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SMART RUE smartgrids Research Unit ECE NTUA

CHIL and PHIL simulation advancing smart grid and microgrid research and testing

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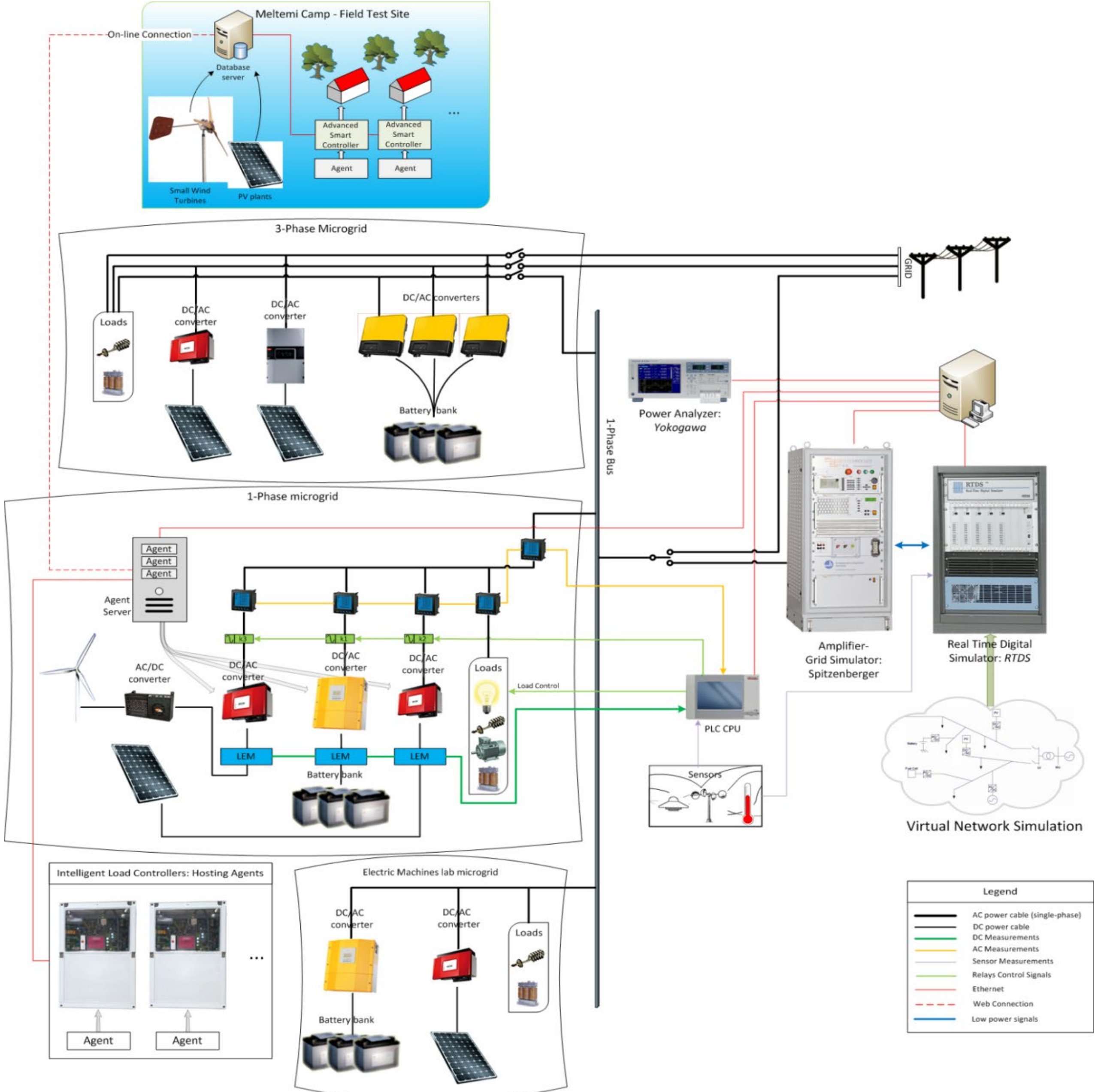
Overview

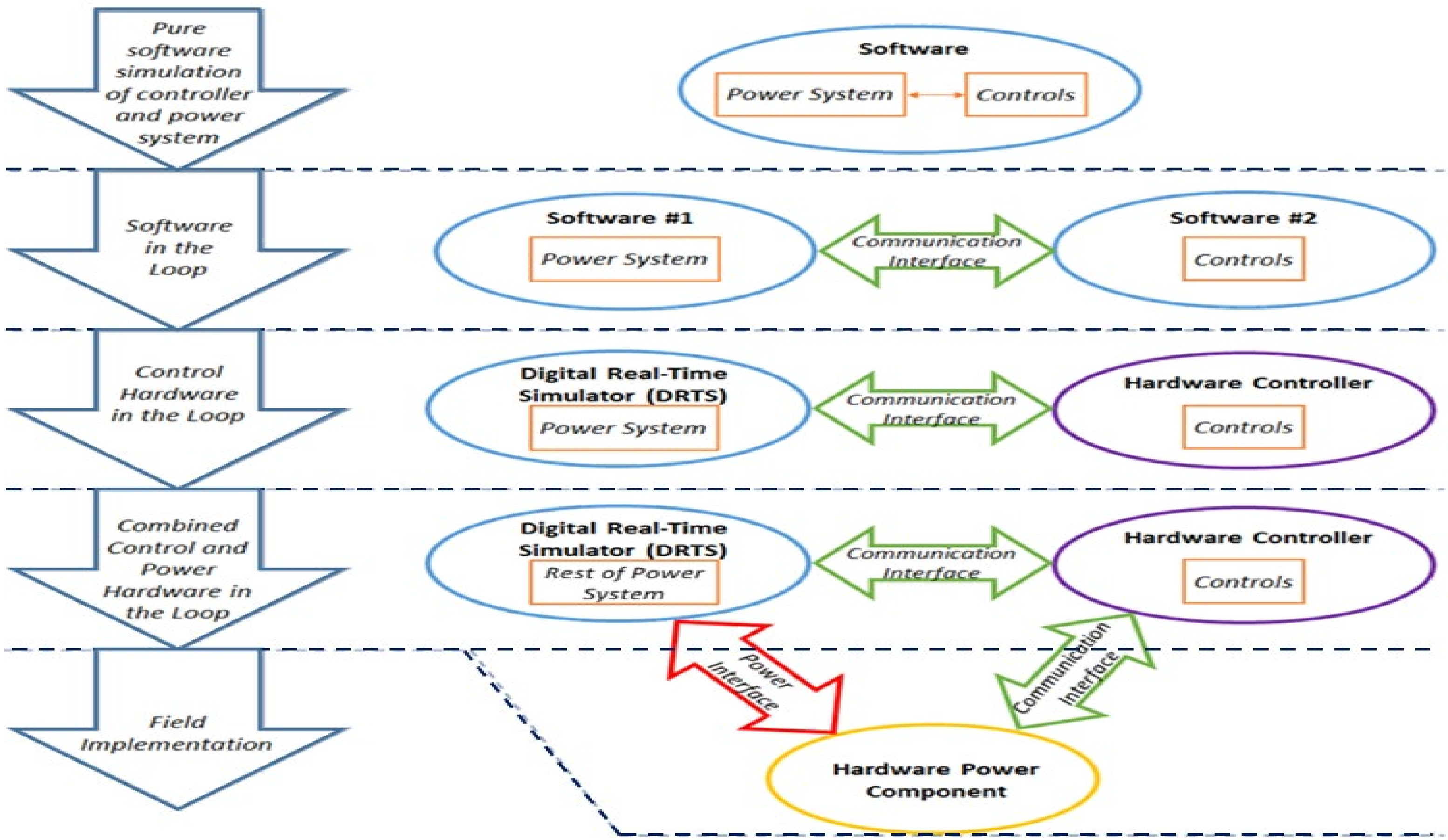
- HIL testing for smart grids and microgrids:
  - **Test case 1**: Combined CHIL-PHIL testing of secondary control of PV-Diesel Driven Generator (DDG) islanded system
  - **Test case 2**: Combined CHIL-PHIL testing of centralized coordinated voltage controller in benchmark microgrid
  - **Test case 3**: Distributed control of loads and DER: Multi-Agent System (CHIL)
- Conclusions

ELECTRIC ENERGY SYSTEMS LABORATORY of NTUA



Application of a Testing Chain for Smart Grid/Microgrid Controllers

Stages from pure simulation to field implementation:



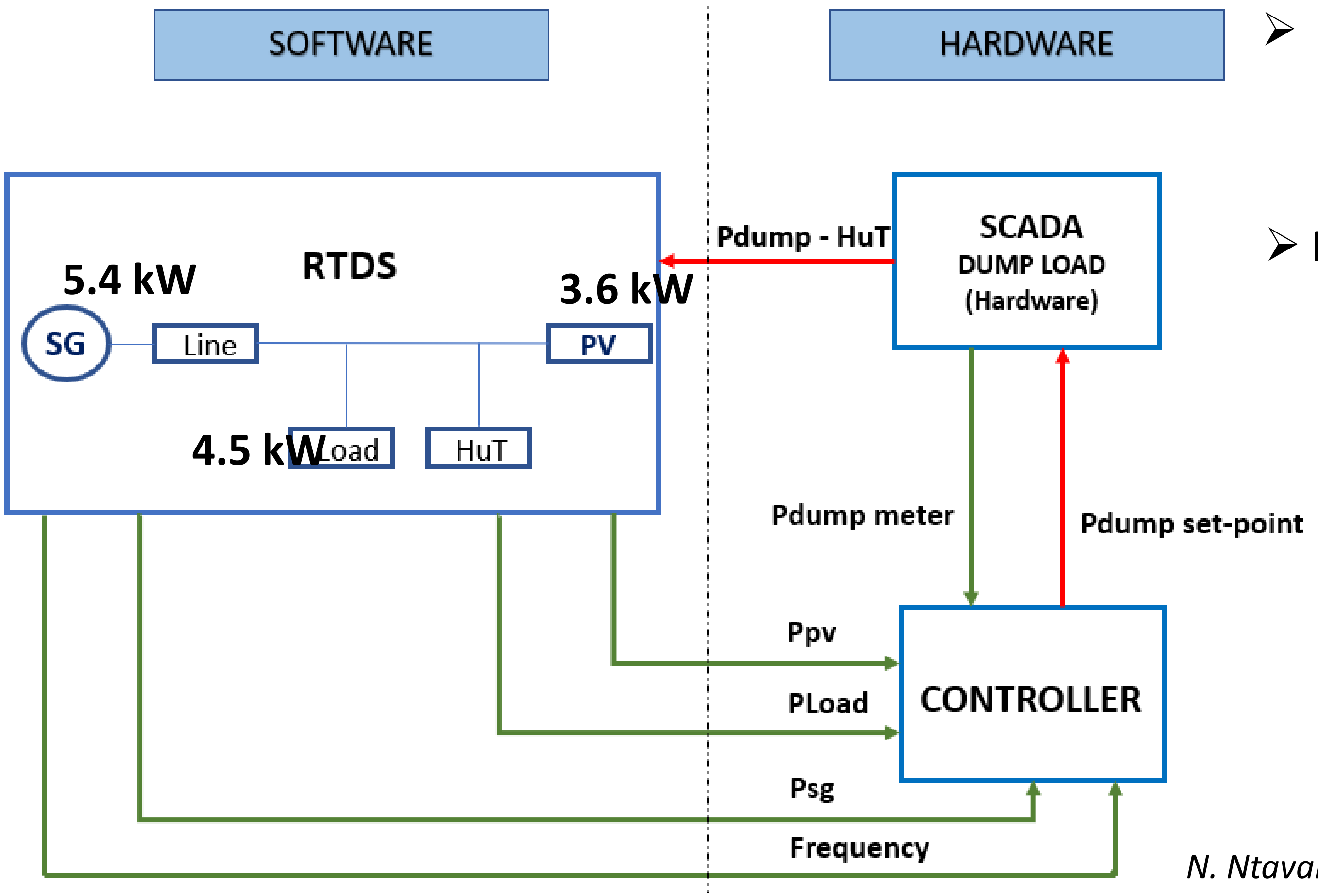
M. Maniatopoulos, D. Lagos, P. Kotsampopoulos and N. Hatziargyriou, "Combined control and power hardware in-the-loop simulation for testing smart grid control algorithms", IET Generation, Transmission & Distribution, vol. 11, no. 12, 2017.

Test Case 1:

Combined CHIL-PHIL testing of **secondary control** of

PV-Diesel Driven Generator (DDG**) islanded system**

Combined CHIL and PHIL laboratory setup – HuT Controllable Loads



1st Combined CHIL and PHIL laboratory setup.

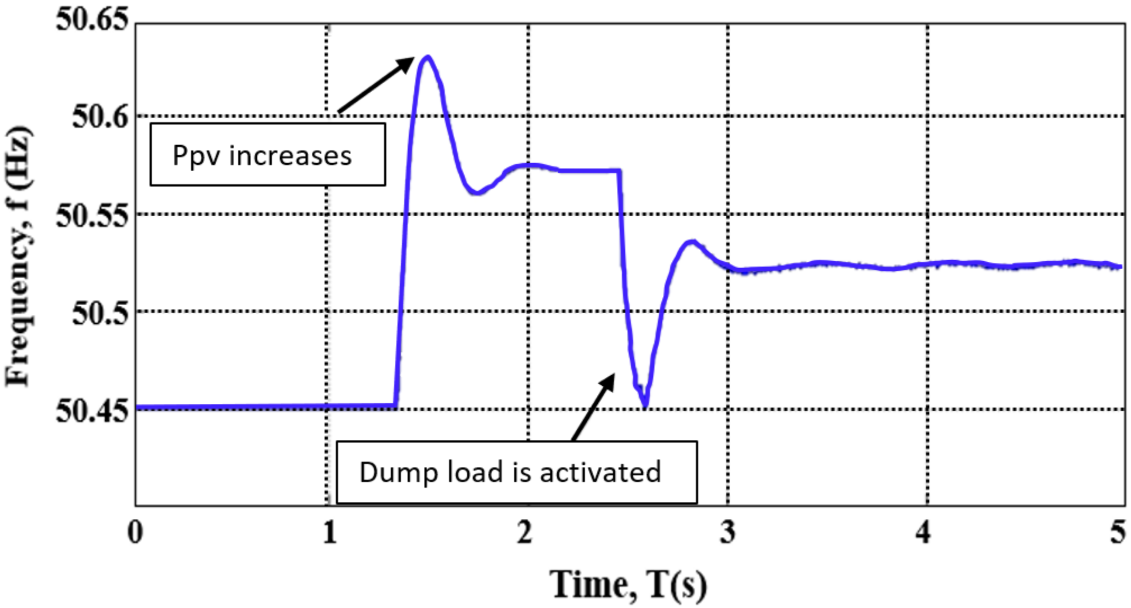
- When high PV production occurs DDG's (SG) production might drop below the minimum load ratio
- Controllable loads are enabled to avoid operation of the DDG below the minimum load ratio

- Hardware microgrid controller:
  1. Receives measurements of demand and PV production
  2. Check of the minimum load ratio of the DDG
  3. Send of the appropriate set-point to the controllable loads if necessary
  4. Restores the operation marginally above the minimum load ratio

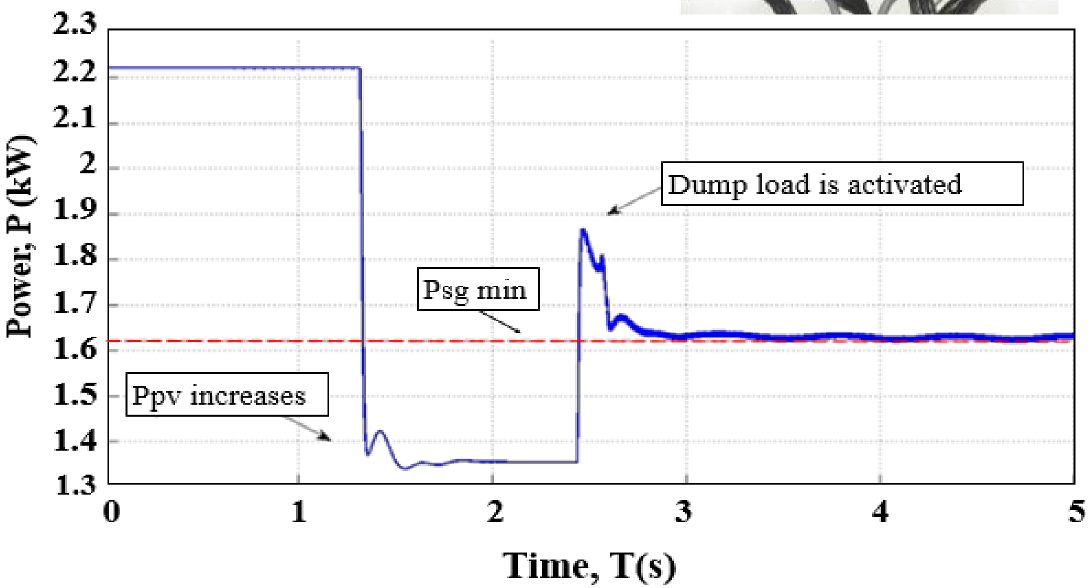
N. Ntavarinos, P. Kotsampopoulos, D. Lagos, N. Hatziargyriou, "Hardware in the Loop testing of Battery-less Hybrid Systems for Off-grid Power Supply", IEEE PES Powertech 2019

Dynamic behavior at the CHIL/PHIL test

- When PV power increases the frequency increases and the SG's production drop below the minimum load ratio
- The controller activates controllable loads to restore the SG's production at minimum load ratio
- Positive effect of the control also on frequency response restoring the frequency in a value closer to 50 Hz



Frequency at CHIL/PHIL test: use of hardware controllable loads.



Active power of the DDG at the CHIL/PHIL test: use of hardware controllable loads.

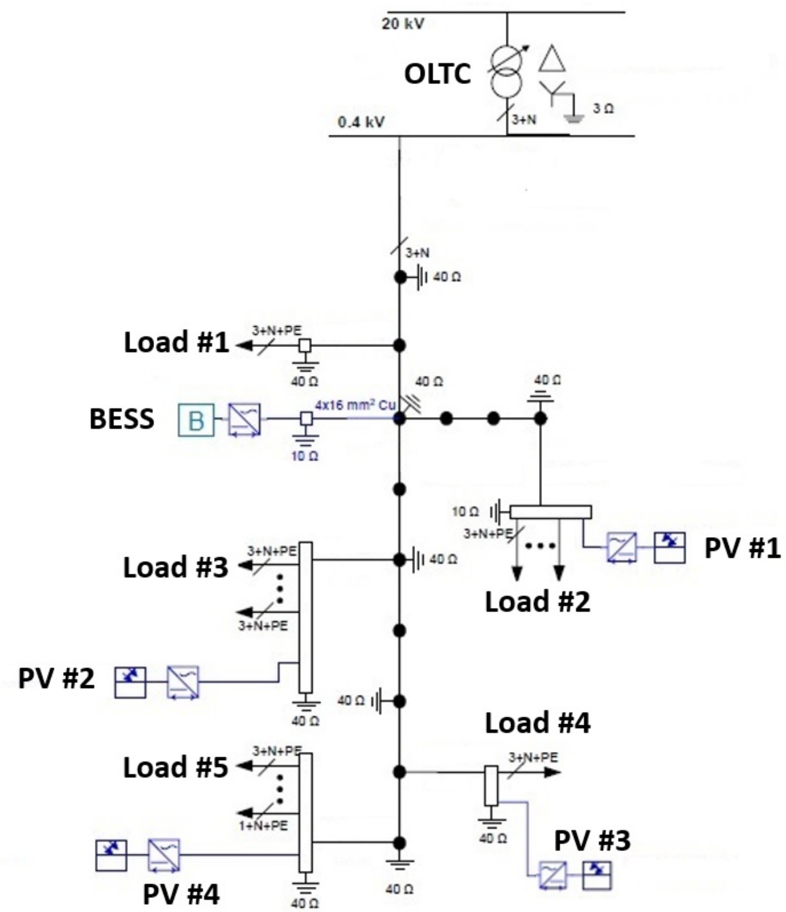
*Next: use of **controllable hardware PV inverter** (curtails active power) instead of controllable hardware loads*

Test case 2:

Combined CHIL-PHIL testing of **centralized coordinated voltage controller in benchmark microgrid**

Coordinated Voltage Controller (CVC) Testing

Modified CIGRE Benchmark Low Voltage Microgrid



Coordinated Voltage Control algorithm

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

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

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

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

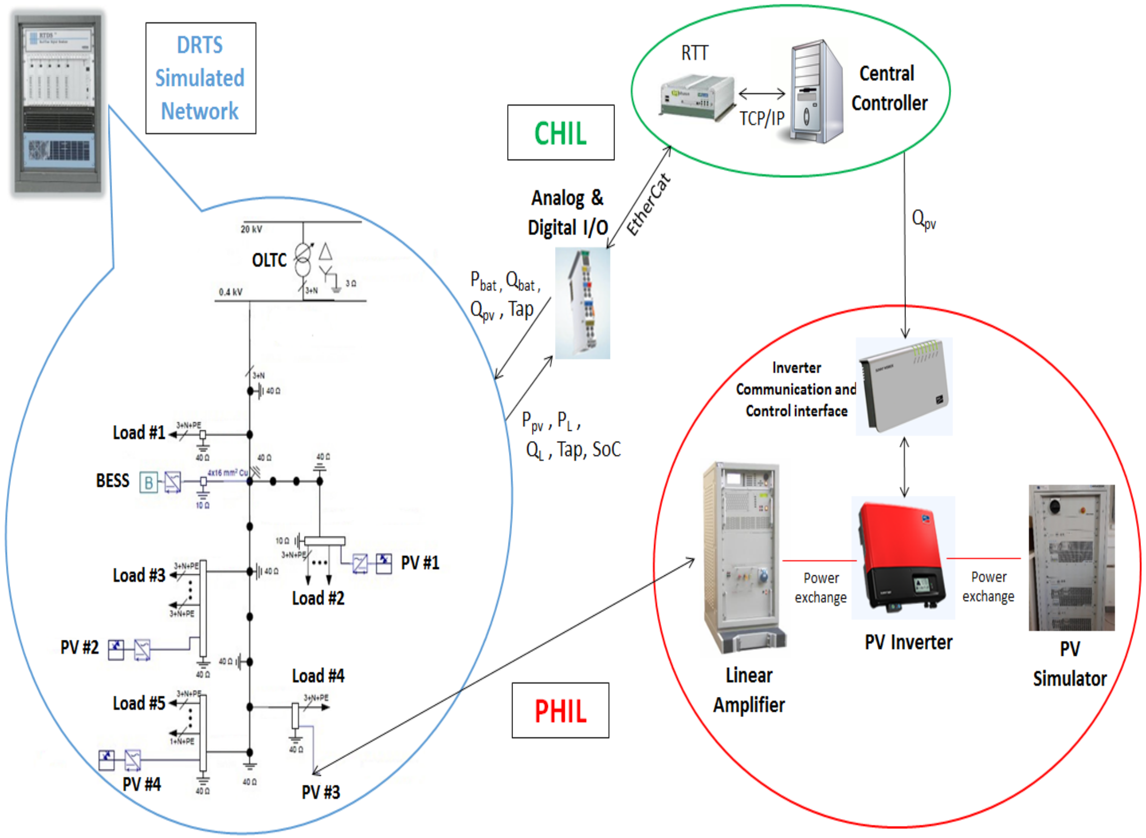
Line Current Constraints

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

Coordinated Voltage Controller Testing: combined CHIL and PHIL

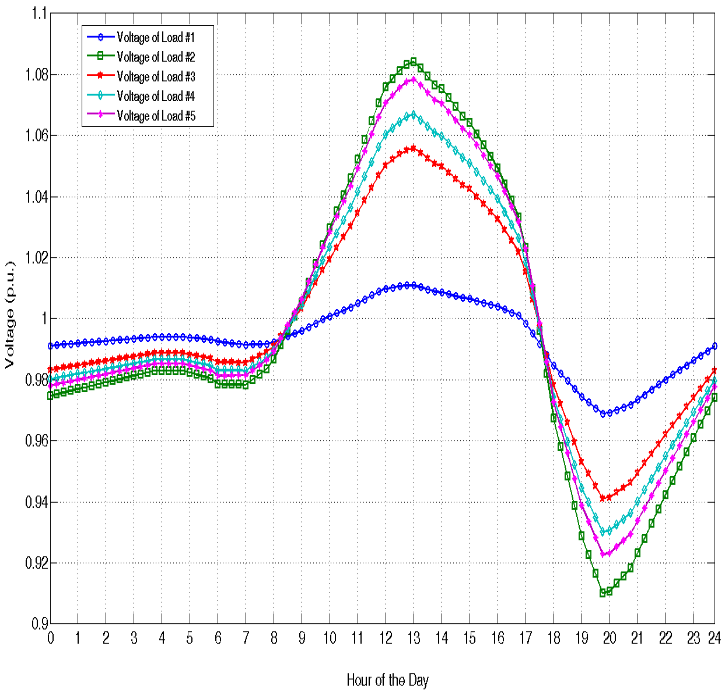
- Hardware controller (CHIL) and Hardware PV inverter (PHIL)

- 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

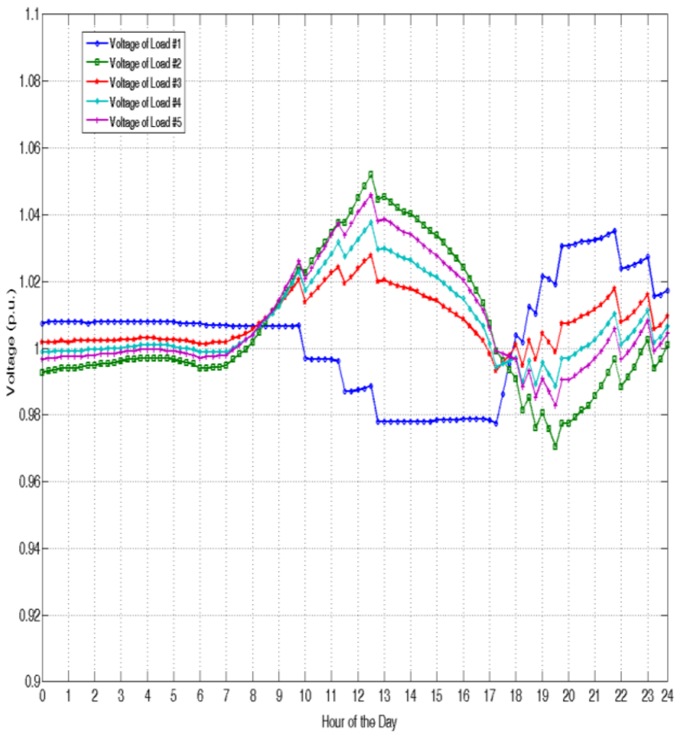


M. Maniatopoulos, D. Lagos, P. Kotsampopoulos, N. Hatziargyriou, "Combined Control and Power Hardware-in-the-Loop simulation for testing Smart grid control algorithms", IET Generation, Transmission & Distribution, 2017

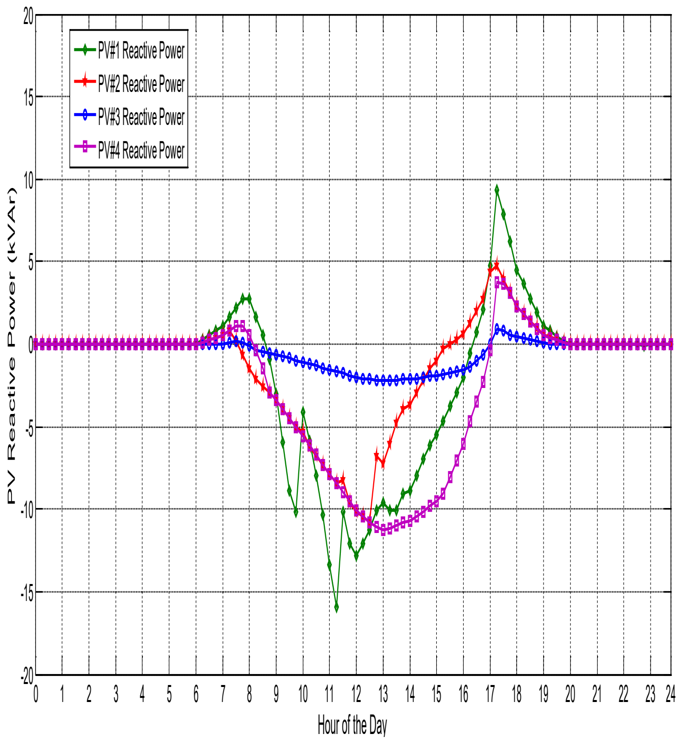
Coordinated Voltage Controller Testing



Voltage of all nodes without voltage control



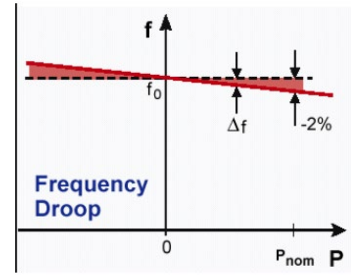
Voltage of all nodes with coordinated voltage control

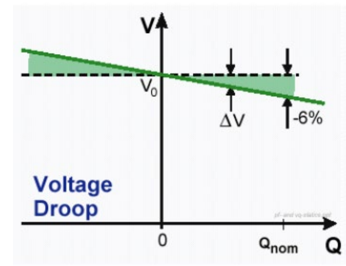


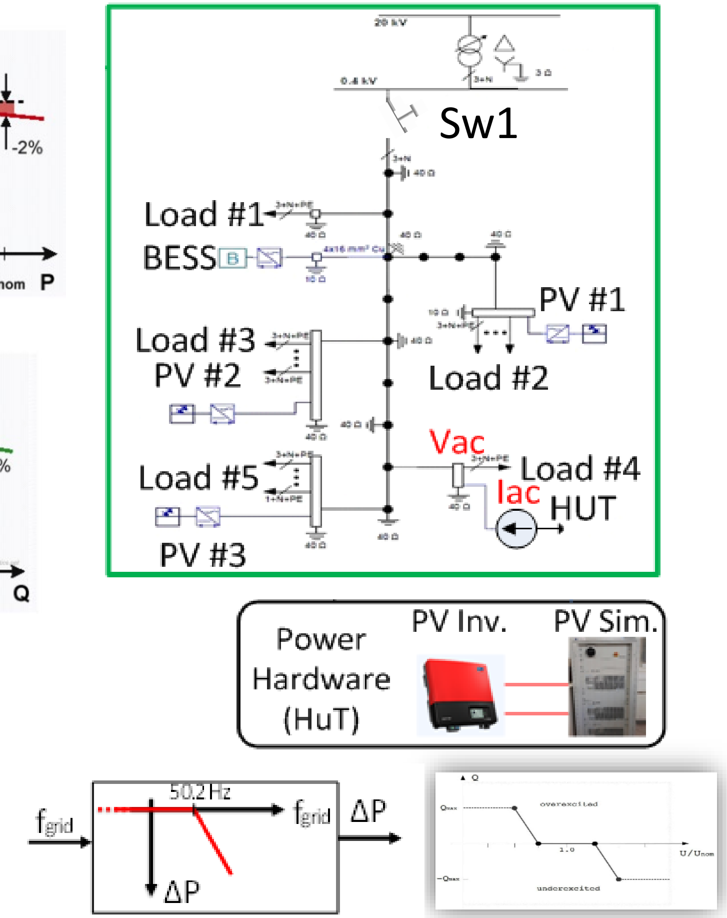
PV reactive power

PHIL test at the transition from grid connected to islanded mode: primary control

- Storage system: island mode operation with *f (P), V (Q)* droop curves
- Simulated and hardware DGs operate with Q(V) and P(f) droop control
- Excess of active power prior to disconnection: frequency rises according to BESS f(P) curve



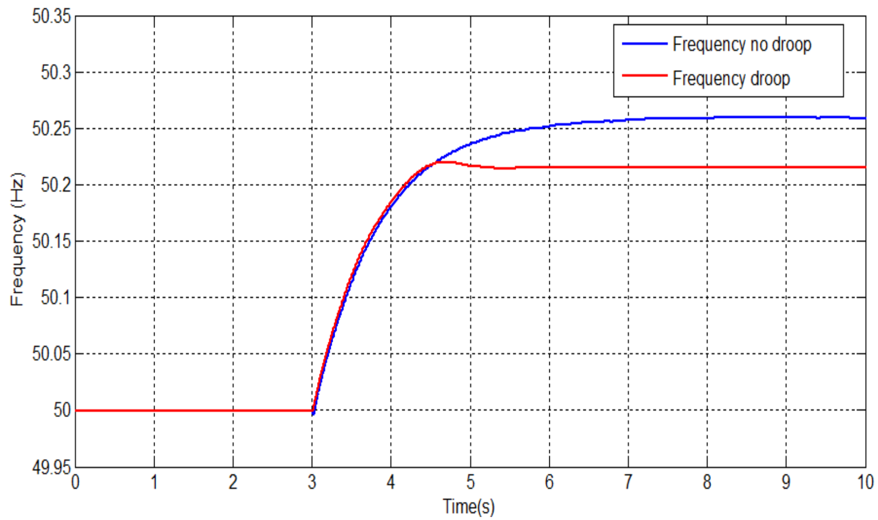




PHIL Setup for transition from Grid Connected to islanded operation

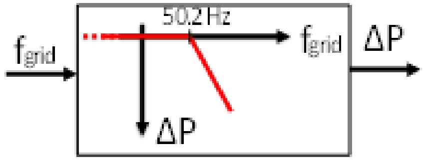
Transition from grid-connected to island mode – Frequency Transient

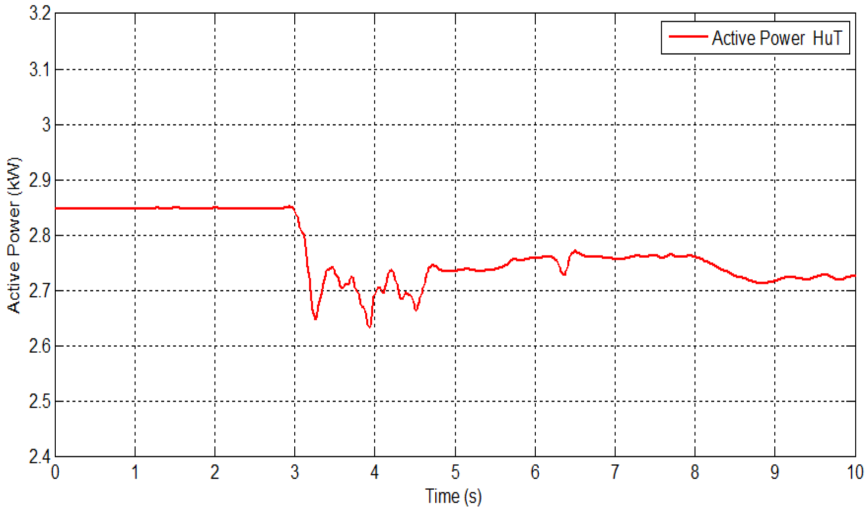
- When the DG units operate with *P (f)* droop control, they decrease their active power, leading to improved frequency response



Frequency transient comparison

- Curtailment from the Hardware inverter according to its P(f) droop





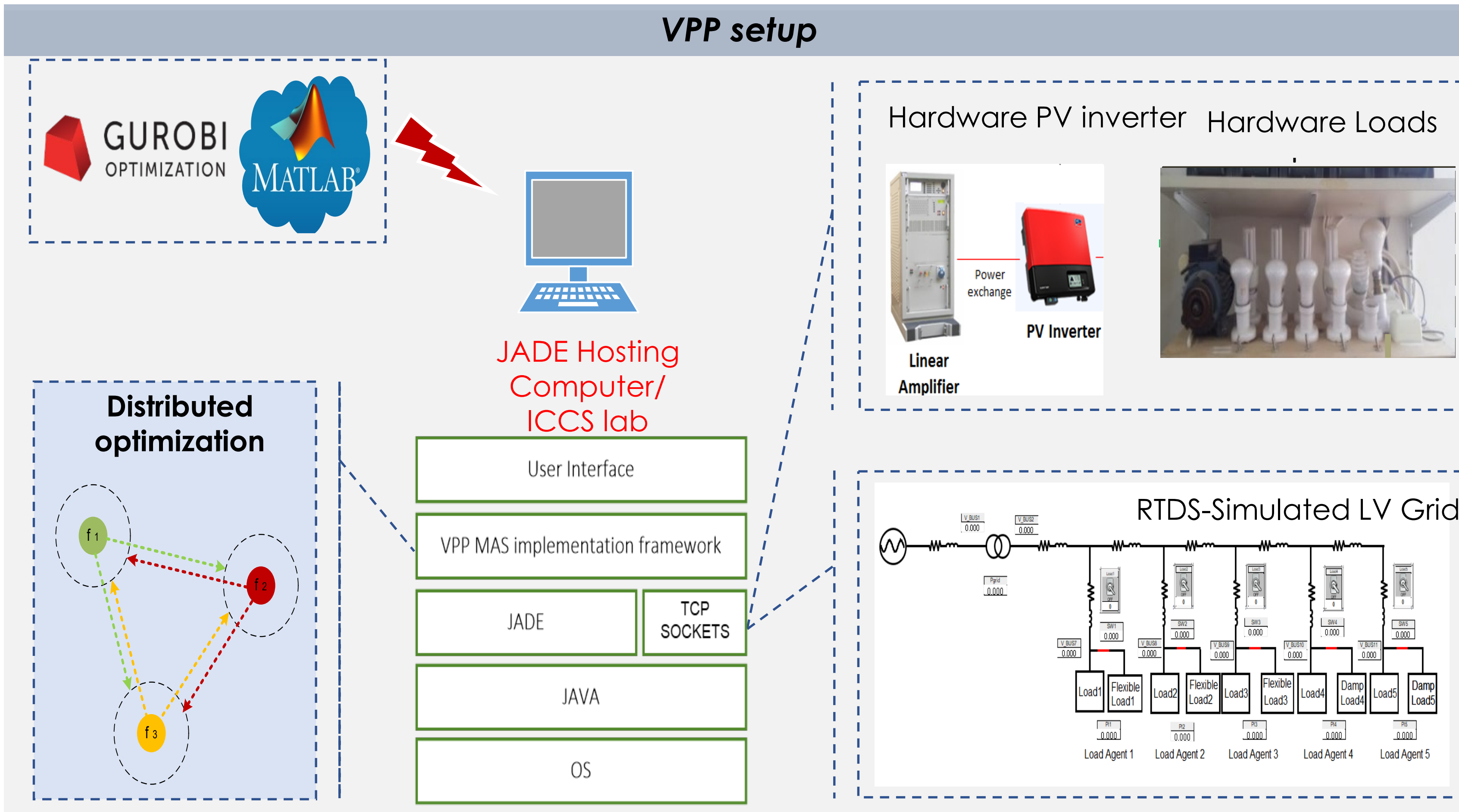
Active power response of hardware PV inverter

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

Test case 3:

Distributed control of loads and DER: **Multi-Agent System** (CHIL)

Virtual Power Plant laboratory platform using Multi Agent Systems



Conclusions

- Advanced testing and simulation methods for smart grid and microgrid systems are needed
- HIL is a system-level testing method that proves to be beneficial for testing in realistic and flexible conditions. **System level testing**
- 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: actual communication between the hardware controller and hardware inverter. Dynamics of actual inverter
- PHIL setup can prove useful to assess the behavior and impact on the stability of an islanded microgrid by a commercial equipment where its characteristics are unknown (e.g. commercial PV inverter)
- HIL simulation is/must/will be considered for testing of microgrid controllers and equipment

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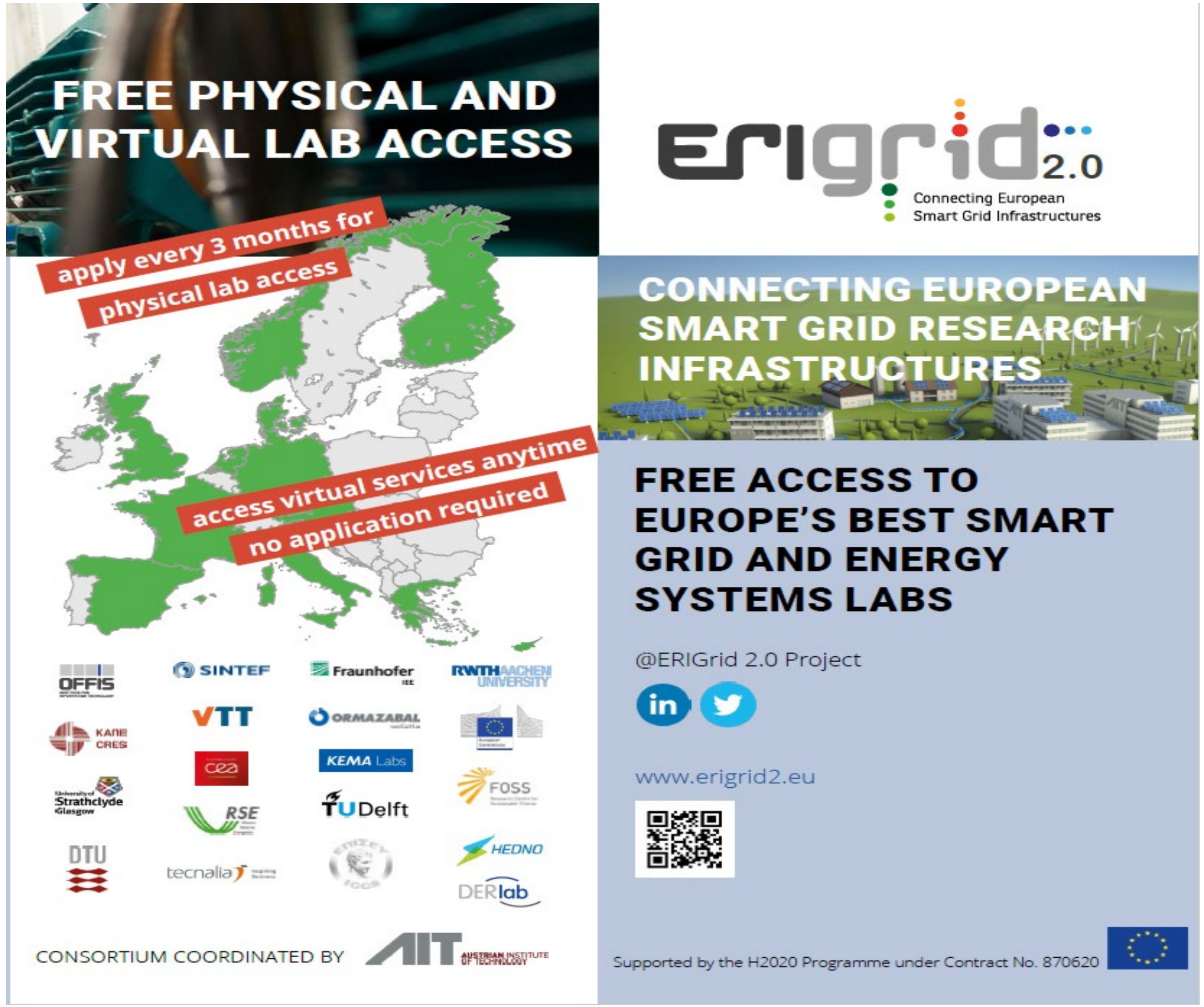

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Thank you for your attention!

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