# *Webinar on: "Demonstration of Multi Research Infrastructure Integration Tests"*

*November 26, 2019*

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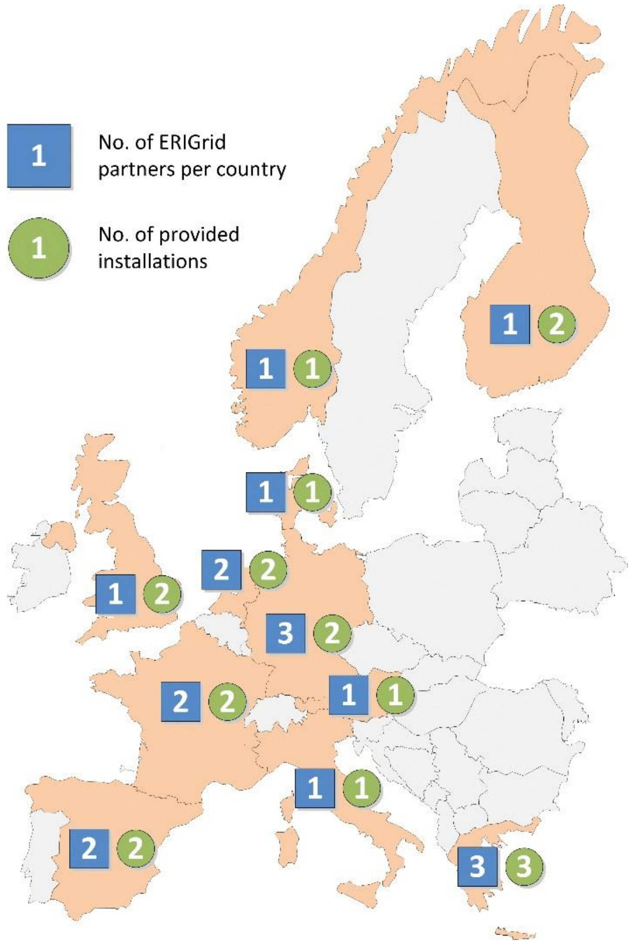
**Supported by**

- IEEE IES Technical Committee on Smart Grids (TC-SG)
- IEEE SMC Technical Committee Cybernetics for Intelligent Industrial Systems (TC-IIS)


EU H2020 Programme GA No. 654113

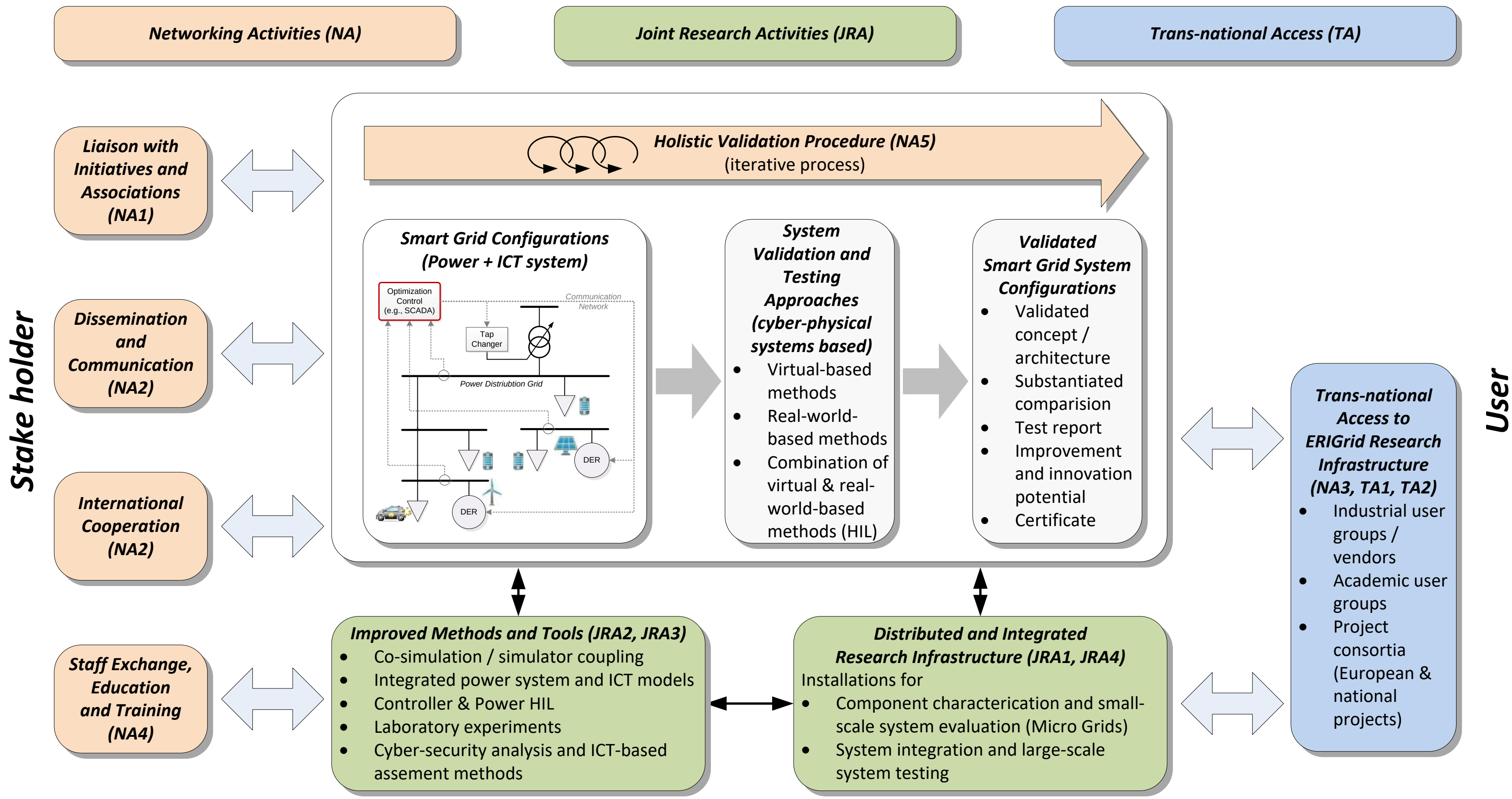
# Project Fact Sheet

- H2020 call
  - INFRAIA-1-2014/2015:
    Integrating and opening existing national and regional research infrastructures of European interest
- Funding instrument
  - Research and Innovation Actions (RIA)
    Integrating Activity (IA)
- 18 Partners from 11 European Countries
  + 3 Third Parties involved
- Involvement of 19 first class Smart Grid labs
- 10 Mio Euro Funding from the EC
- ~1000 Person Month



# Overview ERIGrid Approach

- Leading research infrastructure in Europe for the domain of Smart Grids



# Agenda

- Multi Research Infrastructures integration test (Luigi Pellegrino)
- Testing of converter controller through multi-site testing chain with varied testbeds (Merkebu Zenebe Degefa)
- Industrial controller validation with state of the art laboratory testing methods (Dimitris Lagos)
- The role of geographically separated real-time experiments in the validation of systems readiness levels (Mazher Syed)

# Multi Research Infrastructures integration test

Luigi Pellegrino

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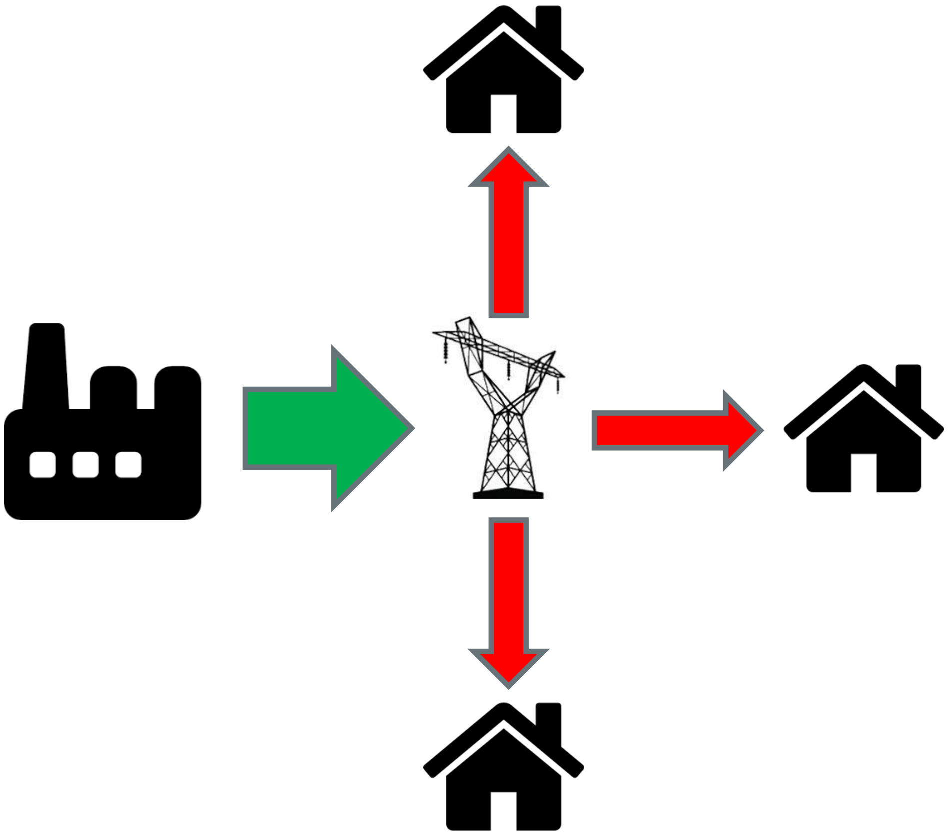
# Power system characteristics

How was the situation of the power system some years ago?

Few big power plants provide energy to the electrical load

Simple voltage and frequency controls

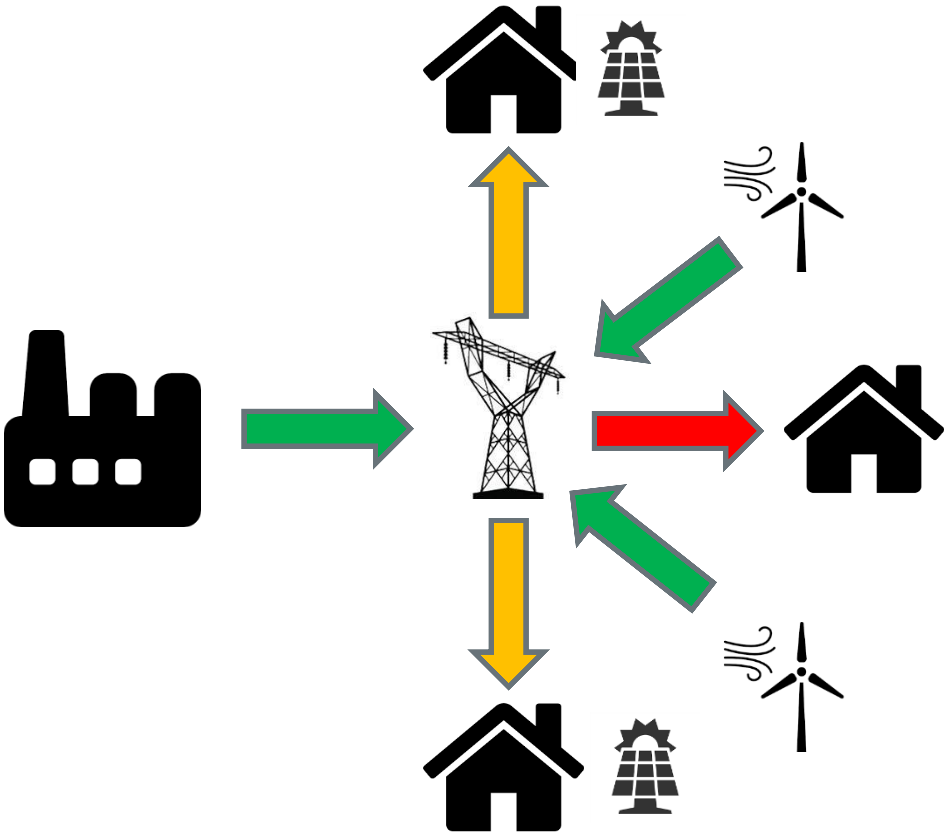


# Power system characteristics

How is the situation of the power system today?

Many RES have replaced some traditional power plants

Voltage and frequency behavior is changing

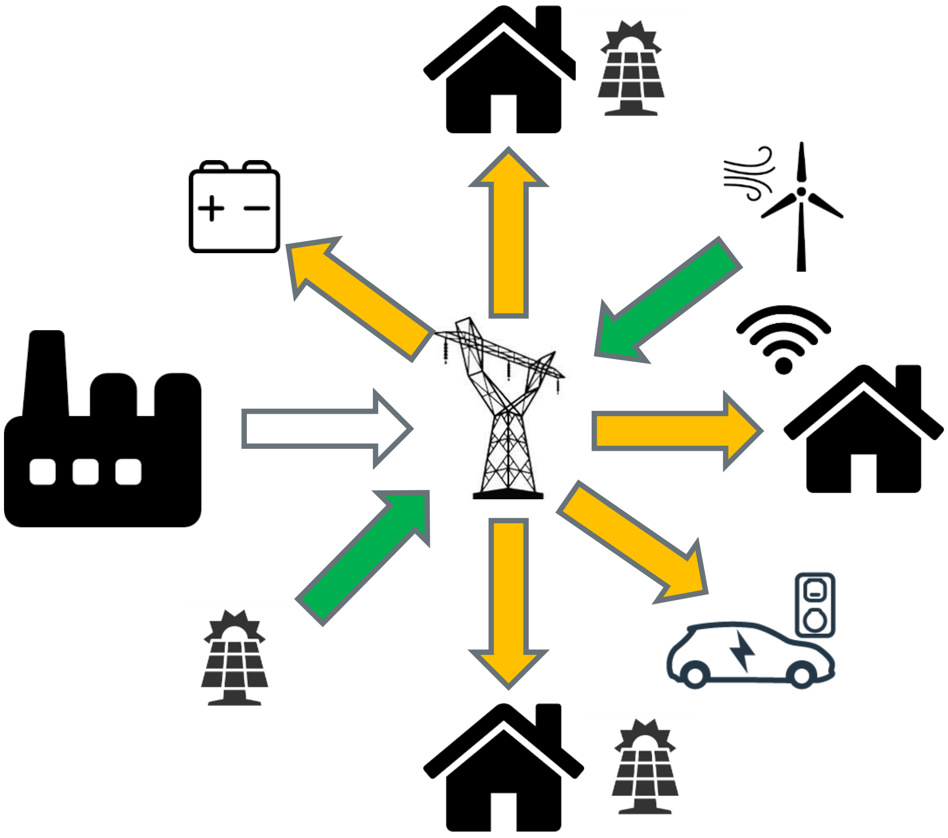


# Power system characteristics

How will be the situation of the power system tomorrow?

Almost all the electrical load will be compensated by RES.

New centralized and distributed voltage and frequency controls



# Challenges

**Low Complexity** → **High Complexity**

**Energy transition**

**Yesterday**

Methods: test the response of a component, component to different voltage and frequency input using a grid simulator

Domain: electrical

Testing procedure: simple test description without a general overview

**Tomorrow**

Methods: test interaction of control, components and power system using Hardware In the Loop

Domain: electrical, ICT, business, ecc.

Testing procedure: need of an holistic appoarach

# Challenges

**Low Complexity** **High Complexity**

**Energy transition**

**Yesterday** **Tomorrow**

Methods: test the response of a component, component to different voltage and frequency input using a grid simulator

Domain: electrical

Testing procedure: simple test description without a general overview

**ADVANCED LABORATORY METHODS**

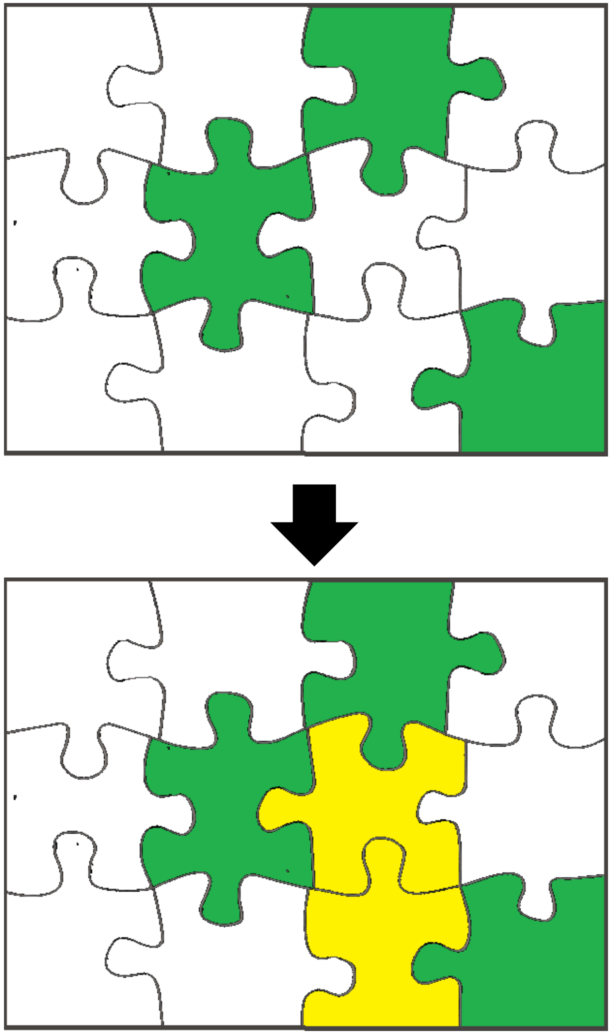
**COSIMULATION**

**HOLISTIC TEST DESCRIPTION**

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

# Concept

Nowadays several Research Infrastructures in Europe are performing experiments on Smart Grid activities, and each of them has particular strengths (hardware, software, models or controls).



**RI integration**

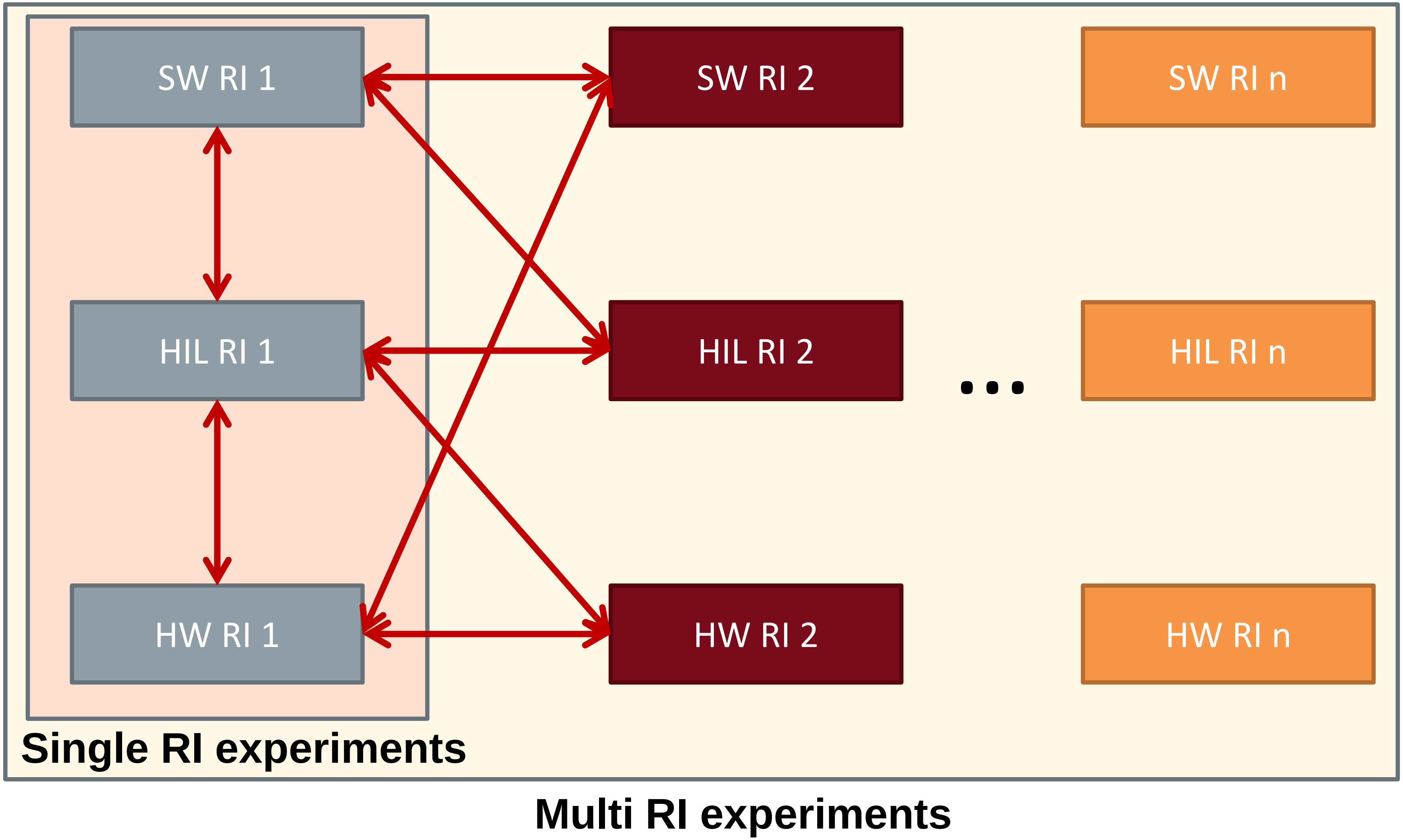
**<u>OFFLINE</u>**

Several tests performed in different RIs

**<u>ONLINE</u>**

One test done in real-time on different RIs

# Synergies



SW RI 1
SW RI 2
SW RI n
HIL RI 1
HIL RI 2
...
HIL RI n
HW RI 1
HW RI 2
HW RI n
Single RI experiments
Multi RI experiments

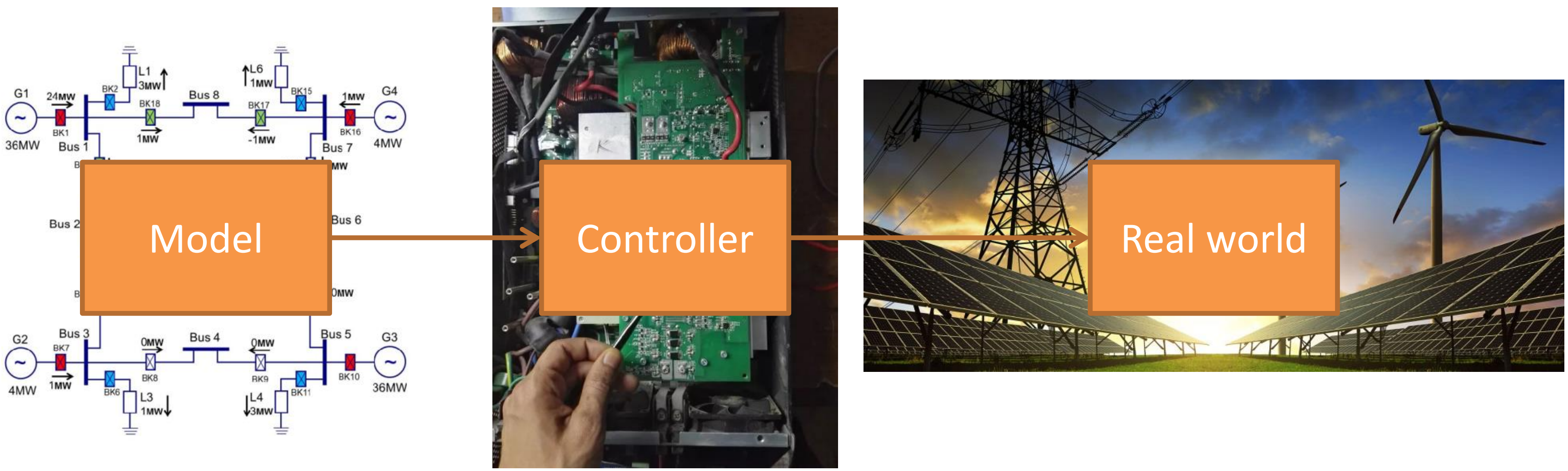
# Testing chain

1

The testing chain approach covers the whole range of testing possibilities including simulation, SIL, CHIL, PHIL and field testing sequentially in order to cover the smart grid functionalities.

**Advantages:**

- Increase of the experiment reality
- Reduce the time to market
- Decrease the risk of failure

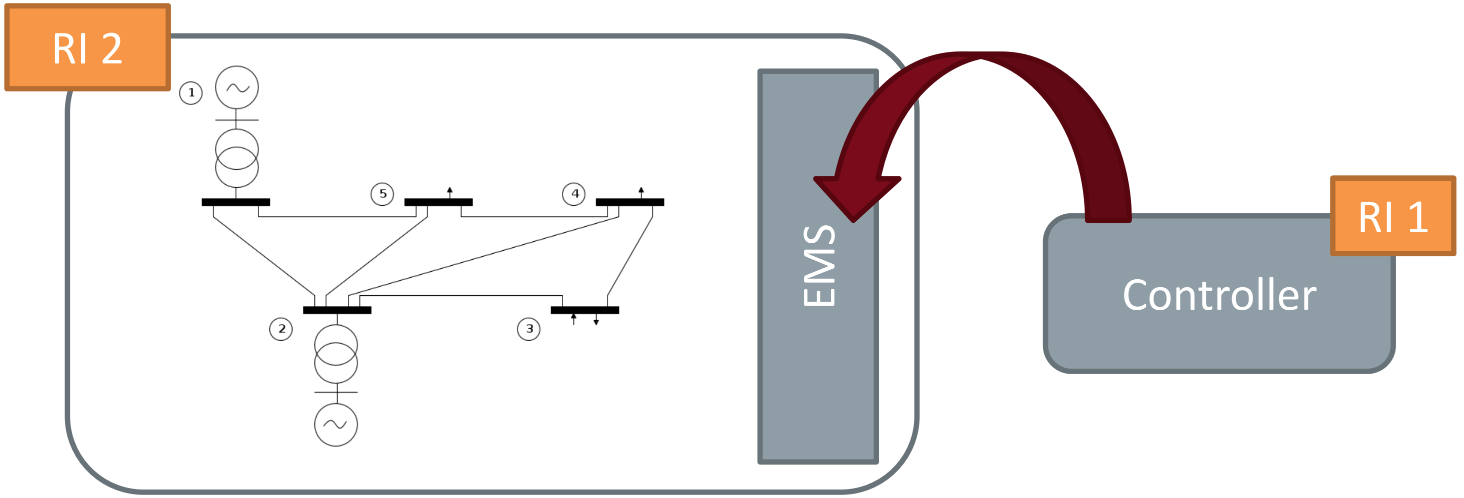


# HW/SW integration

Different solutions (e.g. different control algorithms) in realistic conditions and for different systems and scenarios can be studied implementing a software developed by one RI in another RI.

**Advantages:**

- Exploit synergies among the RIs
- Facilitate the comparison of different solutions



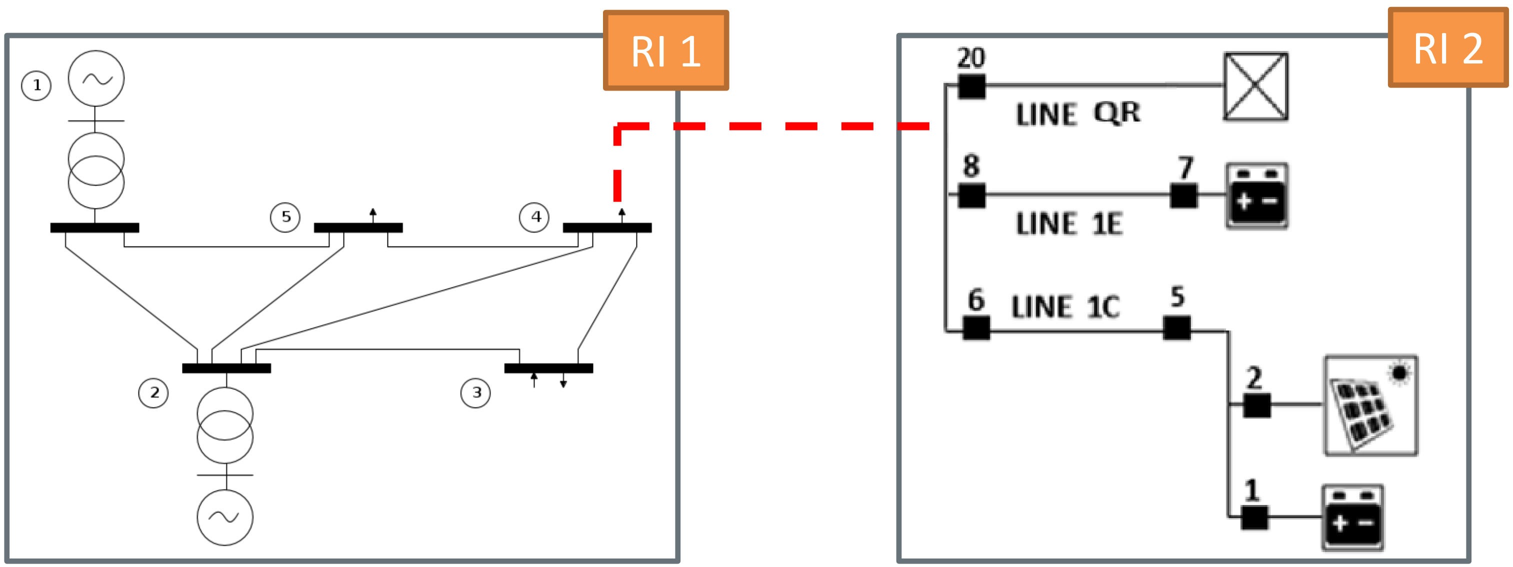
# Geographically Separated Research Infrastructure Coupling

3

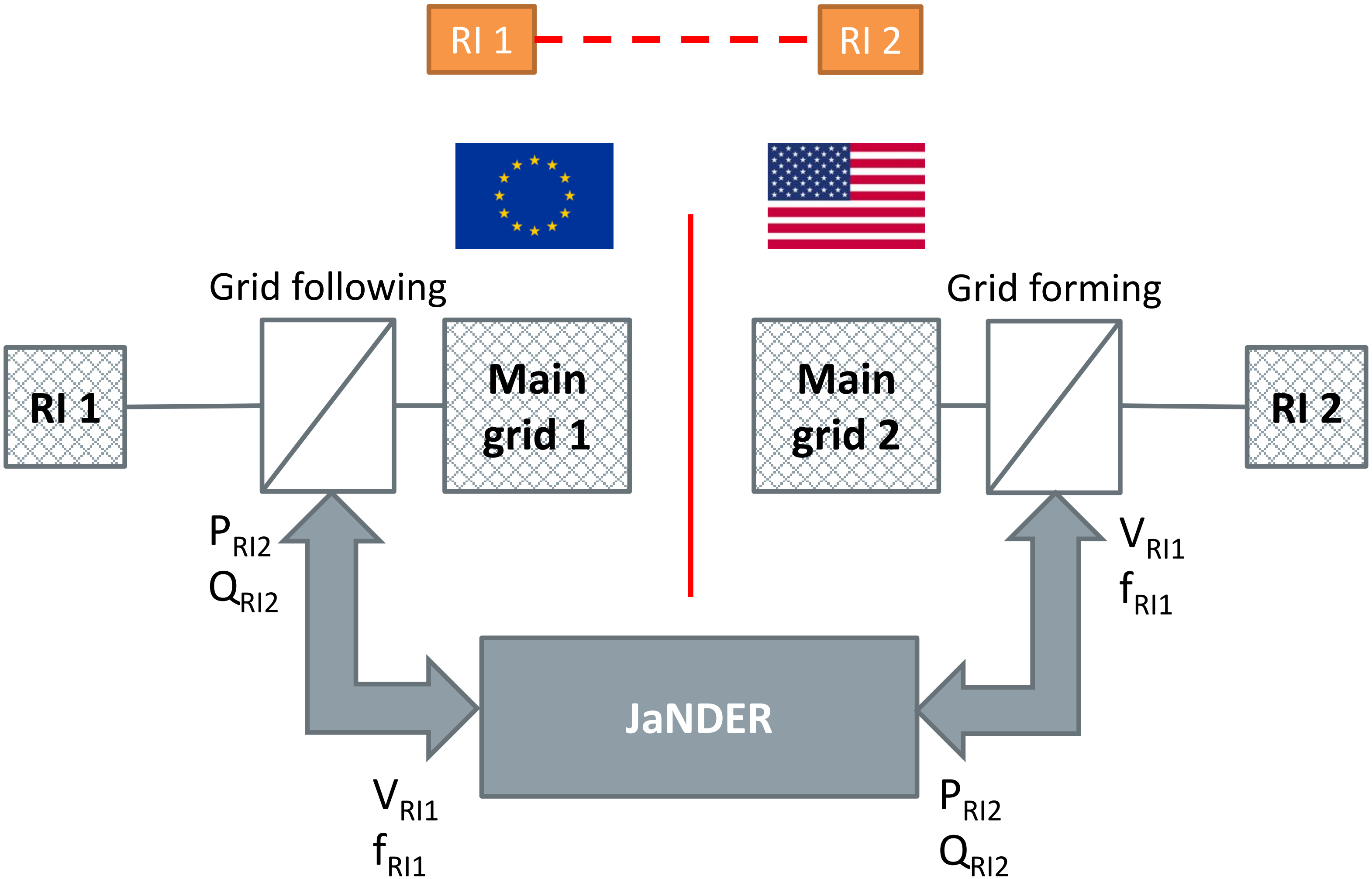
Integrate remote hardware as a part of testing, sharing the components of the integrated RIs. Exchanging real-time data between two or more RIs, a Points of Research Infrastructure Interconnection can be developed.

**Advantages:**

- Extension of the System under Test
- Avoid additional investments in new hardware



# Geographically Separated Research Infrastructure Coupling



1

# Testing of converter controller through multi-site testing chain with varied testbeds

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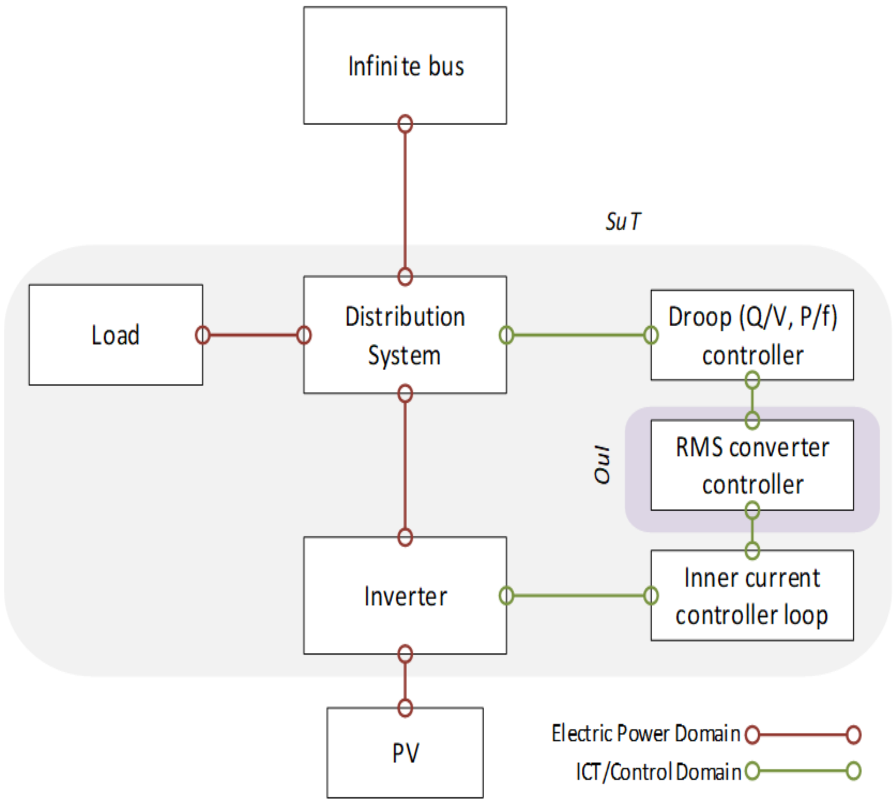
EU H2020 Programme GA No. 654113

# Testing of converter controller through multi-site testing chain with varied testbeds

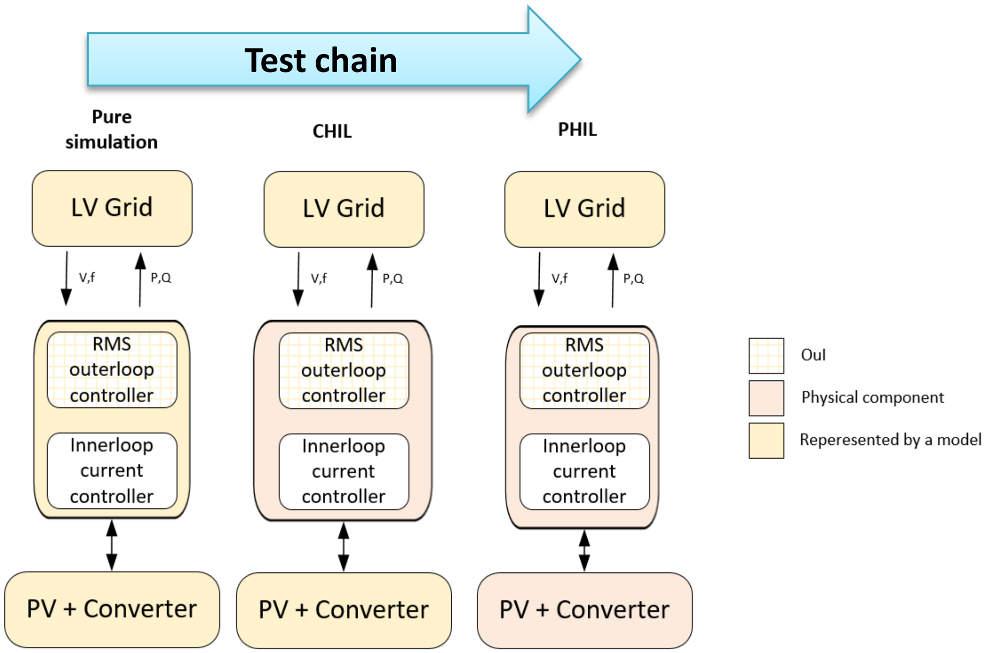
The test system:

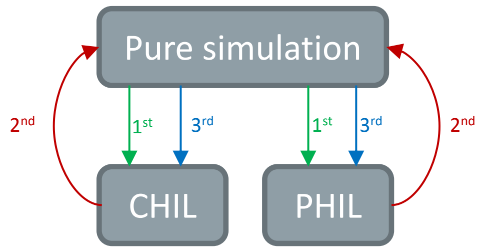


# Testing of converter controller through multi-site testing chain with varied testbeds

ERIGrid Connecting European Smart Grid Infrastructures

The plan:




Step 1: Run simulation and prepare load profiles for consequent tests

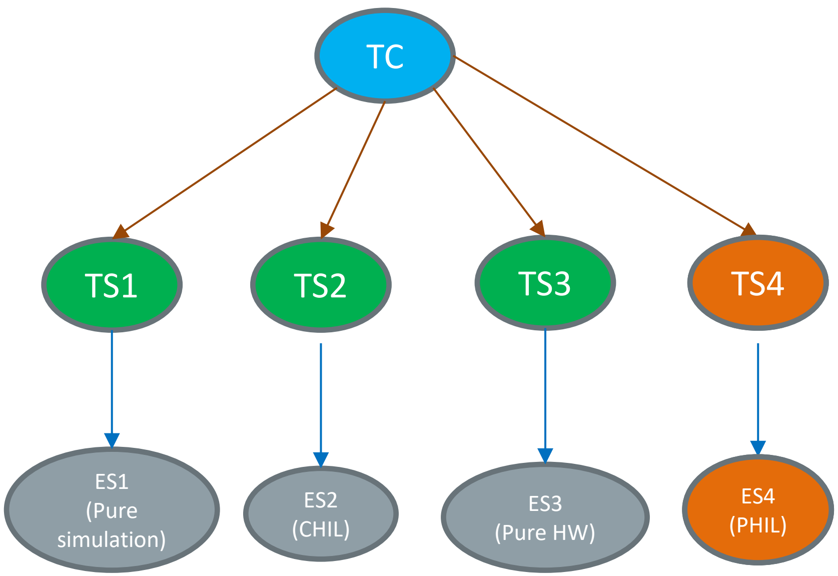
Step 2: CHIL and PHIL results with recommendation for improvement of converter controller

Step 3: Re-run Simulation, CHIL and PHIL tests to validate controller improvements

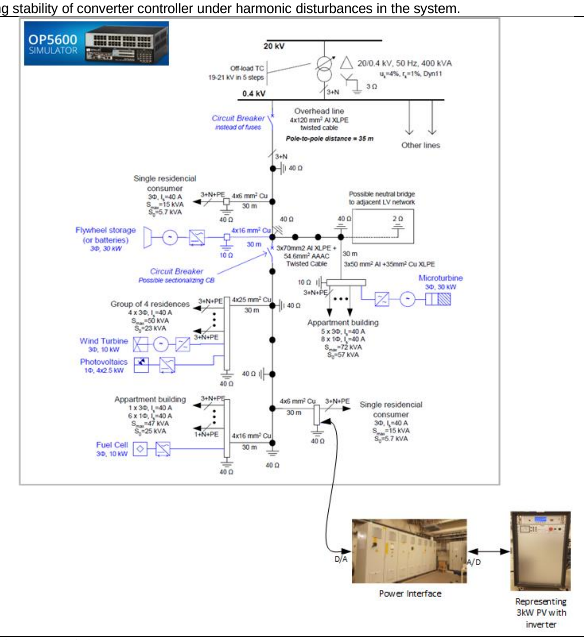
***Purpose of Investigation*** *(PoI): formulation of the test purpose in terms of Characterization, Verification, or Validation*

# Testing of converter controller through multi-site testing chain with varied testbeds

## The coordination:

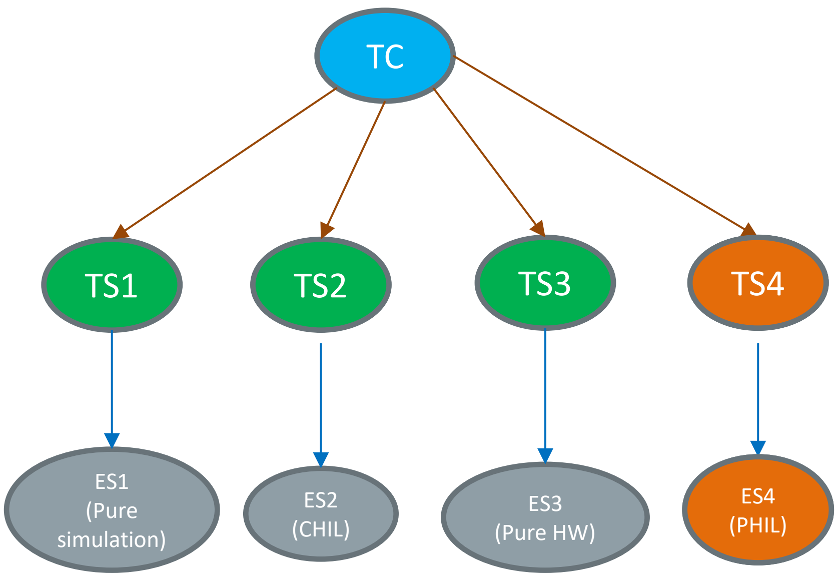



Test Specification

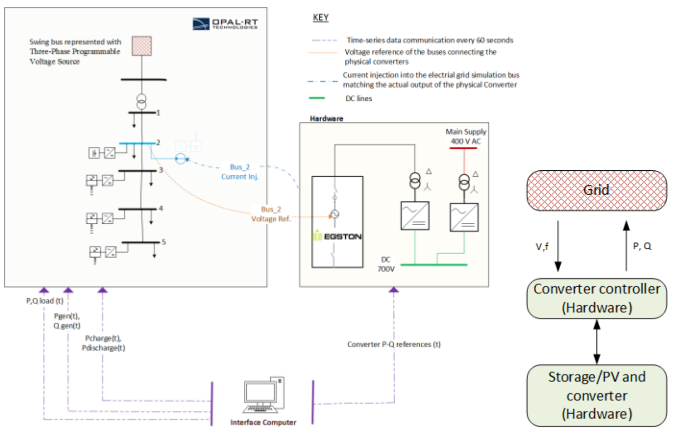
| | |
|---|---|
| **Reference to Test Case** | **TS4:** TESTBED-PoI1.4 |
| **Title of Test** | High fidelity characterization of droop converter controller |
| **Test Rationale** | TESTBED-PoI1.4 Characterize stability of converter controller hardware in closed loop full power se<br>Testing stability of converter controller under harmonic disturbances in the system. |
| **Specific Test System** (graphical) |  |
| **Target measures** | ΔQout/ΔV , ΔPout/Δf and oscillation behaviour |
| **Input and output parameters** | Input: Voltage and frequency references<br>Output: Q and P values from converter |
| **Test Design** | **Step#1**: Run the test for the base case scenario with normal loading scenario<br>**Step#2**: Run the test for variable load and PV output and record the change in voltage<br>**Step#3**: Introduce harmonics at the PCC point and check if the converter controller will filter it out. |
| **Initial system state** | Steady state system with the predefined initial loading condition. |
| **Evolution of system state and test signals** | Perturbation with step change in active power related to load and generation. |
| **Other parameters** | |
| **Temporal resolution** | 120 µSec |
| **Source of uncertainty** | Sources of unstable system can be from the controller or from the PHIL setup itself. Needs careful baseli |
| **Suspension criteria / Stopping criteria** | When steady state operation is reached after perturbation. Otherwise until the predefined simulation ti reached |

# Testing of converter controller through multi-site testing chain with varied testbeds

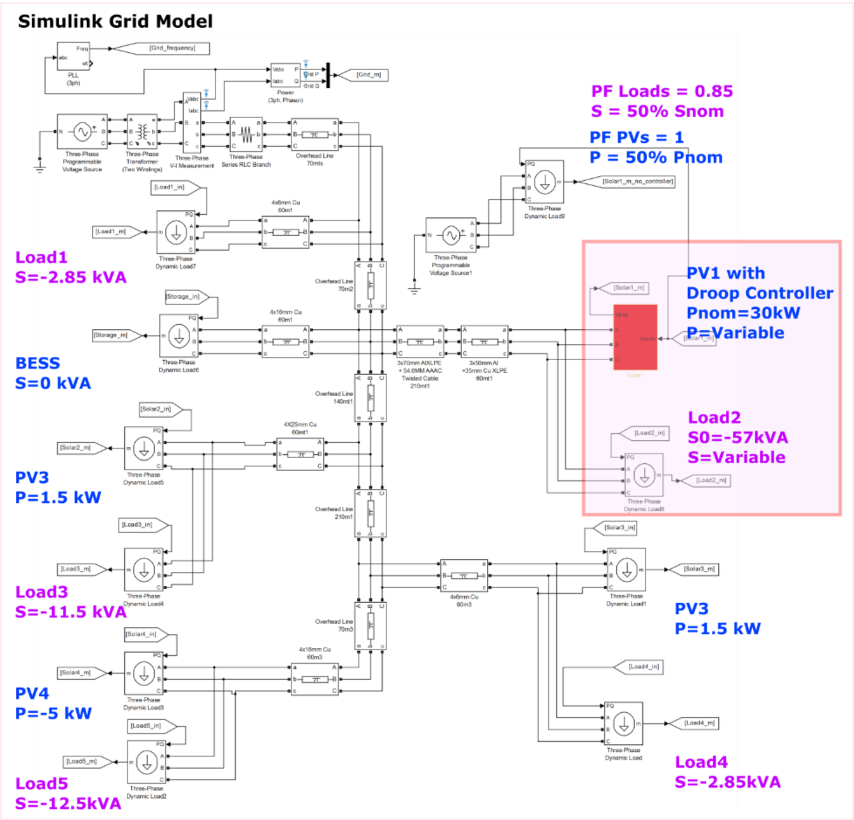
The coordination:




Experiment Specification

| | |
|---|---|
| **Reference to Test Specification** | Test Specification TS.4 |
| **Title of Experiment** | PHIL test of droop controller |
| **Research Infrastructure** | SINTEF |
| **Experiment Realisation** | The experiment is realized in Power-Hardware in the loop (PHIL) setup. The converter controller is simulated however, a physical 2-level 60 kW converter is integrated to the simulation representing Solar PV#1 in the LV test network. |
| **Experiment Setup** (concrete lab equipment) | Equipment used in the network include:<br>• OPAL-RT platform (OP5600 5 core activated)<br>• A 200 kW power converter operating as a grid emulator<br>• A 60 kW two level converter<br>• Interfacing computer<br> |
| **Experimental Design and Justification** | For testing the P-f droop characteristic:<br>• Converter response to ramping to frequency at the source from 50 Hz to 52 Hz.<br>For testing the Q-V droop characteristic and dynamic behaviour of the converter:<br>• Converter response to stepping-up PV1 output<br>• Converter response to stepping-down of PV1 output<br>• Converter response to stepping-up of P and Q of Load2<br>• Converter response to stepping-down of P and Q of Load2<br>(For testing the PHIL stability:<br>• Converter response to introduction of harmonic voltages in the PCC.) |
| **Precision of equipment** | -- |
| **Uncertainty measurement** | |
| **Storage of data** | RT-lab block 'opwriteFile' triggered when needed and file stored in Matlab .dat file format in the model folder |

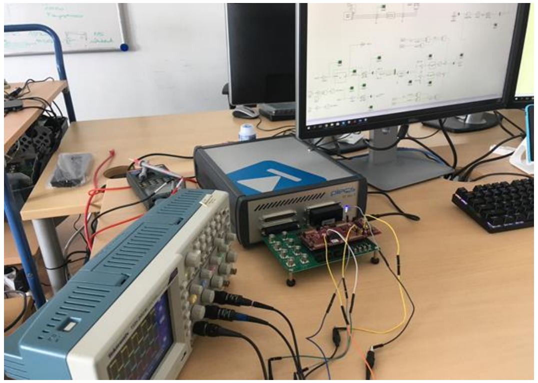
# Implementation#1: Simulation

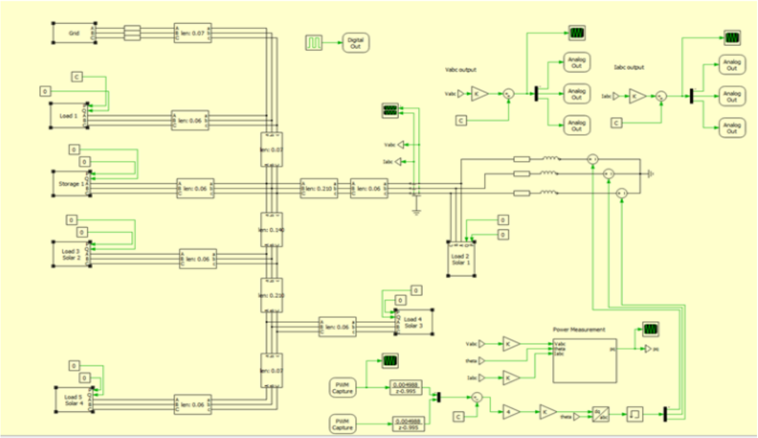



**Matlab Simulink**

**Purpose: Characterize and tune converter controller in simulated environment**

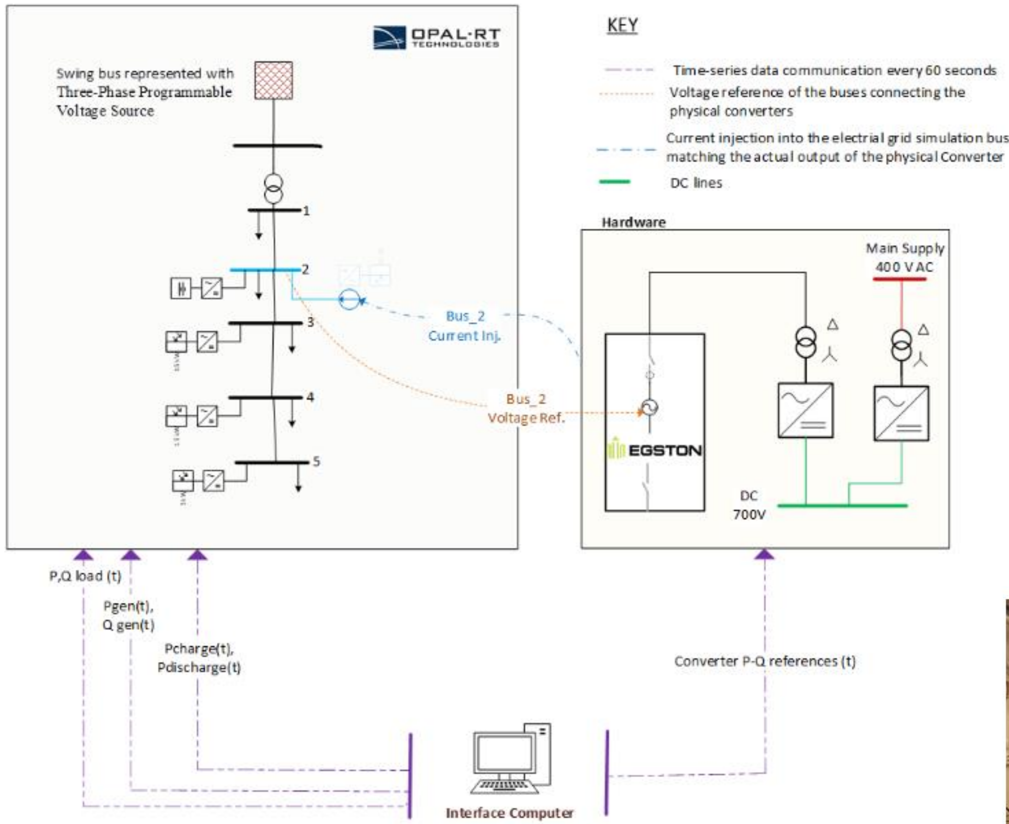
# Implementation#2: Controller Hardware in the Loop





- **PLECS-RT Box – runs a simplified model of the CIGRE LV grid with time step Ts = 50µs**
- **Controller is deployed on the Texas Instruments C2000 F28379D LaunchPad control card**

# Implementation#3: Power Hardware in the Loop



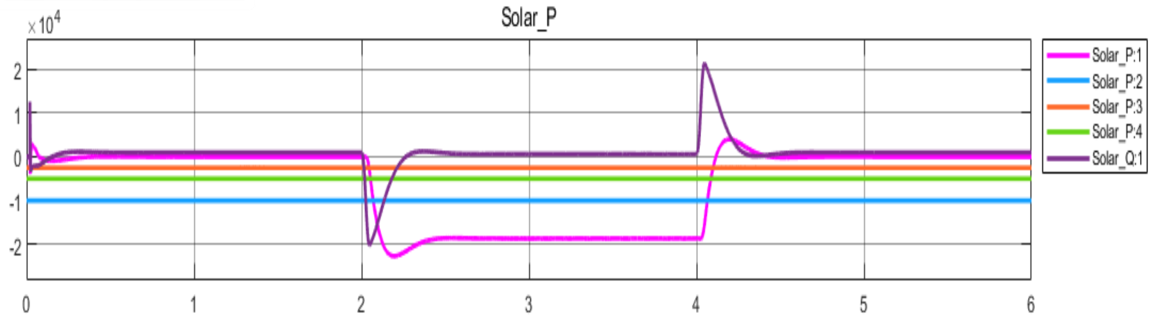

**Equipment used in the network include:**

- **OPAL-RT platform (OP5600 5 core activated)**
- **Egston 200 kW power converter operating as a grid emulator**
- **A 60 kW two level converter**
- **Interfacing computer**

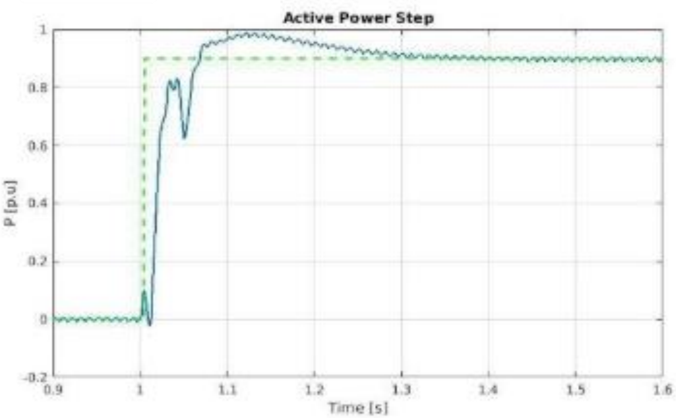
(a) (b)

# Results: Converter response for steping-up of PV output

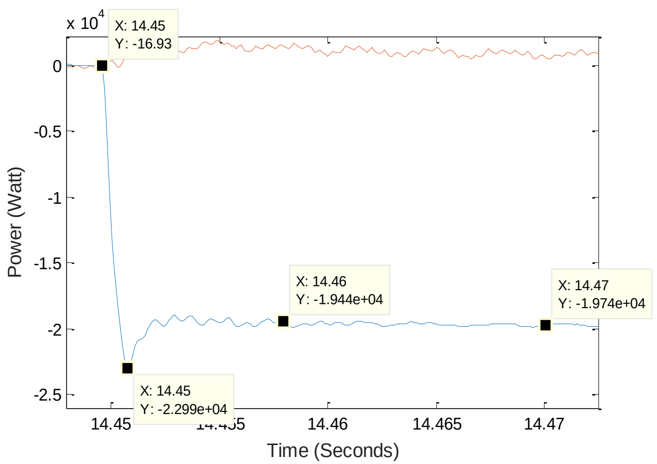
Simulation




CHIL




PHIL



# Results …

*Common coupling point voltage response KPIs for stepping up output of PV connected through the converter for the three different implementations*

| Test type | Action | ST [s] | OS [%] | Tp [s] | Damping [v] |
|---|---|---|---|---|---|
| **Simulation** | Stepup PV output with 1 pu | 0.35 | 4.34 | 0.22 | 0.7 |
| **CHIL** | Active power step from 0 to 0.9 p.u | 0.02 | 0.73 | 0.1 | 0.94 |
| **PHIL** | PV output stepup from 0 to 2 kW. Without 5th harmonics | 0.0102 | 0.25 | 0.02 | 0.8856 |
| | PV output stepup from 0 to 2 kW. With 5th harmonics | 0.0104 | 0.254 | 0.02 | 0.8851 |

# Conclusion

- Through the chain testing the controller is improved and the improvement is validated in the three setups.
- The improved controller reduced the ST of the system, however the phase margin of the control loop has been considerably reduced, thus resulting in larger overshoots and an overall more oscillatory behaviour.
- The use of the holistic test description methodology has helped the planning and execution of this test-chain.

2

# Industrial controller validation with state of the art laboratory testing methods

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# Advanced Testing Methods for smart grid control strategies

- Electrical networks are becoming increasingly ‘smarter’, as well as more complex
- Advanced control strategies to manage such networks are becoming necessary
- These strategies need to be thoroughly tested and validated, before they can be implemented in a real network
- Rapid prototyping tools, such as the Hardware in the Loop techniques, can be the intermediate step between simulations and field deployment.
- HIL techniques require expensive equipment.
- Collaboration between industry and research centers in testing of advanced control algorithms

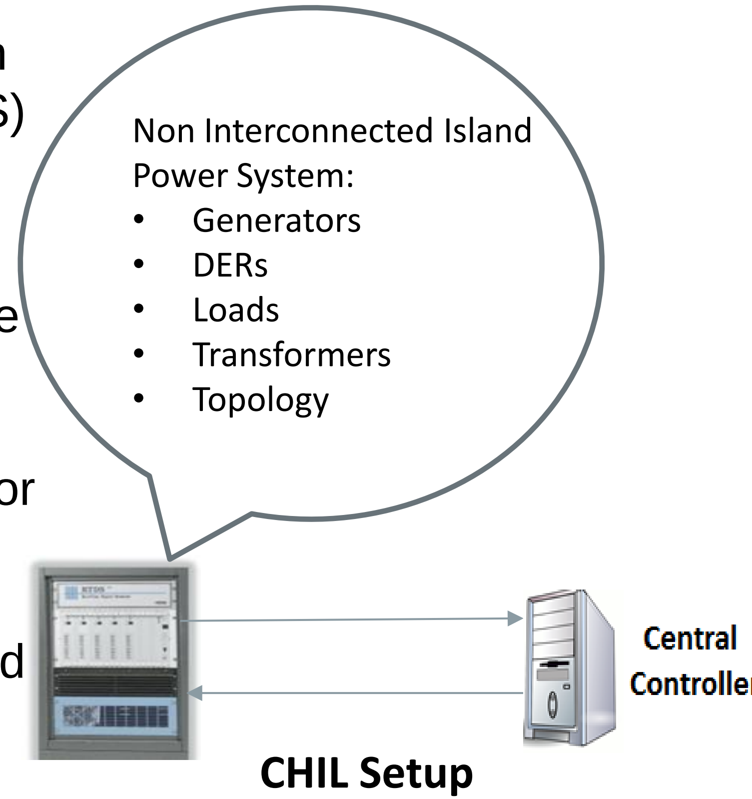
*M. Maniatopoulos, D. Lagos, P. Kotsampopoulos, N. Hatziargyriou, “Combined Control and Power Hardware-in-the-Loop simulation for testing Smart grid control algorithms”, IET Generation, Transmission & Distribution, Vol. 11, Issue 12, August 2017*

# System Under Test

- Under Erigrid umbrella control algorithms of an industrial partner (DSO) was tested in realistic conditions using the Control Hardware in the Loop (CHIL) setup of a research infrastructure.

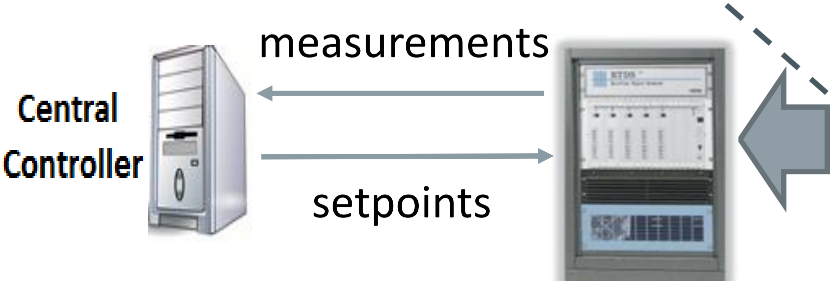
- HEDNO is the greek DSO responsible for Non Interconnected Islands Power Systems (NIIPS) operation

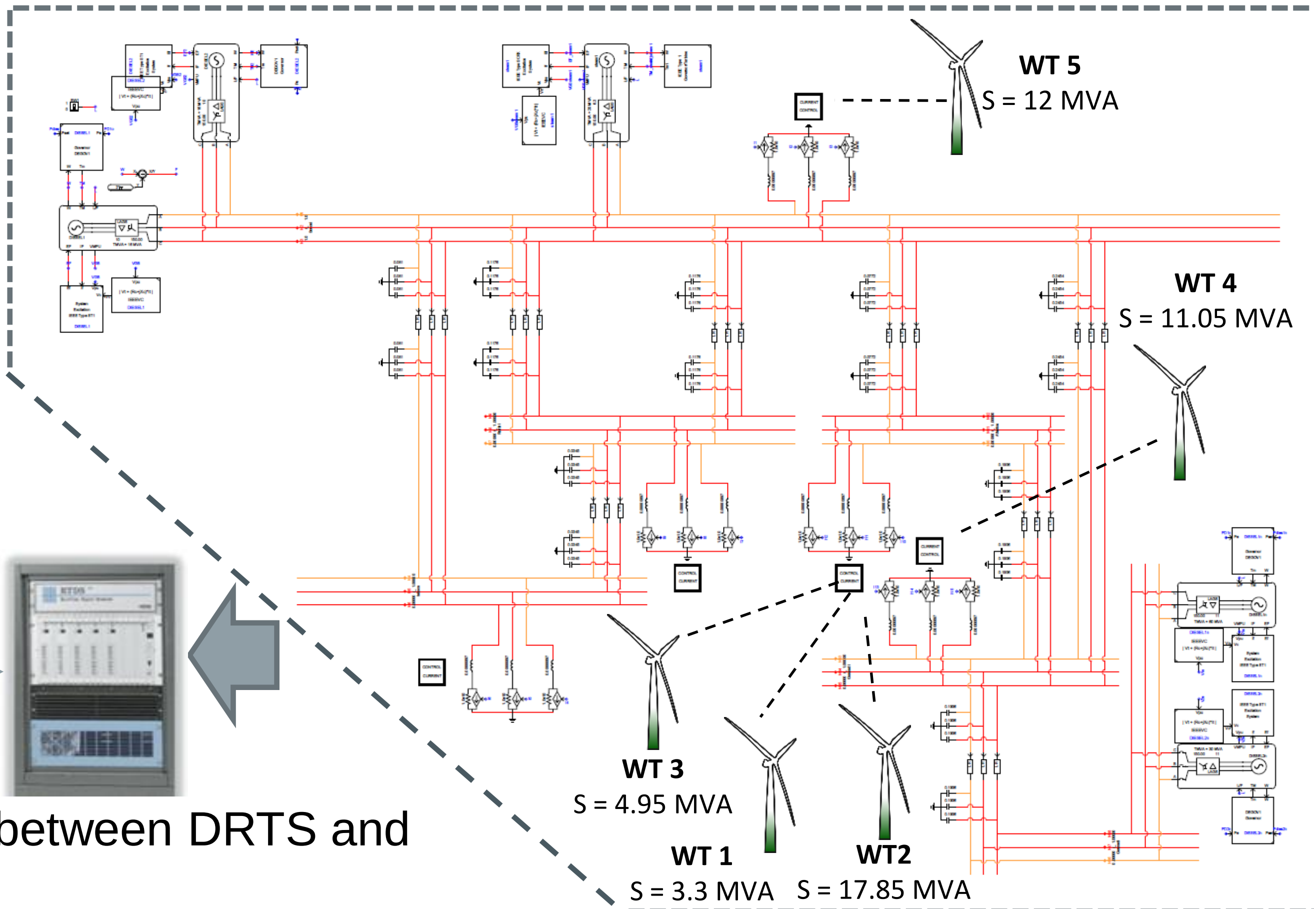
- 2 centralized control algorithms for NIIPS tested in ICCS/NTUA premises under real-time conditions in Control HIL setup
  - Existing dynamic security algorithm
  - A proposed centralized control algorithm for NIIPS
- Both tested in **Rhodes** island power system, which is the second largest non-interconnected power system in Greece



# Control Hardware in the Loop Setup

1) Dynamic Model of Rhodes Island System designed and validated in DRTS with actual measurements from Rhodes island.




2) Establish connection between DRTS and Controller

3) Test both algorithms in realistic conditions and under contingencies


EU H2020 Programme GA No. 654113

# Existing Algorithm

***Measurements acquisition*** (WT Power, Thermal Units Production, WT Available Power)

↓

***Calculation of Maximum Permitted WT Production***

$$P_{max}^{res} = \min\{\underbrace{cd \cdot Load}_{\text{Dynamic Constraint}}, \underbrace{Load - \sum_{i=1}^{ngen} P_{min}^{G}}_{\text{Constraint due to Thermal Generators Technical Minimum}}\}$$

**Dynamic Constraint (e.g 30% Load)**

**Constraint due to Thermal Generators Technical Minimum**

↓

**Calculate the setpoint of each WT by distributing $P_{max}^{res}$ according to their maximum available power and nominal rating**

↓

**Calculate new operating points for Thermal Generators according to economic operation and spinning reserve requirements (e.g. total reserves > 15% of Load) and technical minimum of generators**

↓

**Send Setpoints For Thermal Generators and WT**

# Proposed Control Algorithm

**_Measurements acquisition_** (WT Power, Thermal Units Production, WT Available Power**, Active and Reactive Power of the 5 HV/MV Substations**)

↓

**_Solve Optimization Problem_**

↓

**_Send Setpoints_** (WT Active and Reactive Power Setpoints, Thermal Generators Setpoints)

**Objective Function:**

$$\min_{x}\{w_{cost}\sum_{i=1}^{Ng} Cost_i \cdot P_g + w_v \sum_{j=1}^{n}(V_n - V_j)^2\}$$

**Variables**:

Voltages, angles, Thermal units production, WT Active Power, WT Reactive Power

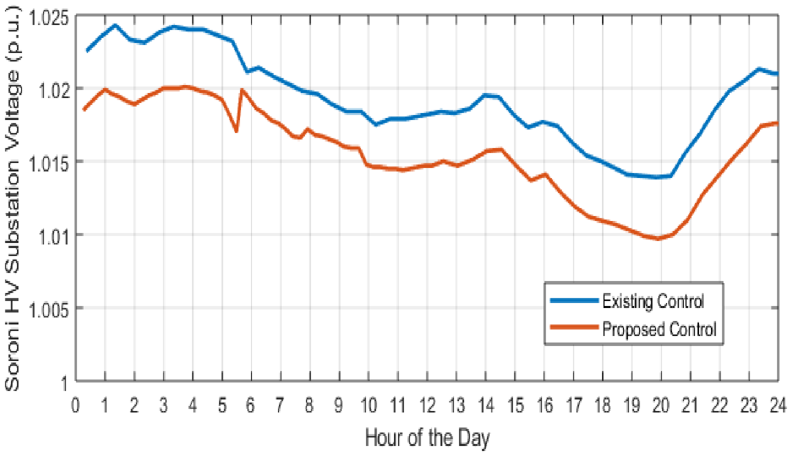
**Constraints:**

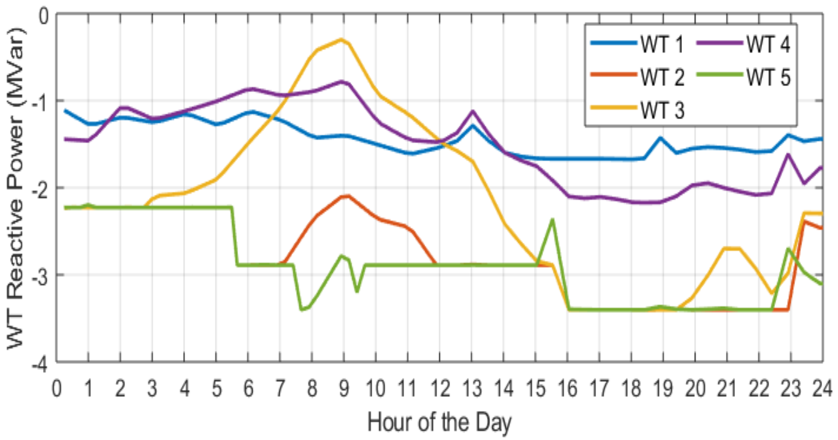
- Power Balance Equations
- Voltage $V_{min} \leq V_j \leq V_{max}$
- Angle $-180° \leq d_j \leq 180°$
- Thermal Generator $P_{min} \leq P_i \leq P_{max}$
- WT Active Power $P_i^{WT} \leq P_i^{WT\_avail}$
- WT Reactive Power $Q_i^{WT} \leq P_i^{WT} \cdot \tan(\mathrm{acos}(0.9))$
- Dynamic Frequency Constraints $F(H, P_{dis}) \leq 49.4$

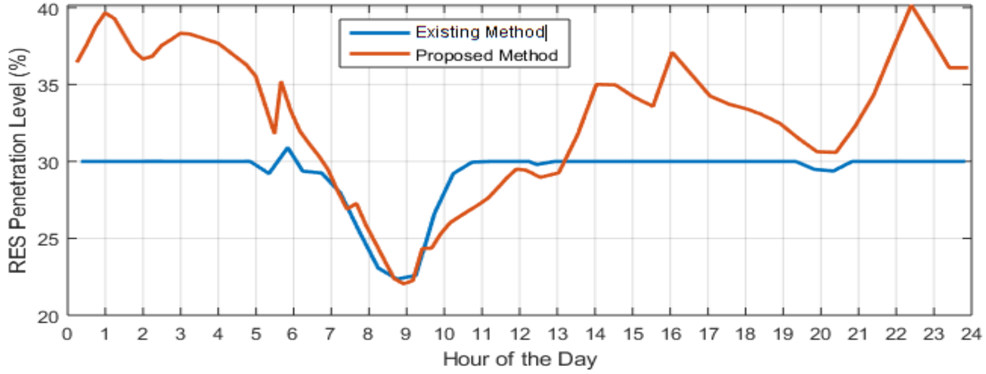
*V. Trovato, A. Bialecki and A. Dallagi, "Unit Commitment With Inertia-Dependent and Multispeed Allocation of Frequency Response Services", IEEE Transactions on Power Systems, vol. 34, no. 2, pp. 1537-1548, 2019.*

# Real Time Operation Compare

- Examine Performance in real time operation
  - Winter day scenario of reduced Demand and high Wind Power potential
  - Compare Voltage profiles and RES penetration levels for both methods

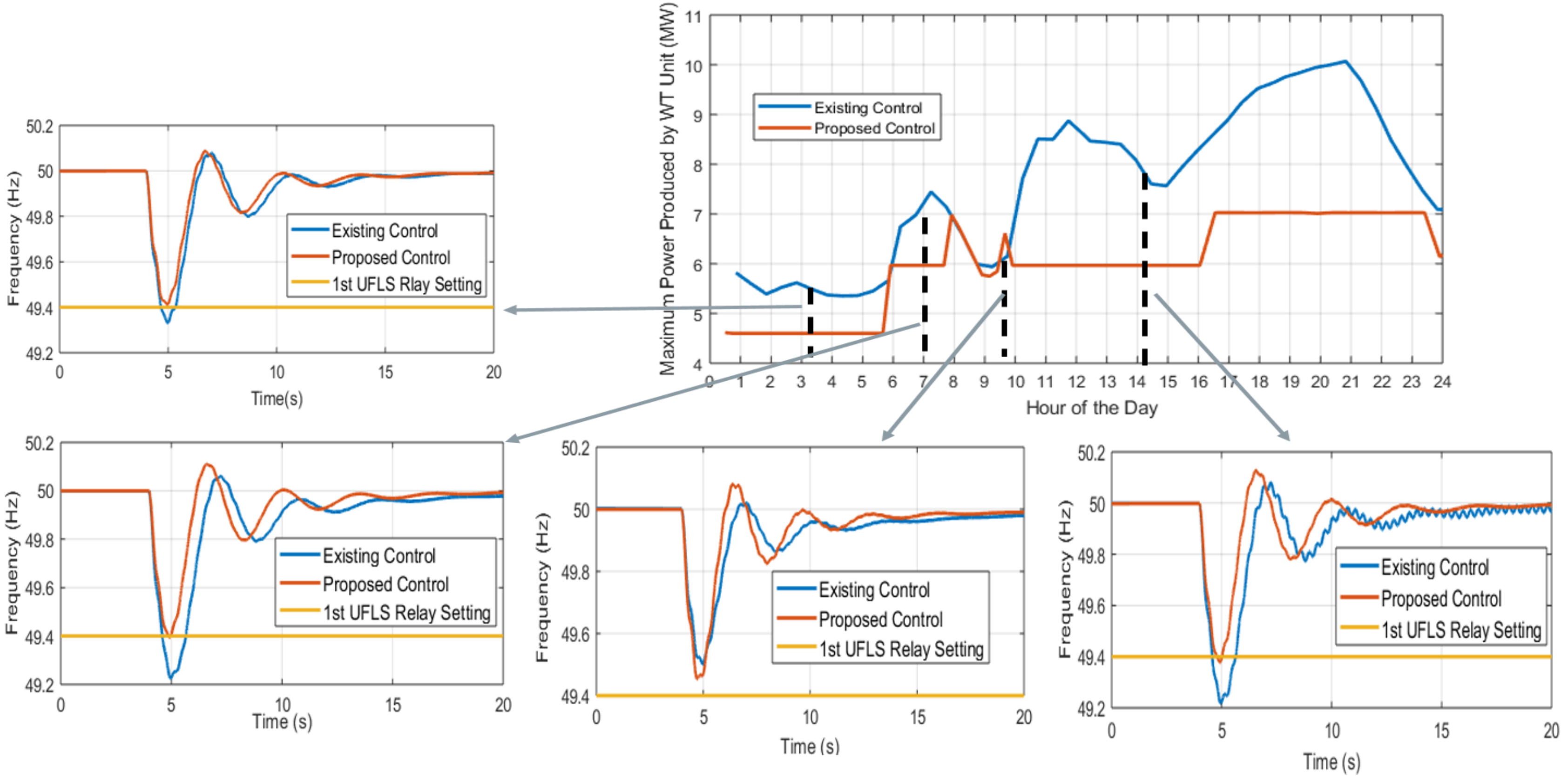


# Dynamic Security Validation

- Implement a contingency (disconnection of the largest producing WT) at different times of the day
- Compare the performance of the dynamic constraint of HEDNO control and the proposed dynamic frequency constraint



# Conclusions & Lessons Learned

- Advanced Control Algorithms of an industrial partner tested in a research infrastructure with a state of art testing approach (CHIL)
- This approach revealed weaknesses of the existing method compared to the proposed control (dynamic security)
- Validated the performance in realistic conditions (time delays, noise in measurements)

**Lessons Learned:**

- Similar approaches can promote the collaboration of industry and research centers
- State of the art approaches (e.g. HIL) that offer testing in realistic conditions can decrease the time required to validate an advanced smart grid solution before the actual field implementation.

3

# The role of geographically separated real-time experiments in the validation of systems readiness levels

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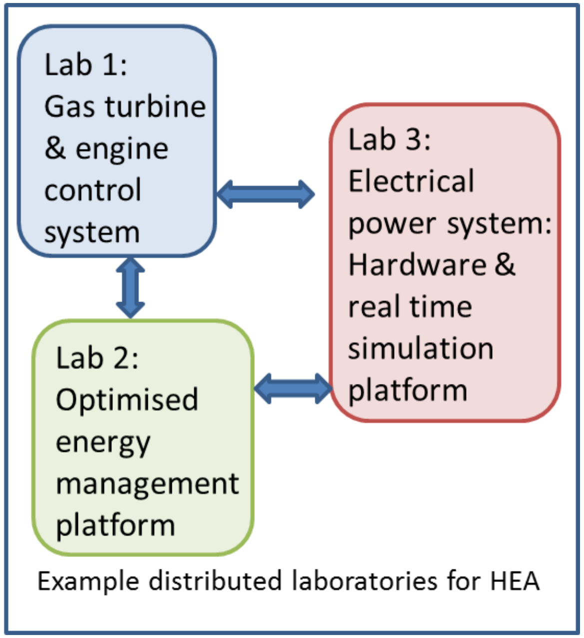
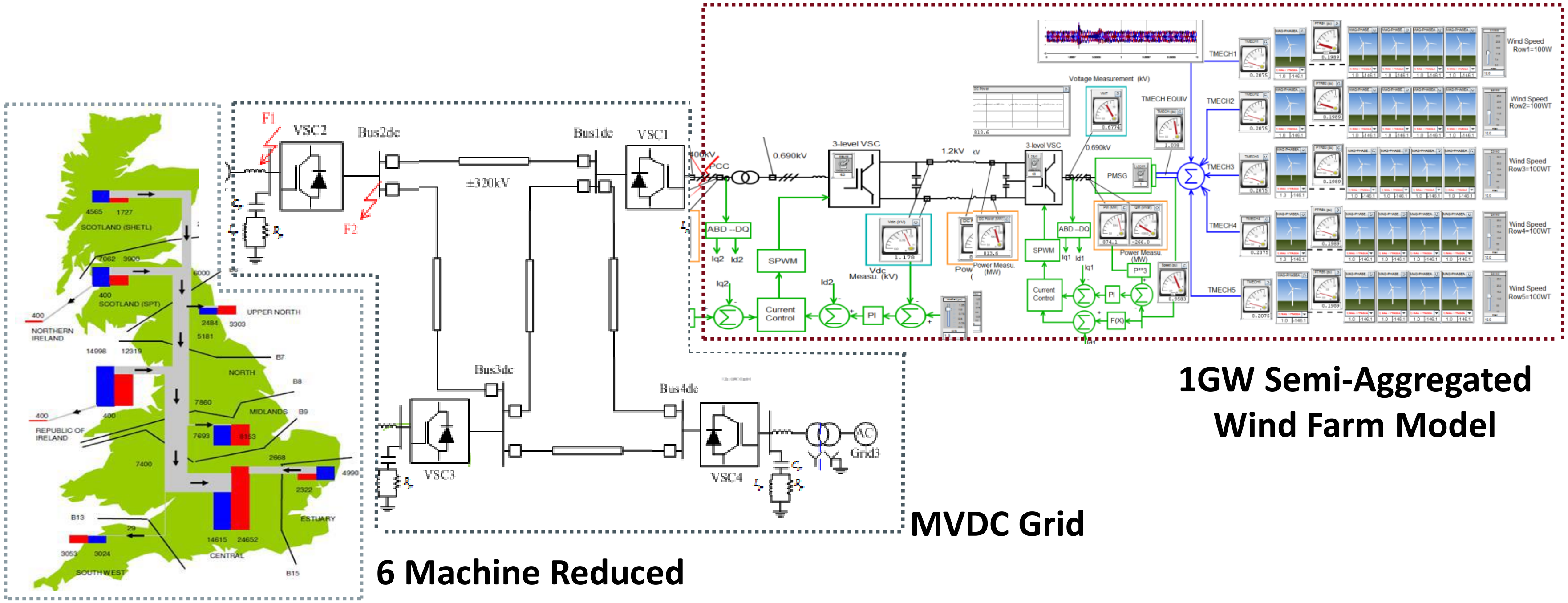
# Geographically Separated Research Infrastructure Coupling

- Comprehensive characterization and effective demonstration
  - Representative system studies → Realism
  - Large system studies → Scalability
  - Detailed system studies → Fidelity




**1GW Semi-Aggregated Wind Farm Model**

# Geographically Separated Research Infrastructure Coupling

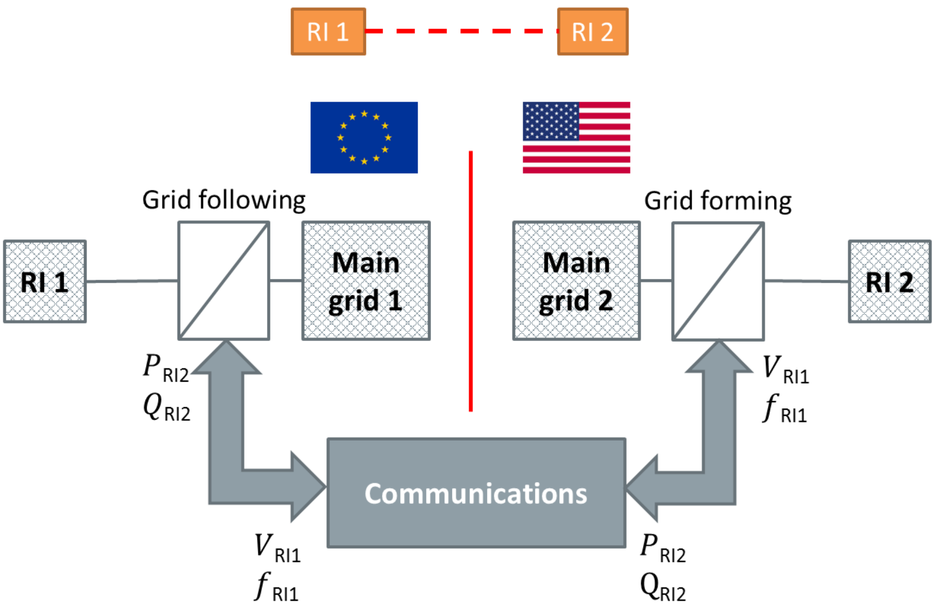


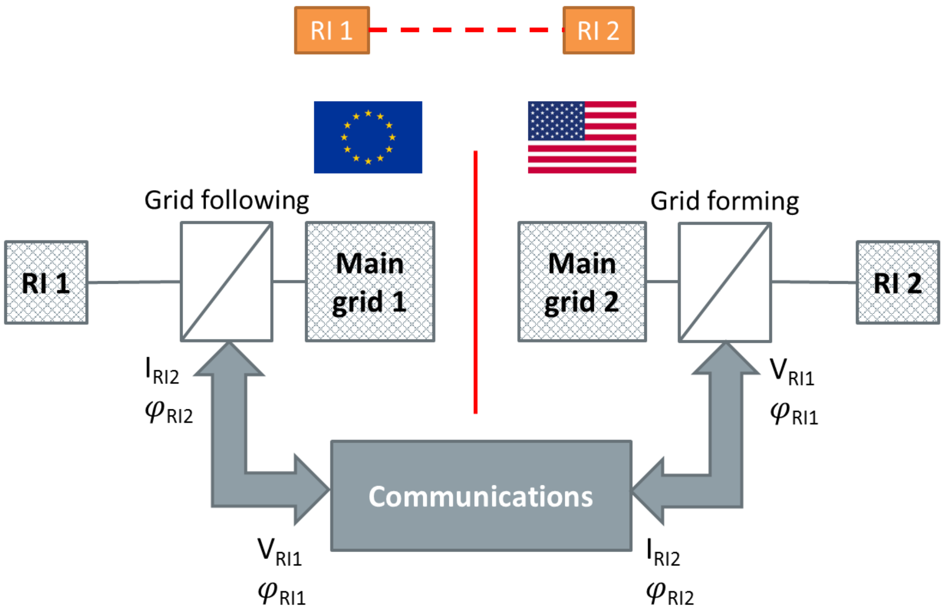

6 Machine Reduced Equivalent Model of GB

MVDC Grid

1GW Semi-Aggregated Wind Farm Model

# Types of Coupling




- Asynchronous Coupling
  - RMS value of interface signals
  - No phase information
  - Application: Slower Dynamics
- Synchronous Coupling
  - Instantaneous values
  - Carries phase information
  - Application: Faster dynamics and potentially transients

# Geographically separated multi RI integration

- Research Questions:
  - Can geographically separated RIs coupled over the internet be meaningfully utilized for power system dynamics evaluation?
- Choice of Coupling:
  - Asynchronous, to allow first demonstration of the proof of concept utilizing the newly developed JaNDER
- Methodology:
  - Two setups under consideration:

  a) Monolithic Implementation: Implemented within a single RI, such a setup serves as reference for fidelity analysis.

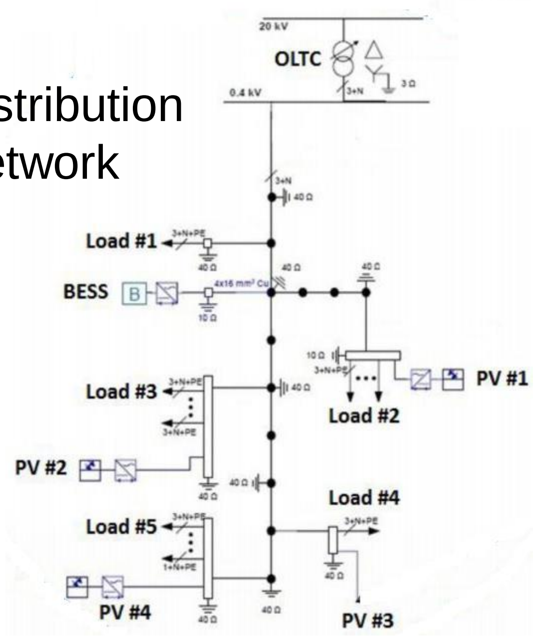
  b) Multi-RI Implementation: Implemented within more than one RI that is geographically separated.

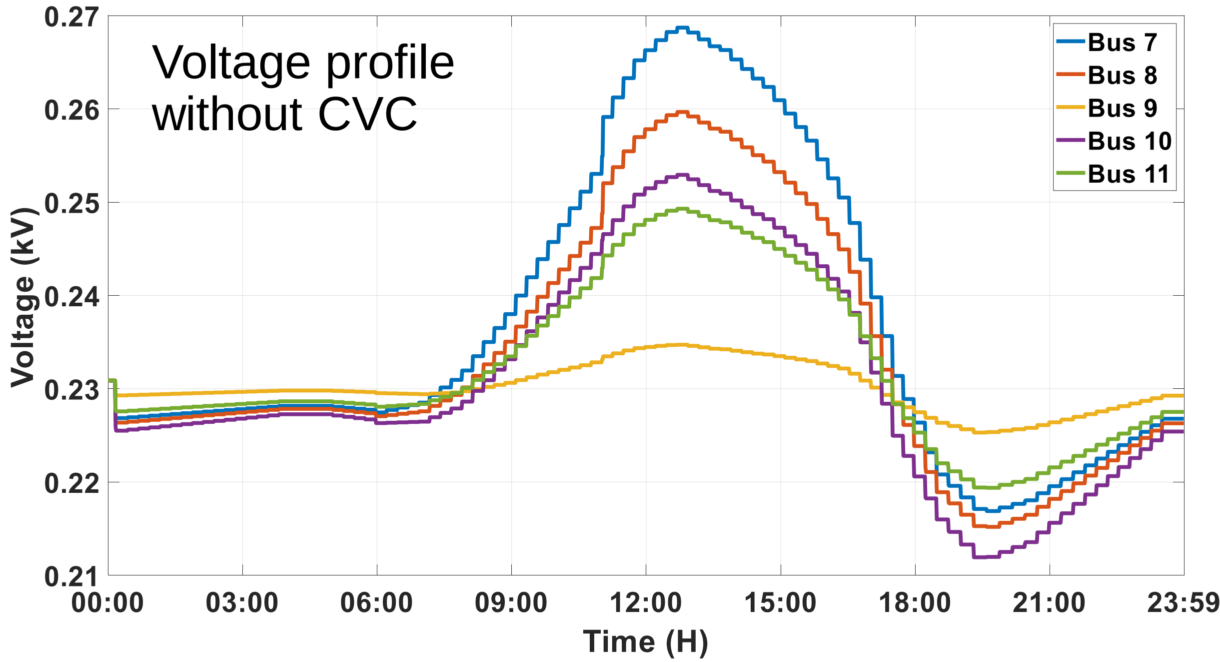
# Coordinated Voltage Control (CVC)

The distribution network experiences overvoltage's due to the feed-in from PV installations across the length of the feeder.

CVC implemented coordinates the on load tap changer (OLTC), the battery energy storage system (BESS) and the capability of PV inverters to control reactive power.

Distribution Network

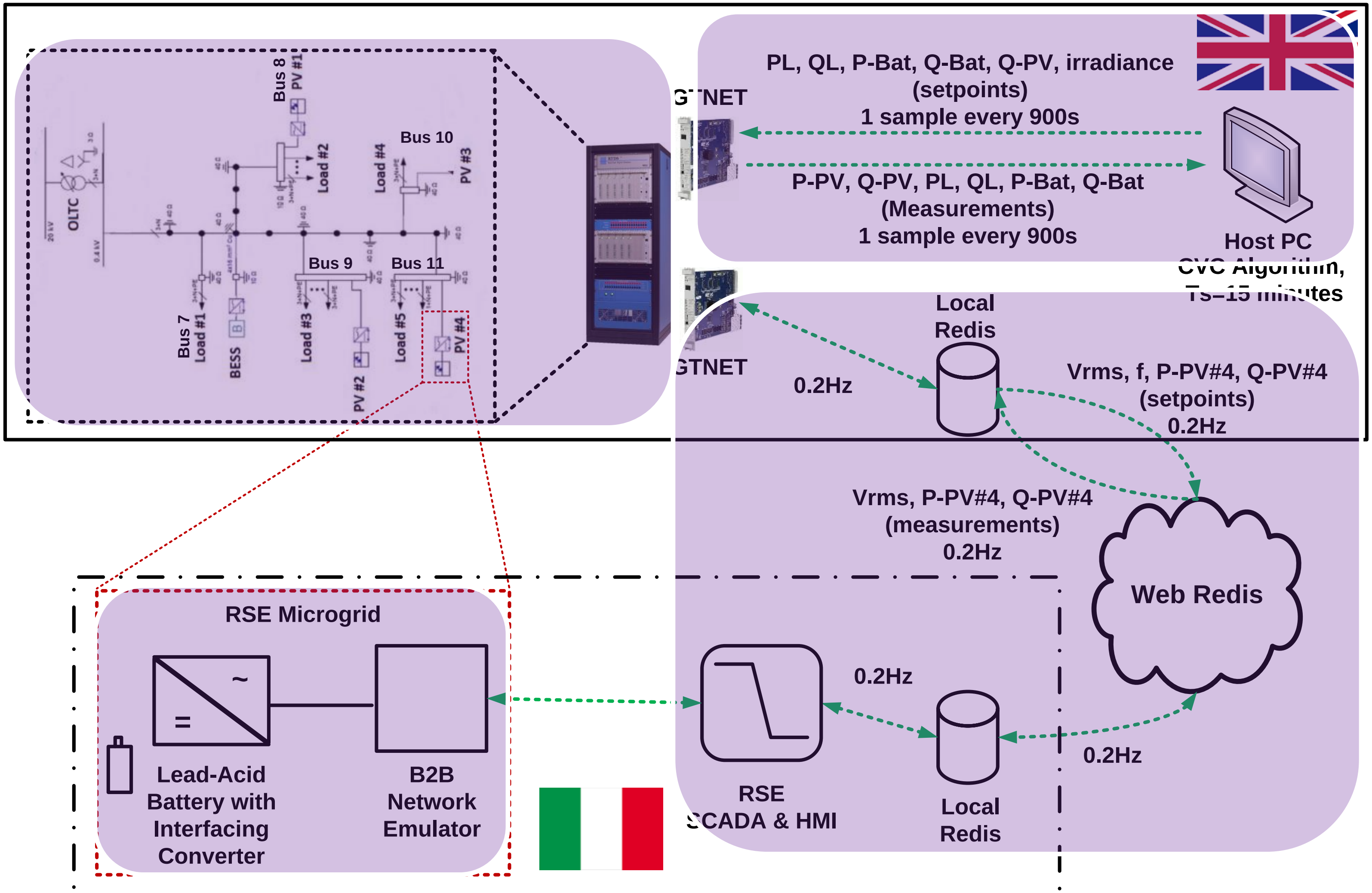




EU H2020 Programme GA No. 654113

# Controller and Power Hardware in the Loop Experimental Setup

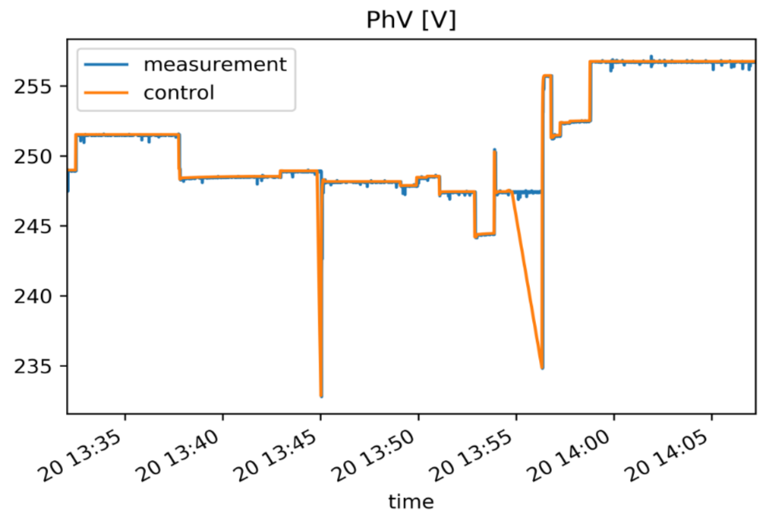


# Staged Validation Approach

Exchange of real time data between partner institutions using JaNDER

Remote HIL coupling between Research Infrastructures

Testing of Coordinated Voltage Control (CVC) Algorithm



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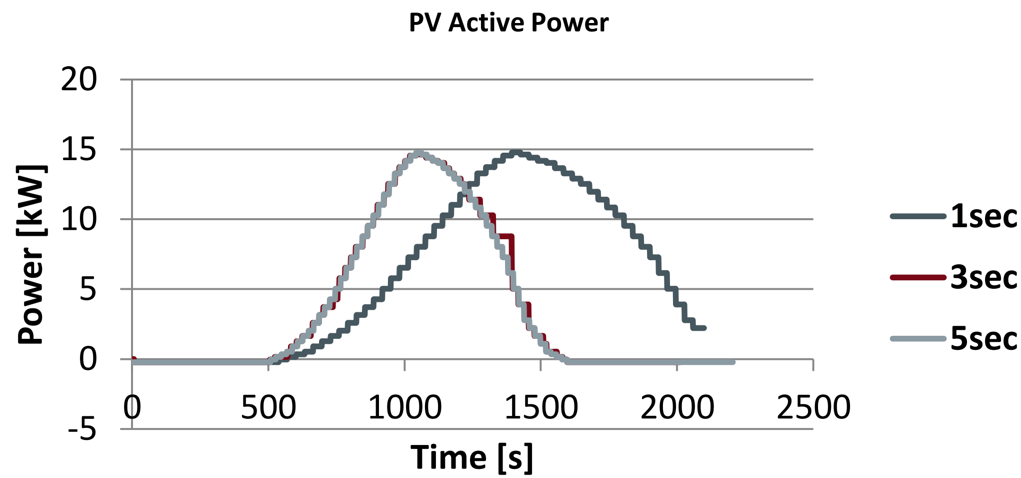
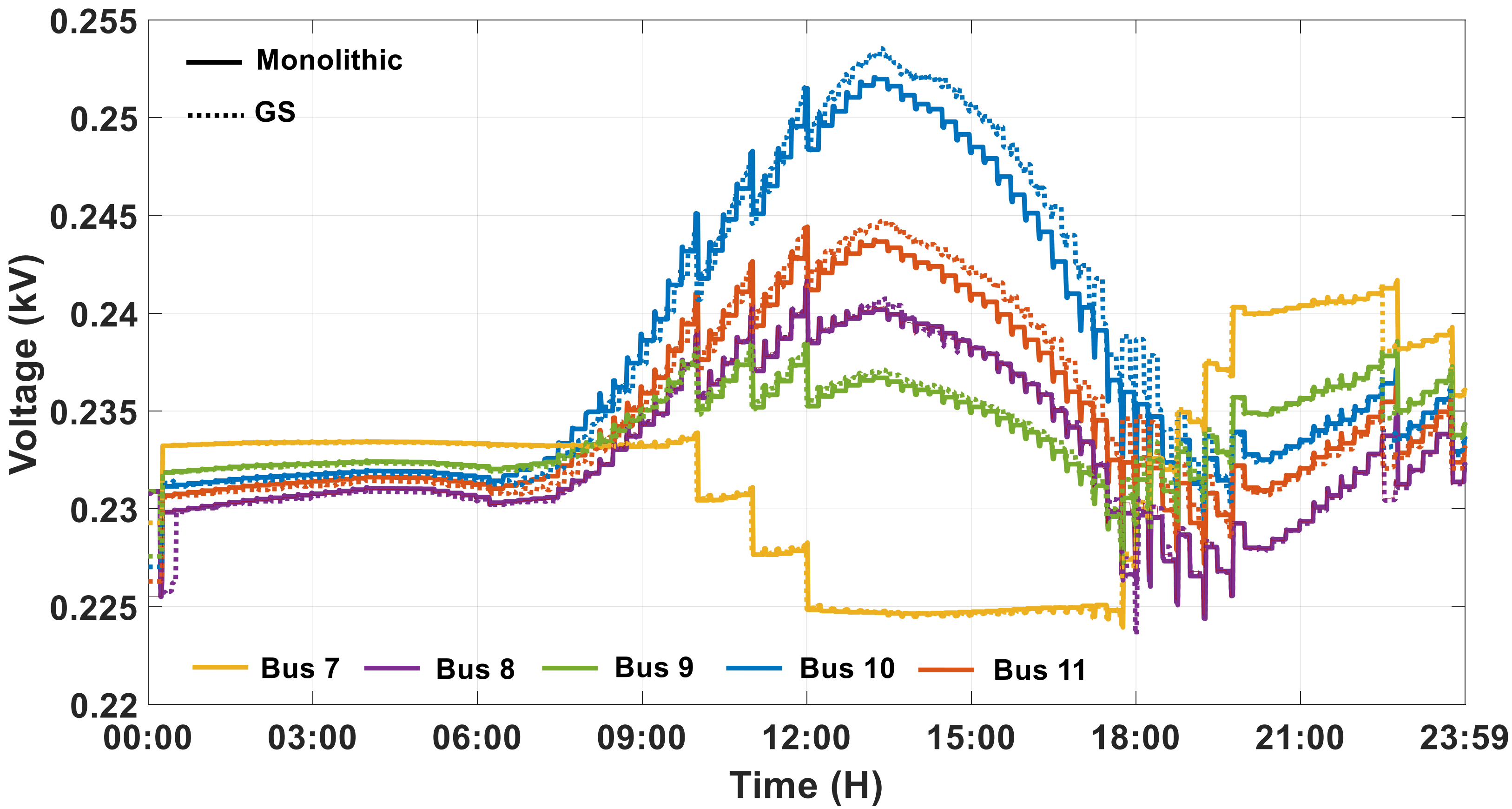
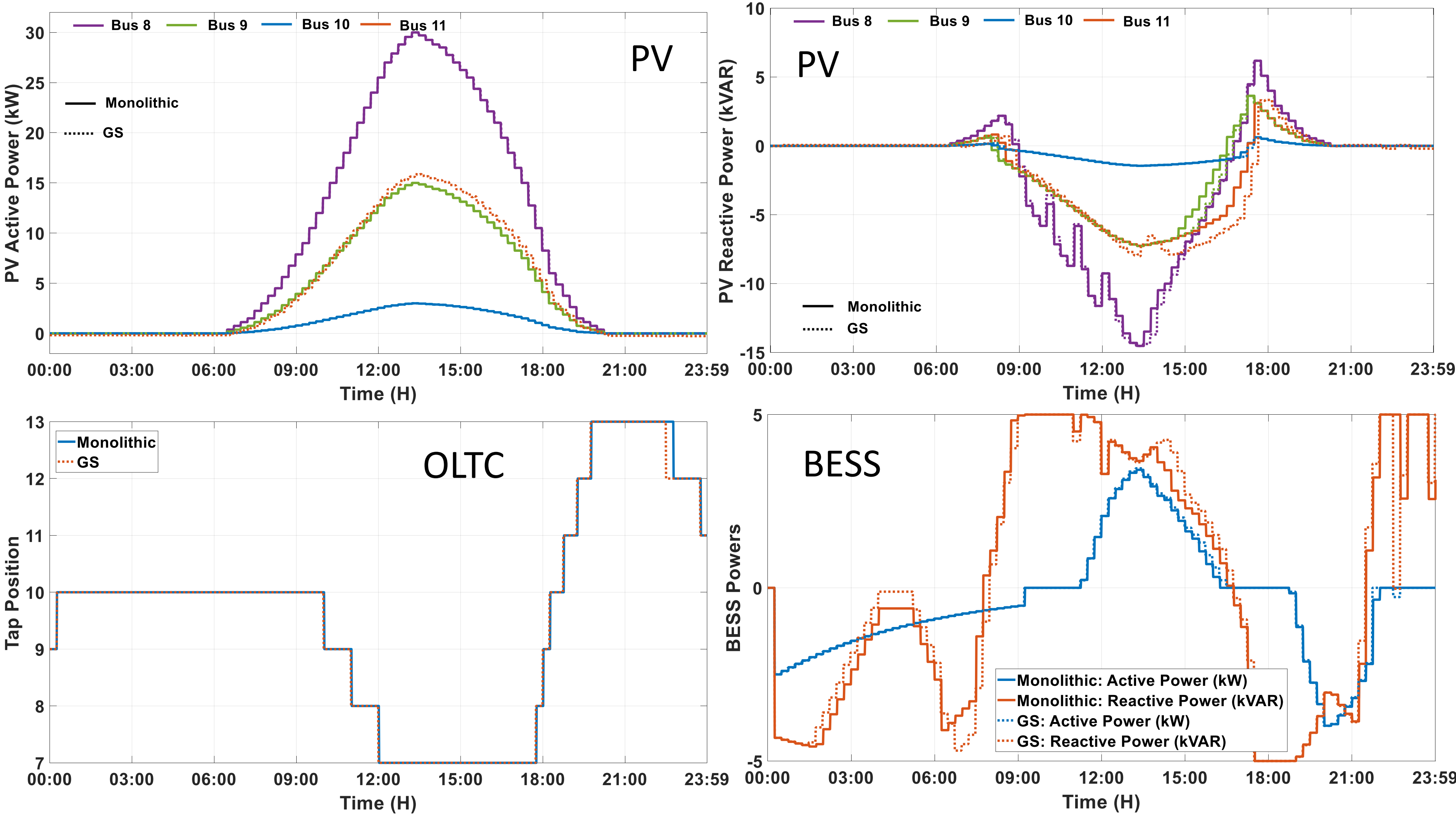


# Voltage Profile with CVC



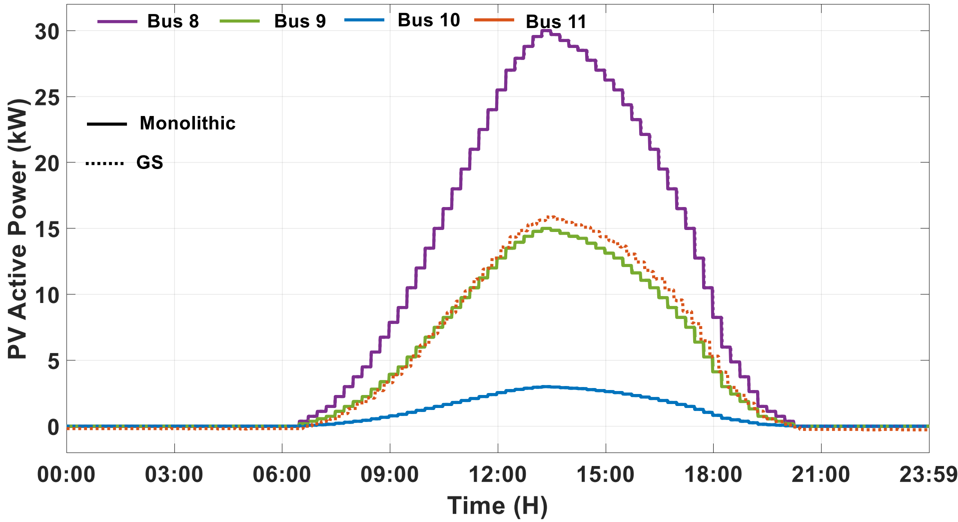

- CVC regulates the voltage as desired.
- An obvious discrepancy between the monolithic and geographically separated approach.

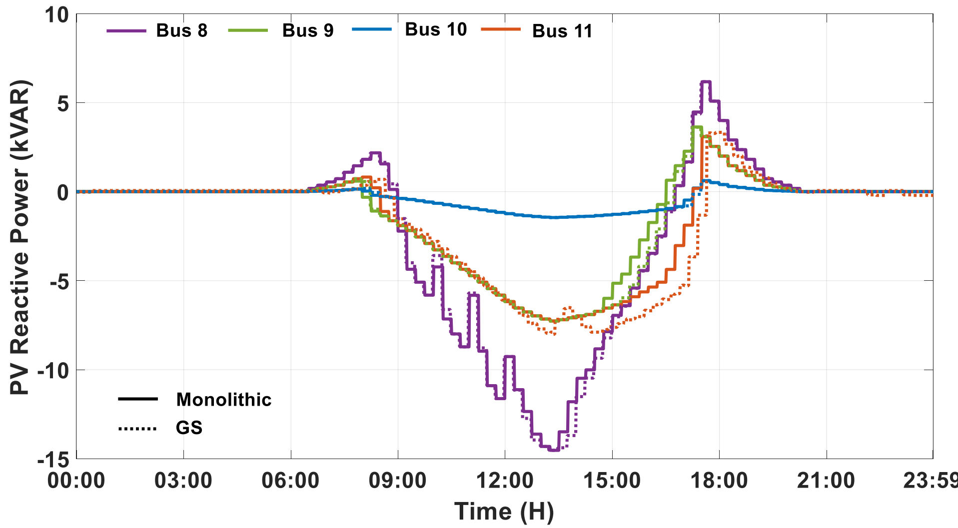
# CVC Participating Devices



# Lessons learnt

- Some discrepancies are expected while others can be minimized.
- Immediate Improvements:
  - Higher update rates help reduce the delay in response observed
  - Asynchronous update at every interface to avoid data queuing
  - An orchestrator to facilitate data exchange
  - Feed forward time delay compensating control implementation.



# Conclusions and Outlook

- The feasibility of geographically separated Ris coupled over internet to undertake voltage control study for a power distribution network has been demonstrated.
- The approach promises a number of discrete benefits that are timely and relevant to the needs of the modern power system.
- A more rigorous understanding of the errors is required.

- The future objective is to move towards a unified architecture for geagraphically separated simulations/experiments
- Technical challenges of the approach offer interesting research directions.