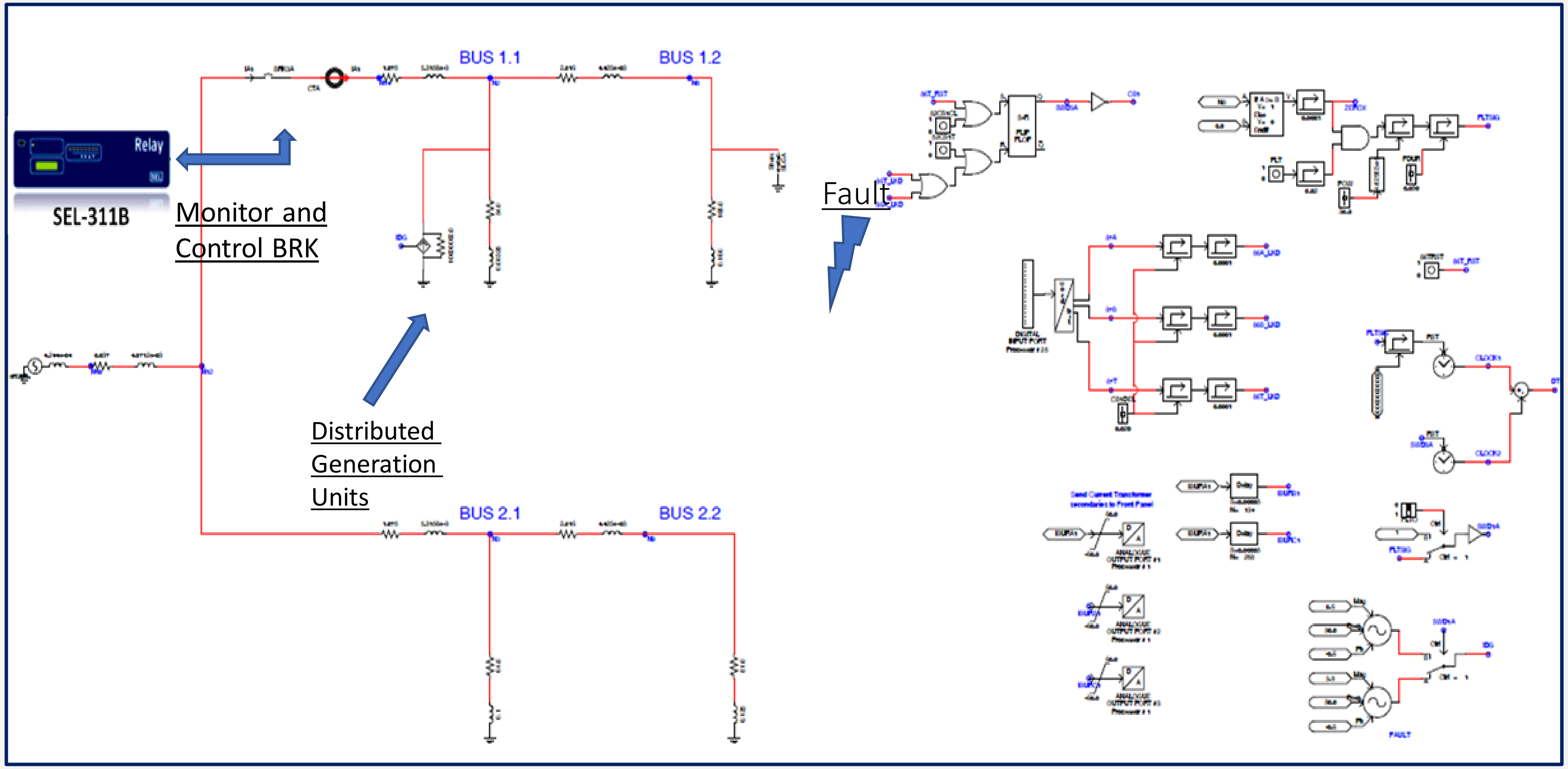


ADAPTIVE PROTECTION TESTING VIA HIL SIMULATION



V. Papaspiliotopoulos, G. Korres, V. Kleftakis, N. Hatziargyriou, "Hardware-In-the-Loop Design and Optimal Setting of Adaptive Protection Schemes for Distribution Systems With Distributed Generation", IEEE Transactions on Power Delivery, 2017

HIL TESTING-PROTECTION BLINDING



Monitor and Control BRK

Fault

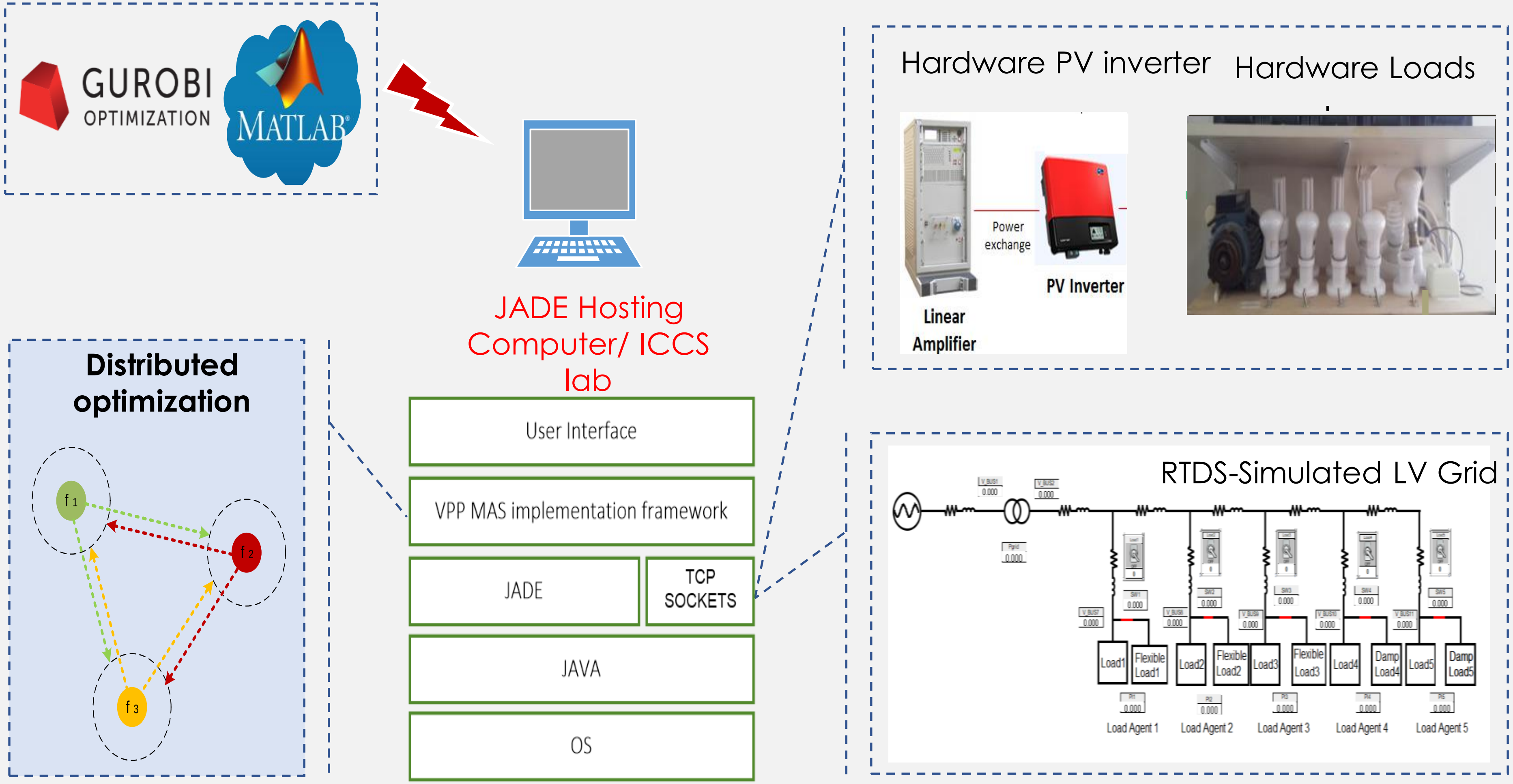
Distributed Generation Units

- Hardware Test (RTDS, SEL-311B)
  - ☐ The current contribution of the DG causes the reduction of the current contribution of the upstream network
  - ☐ **Protection blinding**: Time for fault clearance = 2,28 s
  - ☐ Adaptive protection scheme was able to resolve this issue (change of setting group of the relay)

7) DISTRIBUTED CONTROL OF LOADS AND DER: MULTI-AGENT SYSTEM (CHIL)

VIRTUAL POWER PLANT LABORATORY PLATFORM USING MULTI AGENT SYSTEMS

VPP setup



GUROBI OPTIMIZATION

MATLAB

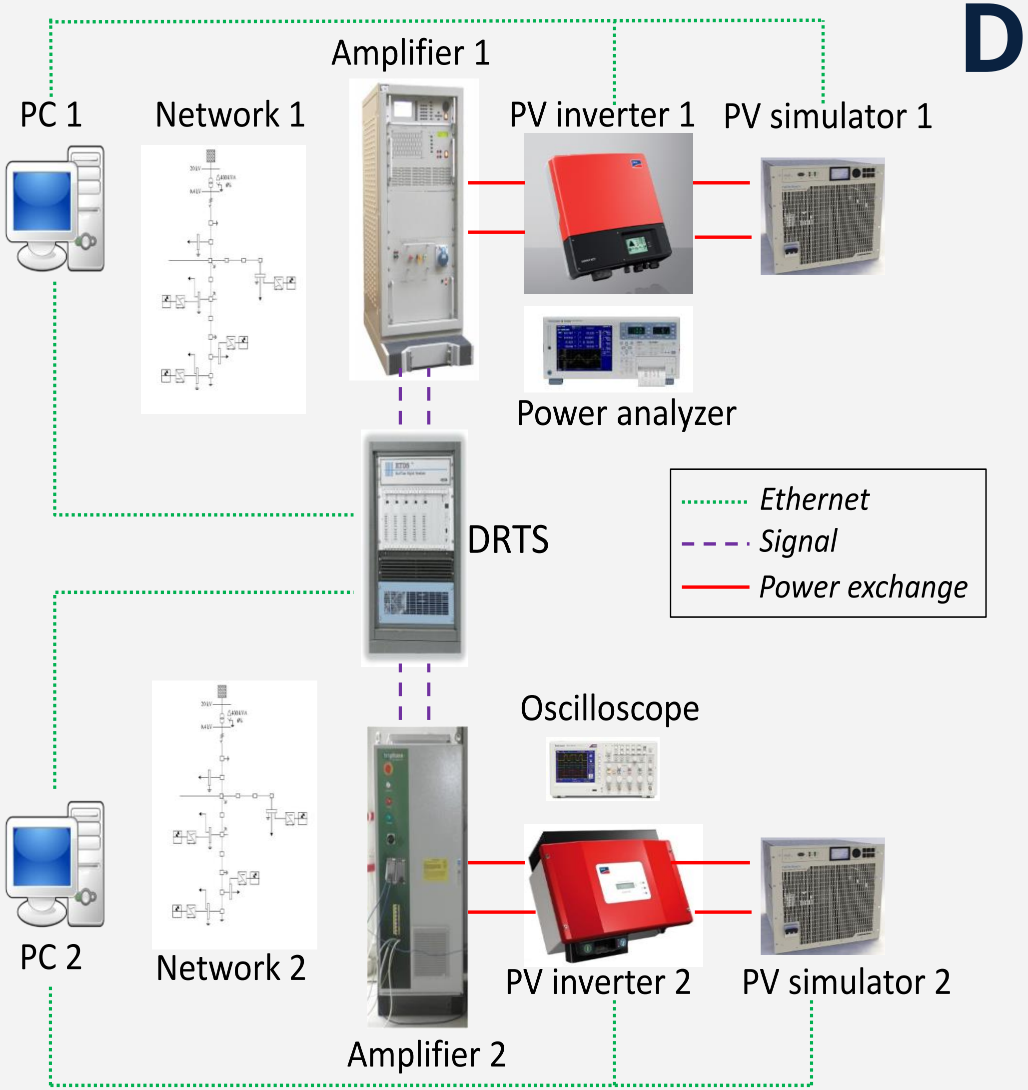
JADE Hosting Computer/ ICCS lab

- User Interface
- VPP MAS implementation framework
- JADE | TCP SOCKETS
- JAVA
- OS

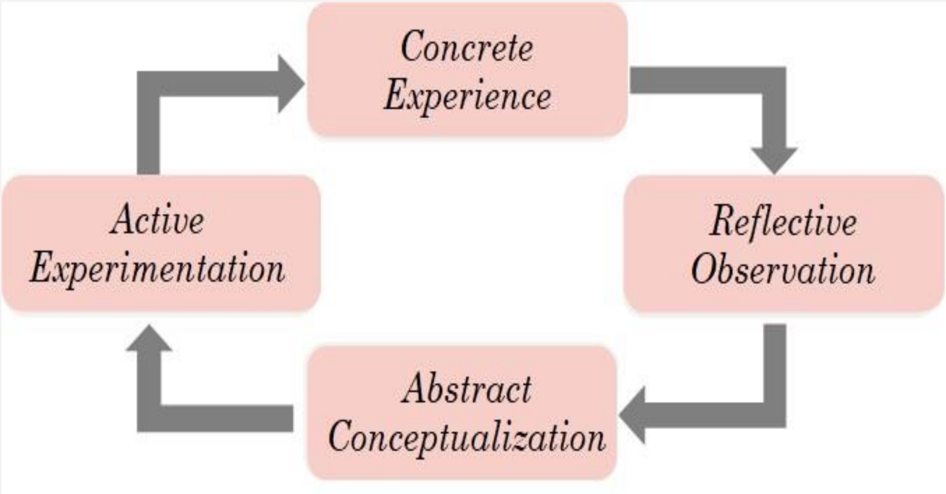
Distributed optimization

PHIL FOR ADVANCED LAB EDUCATION (PHIL/CHIL)

DOUBLE PHIL CONFIGURATION



- 2 independent PHIL setups creating 2 test-benches
- Hands-on work in small groups



Experiential learning

- PHIL simulation provides hands-on experience to students, while maintaining the flexibility of digital simulations

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

CONCLUSIONS

- Active distribution networks require advanced testing and simulation methods
- PHIL simulation: assesses the hardware-under-test behavior in complex conditions, e.g. with other equipment, under faults, etc. **System level testing**
- Inverter-based DER is difficult to model. PHIL simulation can reveal interactions not visible at pure simulation
- Smart grid control algorithms validated in the lab before field deployment. CHIL simulation: realistic conditions (time delays, noise, hardware implementation) and almost risk-free. Combination of CHIL and PHIL is more realistic
- No standard for guidance and best practices for the application of HIL
- *IEEE WG P2004: Recommended Practice for Hardware-in-the-Loop (HIL) Simulation. GET INVOLVED*

National Technical
University of Athens

SMART RUE
smartgrids Research Unit ECE NTUA

THANK YOU FOR YOUR ATTENTION!

contact:
kotsa@power.ece.ntua.gr

www.smartrue.gr