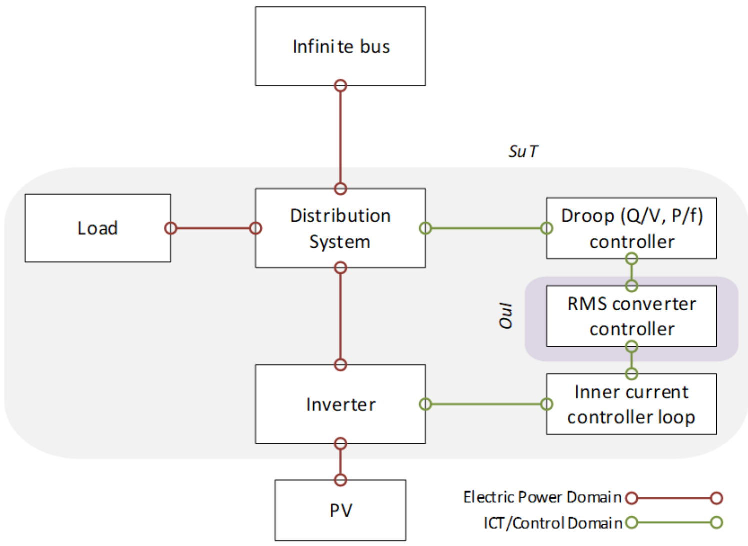
Name of the Test Case	**TC.S.1** Component testing at different RIs with different set-up
Narrative	This test case aims at demonstrating the potential of a multi-site testing chain with varied testbeds for generating systematic improvements on the performance of a converter control function. The approach is to carry out a first set of experiments aimed at characterizing the influence of both control and test system parameters on the control performance. Based on the gathered knowledge, the control system is improved, and the improvements are validated in a second round of experiments. A converter control system is typically 3-layered: outer droop control (measuring RMS voltage and frequency, setting P/Q setpoints) , an intermediate RMS controller (receiving P/Q setpoints and setting d/q axis current setpoints), and an inner current control loop realizing the d/q axis currents. The approach is to test the execution of an experiment in four different software-hardware combination approaches. For that, the P-f and Q-V droop control of a converter controller is characterized through a four experiments testing chain, which results are later compared in this document. An expected outcome from this test case is a repeatable procedure (the structured testing chain). Further by implementing each step of a structured testing chain across the different experiment setups the contribution (value) of each testbed will be clearly demonstrated.
Function(s) under Investigation (*FuI*) “the referenced specification of a function realized (operationalized) by the object under investigation”	Converter RMS controller (receiving P/Q setpoints and setting d/q axis current setpoints)
Object under Investigation (*OuI*) "the component(s) (1..n) that are to be qualified by the test”	Converter RMS controller subsystem
Domain under Investigation (*DuI*): “the relevant domains or sub-domains of test parameters and connectivity.”	Electric power domain Control domain
Purpose of Investigation *(PoI)* formulation of the test purpose in terms of Characterization,	**PoI#1:** Characterization of converter controller influence of the system performance. (Fine tuning of models using results of hardware tests) (System PoI).

Verification, or Validation	• **PoI#1.1** Characterize converter controller model in simulated environment. Controller model tuning to match the responses observed in the other three tests. • **PoI#1.2** Characterize converter controller hardware in simulated environment. Controller tested under highly dynamic and transient power system phenomena under real-time constraints. Stability of controller under grid frequency and voltage disturbances induced by the variability attribute (i.e., variable load) • **PoI#1.3** Characterize interaction converter controller hardware with physical P and Q source. Testing the capability of the converter controller to regulate the P and Q outputs of the source hardware in full power without the restriction of stability challenges coming from closed loop systems. Wider range and higher dynamics (variation in load) be tested in full power. • **PoI#1.4** Characterize stability of converter controller hardware in closed loop full power setting. Testing stability of converter controller under harmonic disturbances in the system. **PoI#2:** Validation of model exchange among RIs. **PoI#3:** Validate improved control system performance.
System under Test (*SuT*): A list of systems, subsystems, components included in the test case or test setup.	The test system includes: distribution system (grid), converter controller, load, inverter. There will not be external environmental variables. However, the only external interaction will be voltage at the PCC connecting the distribution grid with the mains. 
Functions under Test (*FuT*) Functions relevant to the operation of the system under test, including FuI and relevant interactions btw. OuI and SuT..	Converter Q/V and P/f controller algorithm, inner current controller, a low voltage distribution grid connecting five loads, four PV and a battery.

Test criteria: "the measures of satisfaction that a need to be evaluated for a given test to be considered successful. Formalization of the PoI wrt. SuT and FuT attributes.	Settling time, overshoot, damping factor and peak time for a step response after step changes of PV output and the load connected with the PV.
target metrics (test factors): A numbered list of measures to quantify each identified Purpose of Investigation	Limit overshoot, settling time, damping factor and peak time of voltage and PV active power output to the 'acceptable' level.
variability attributes identification of the sets of attributes (controllable or uncontrollable parameters) and qualification of the required variability; includes reference to purpose of investigation.	1. Variable load to create frequency and voltage variation. 2. Steps in the generation coming from the PV sources of the grid
quality attributes (thresholds): reference to PoI and target metrics, the threshold level required to pass a test and precision level.	---

- **Qualification Strategy**

i.e. how are the PoI to be met by the different tests and how will the test results be combined to yield the desired PoI outcomes (see guideline)

The objective is to characterize outerloop RMS converter controller using the specific capabilities of four implementation methods. Fulfilling the general objective, the individual implementations will contribute with specific information about the capability of the controller. The four implementations have specific purposes of investigations.

- Implement a test case in four implementations and verify the applicability of the test case specification. (i.e. verify information in the template is enough for all the four implementations. If not, document results) [PoI#1.1]
- Characterize converter controller and document controller improvement opportunities comparing the implementations of CHIL, HIL and PHIL with the pure simulation results. [PoI#1.2]
- Validate the possibility of exchange of converter controller model documenting the required compatibility adjustments and tuning needed during the four implementation phases. [PoI#1.3]
- Characterization of the results of the four implementations of similar test case for its comparability. Issues such as time step differences. [PoI#1.4]

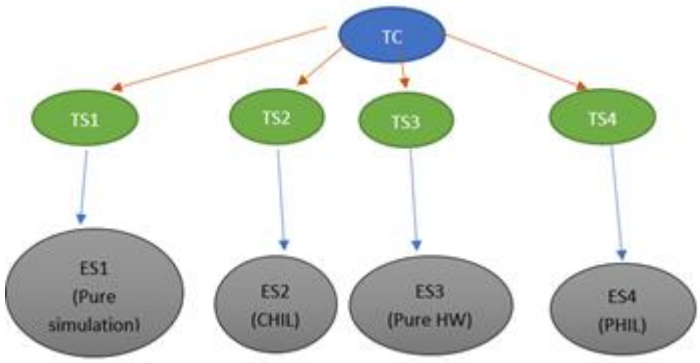
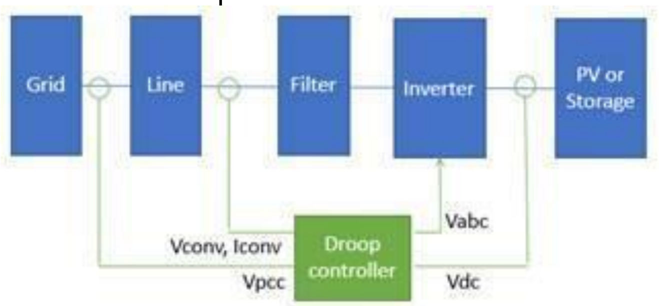


Figure 1. Graphical representation of the qualification strategy

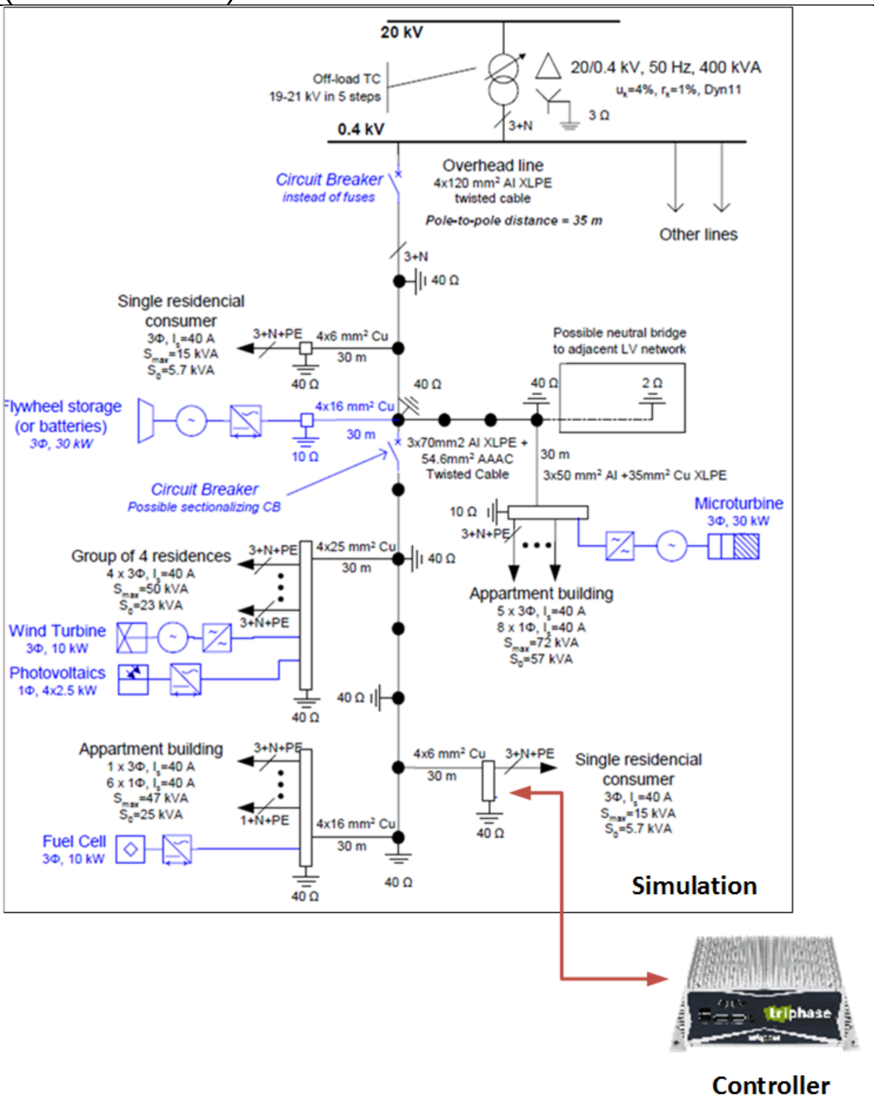
Test Specification TS.1

Reference to Test Case	**TS1:** TESTBED-PoI1.1
Title of Test	Characterize and tune converter controller parameters in purely simulated environment.
Test Rationale	This test corresponds to the **PoI#1.1**. *The flexibility and speed of performing simulated environment experiments is used to perform an initial tuning and characterization of the controller. The power grid, converter and load are integrated as models in simulation software. This test will provide a reference for the implementations of the other tests, and will be improved using this other tests results for validation purposes.*
Specific Test System (graphical)	It includes a distribution grid, the inverters connected to a PV or a storage system and the inverter droop controllers. 
Target measures	The target measures are the ones that allow characterizing the droop curves of the controller: 1. ΔP/Δf 2. ΔQ/ ΔV The following KPIs are used to characterize the behavior of the controller: 1. Settling time (ST) to 2% of final value. 2. Overshoot (%): $$\boxed{OS(\%) = \frac{V_{peak} - Vss}{Vss}\ 100}$$ 1. Time of peak (Tp) 2. Damping factor (ϑ): $$\boxed{\vartheta = \frac{\ln(\frac{OS}{100})}{\sqrt{\pi + \ln^2(\frac{OS}{100})}} \qquad \begin{cases} \vartheta < 1 & Underdamped \\ \vartheta = 1 & Critically\ damped \\ \vartheta > 1 & Overdamped \end{cases}}$$

Input and output parameters	<u>Input:</u> 1. Loads Profile 2. PV (Generator) Profiles <u>Output:</u> 1. Active power from inverter 2. Reactive power from inverter 3. Grid voltage measurement
Test Design	1. Simulink as simulation environment.Development of the models of all the elements involved in the test system. 2. System setup definition and static parameters selection: Selection of the initial load connectivity and the parameters (impedance of the line segment). 3. Definition and initialization of controllable/uncontrollable parameters (Droop controller curves, PV profile, temperature, irradiance, storage state of charge, temperature…) 4. Selection of test duration: in this case, test duration is not very relevant, as it is a quasi-static analysis. 5. Selection of system disturbances: load or generation variation significant enough to cause a P/Q change by the inverter 6. Start the simulation and data recording. 7. Test termination: The test is terminated after the specified time and the results are stored for post processing. 8. If needed, refine the setup and parameters and repeat the test How will the variables (load...) change? Why (motive, test sequence, decision criteria, controlled parameters, ranges and variations, etc)?
Initial system state	All required models and predefined initial set points are known, and they have been agreed and tested separately in advance. Also, a base case is used to initialize the models through a load flow. The distribution network has a nominal voltage and frequency (400V, 50Hz), and the test system has reached the steady state before applying the perturbations.
Evolution of system state and test signals	Once the steady state has been reached, the predefined perturbations can be applied to the test system to achieve frequency and voltage changes: • load profile. • PV power profile. Ideally, the perturbation will be kept constant untill the system reaches a steady state.
Other parameters	
Temporal resolution	A discrete simulation was performed with a time step of 0.1 ms. The temporal resolution is not critical because the aim of the test is the characterization of the droop controller in a simulated environment, where the final value of controller outputs is more relevant than the transient value. Moreover, the temporal resolution of the simulation software is enough to the test.
Source of uncertainty	Accuracy of the models used in the simulation

Suspension criteria / Stopping criteria	<u>Stopping criteria:</u> • Reach to the predefined end of simulation <u>Suspension criteria</u> • Reach to the system limits If stable operation has not been reached after predefined end of simulation

- **Test Specification TS.2**

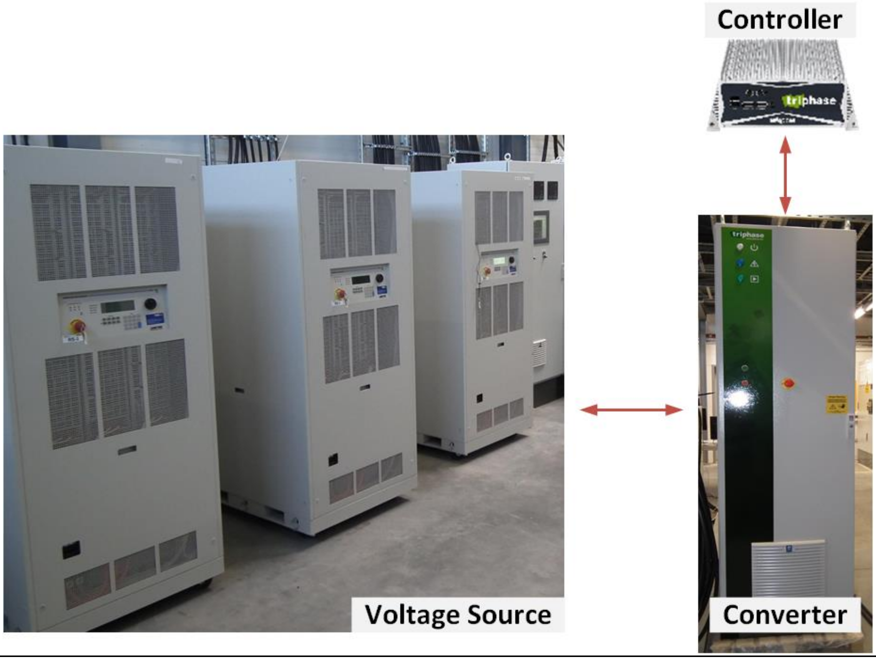
<table>
<tr><td>Reference to Test Case</td><td>TS2: TESTBED-PoI1.2</td></tr>
<tr><td>Title of Test</td><td>Droop converter controller behavior in realistic network cases</td></tr>
<tr><td>Test Rationale</td><td>TESTBED-PoI1.2 Characterize converter controller hardware in simulated environment. Controller tested under highly dynamic and transient power system phenomena under real-time constraints. Stability of controller under grid frequency and voltage disturbances induced by the variability attribute (i.e. variable load).</td></tr>
<tr><td>Specific Test System
(graphical)</td><td>


</td></tr>
<tr><td>Target measures</td><td>The target measures are the ones that allow characterizing the droop curves of the controller:
1. ΔP/Δf
2. ΔQ/ ΔV</td></tr>
</table>

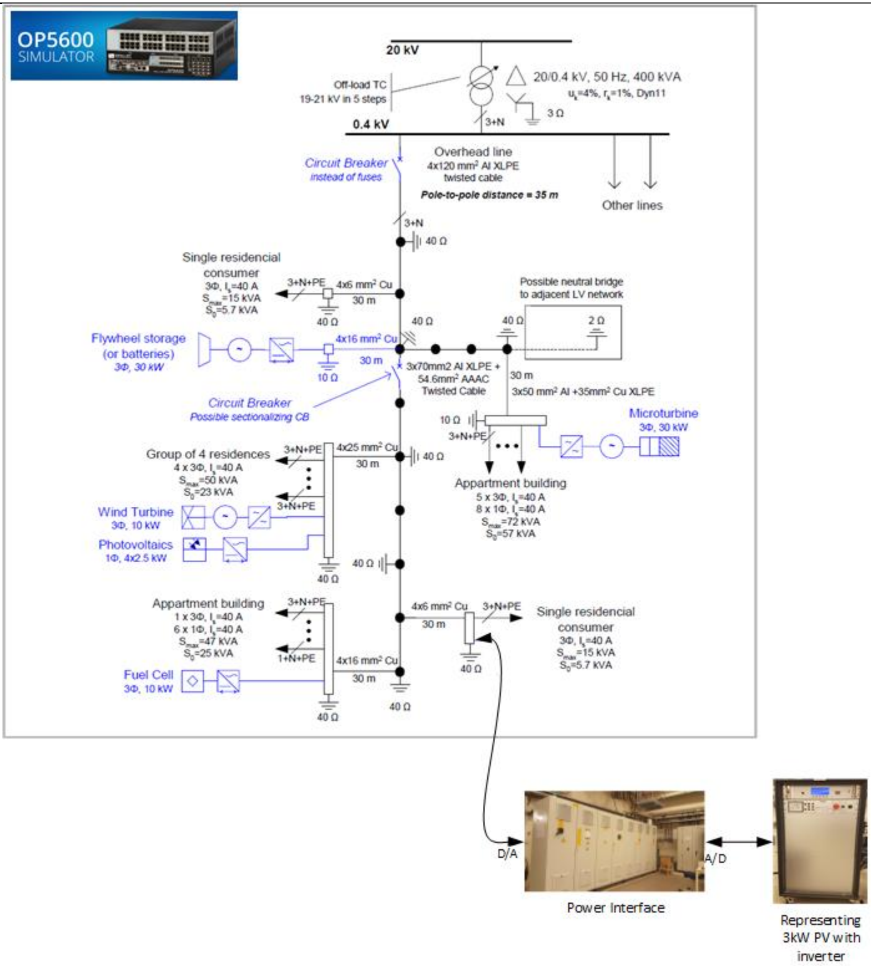
Input and output parameters	Input: Voltage and frequency references Output: Q and P values from converter
Test Design	The test design includes the following steps: 1. Selection of test duration: in this case, test duration is not very relevant, as it is a quasi-static analysis. 2. Selection of system disturbances: load variation or frequency disturbance significant enough to cause a P/Q change by the inverter 3. Start the simulation and data recording. 4. Test termination: The test is terminated after the specified time and the results are stored for post processing. 5. If needed, refine the setup and parameters and repeat the test
Initial system state	All required models and predefined initial set points are known, and they have been agreed and tested separately in advance. Also, a base case is used to initialize the models through a load flow. **Distribution network has nominal voltage and frequency (400V, 50Hz), and the test system has reached the steady state before applying the perturbations.** **The controller is running steady state.**
Evolution of system state and test signals	Once the steady state has been reached, the predefined perturbations can be applied to the test system to achieve frequency and voltage changes: • load profile. • PV power profile.
Other parameters	----
Temporal resolution	The network model will be running in discrete mode and in real-time to exchange real signals between the Real-Time Simulation and the controller hardware device. The resolution of the network simulation will be executed with a 50µs step size
Source of uncertainty	No critical uncertainties are foreseen. General uncertainties can be the inaccuracy of data exchange between the controller and simulation.
Suspension criteria / Stopping criteria	<u>Stopping criteria:</u> • Reach to the predefined end of simulation <u>Suspension criteria</u> • Reach to the system limits If stable operation has not been reached after predefined end of simulation

- **Test Specification TS.3**

Reference to Test Case	**TS3:** TESTBED-PoI1.3
Title of Test	Validation of characterization and behavior of droop control algorithm and power converter
Test Rational	TESTBED-PoI1.3 Characterize interaction converter controller hardware with physical P and Q source. Testing the capability of the converter controller to regulate the P and Q outputs of the source hardware in full power without the restriction of stability challenges coming from closed loop systems. Wider range and higher dynamics (variation in load) be tested in full power.

Specific Test System (graphical)	
Target measures	The target measures are the ones that allow characterizing the droop curves of the controller: 1. ΔP/Δf 2. ΔQ/ ΔV
Input and output parameters	Voltage Source <-> converter: • Voltage and frequency Converter <-> Controller: • Q and P values
Test Design	Step1: Steady State Test running with nominal voltage and frequency Step2: Voltage variation Several voltage ramps and steps will be performed Step3: Frequency variation Several frequency ramps and steps will be performed
Initial system state	Distribution network is represented by a voltage source with nominal voltage and frequency (400V, 50Hz), and the test system has reached the steady state before applying the perturbations. The controller is running steady state.
Evolution of system state and test signals	Once the steady state has been reached, the predefined perturbations can be applied to the test system to achieve frequency and voltage changes: • Voltage variation • Frequency variation
Other parameters	----
Temporal resolution	----
Source of uncertainty	General uncertainties can be the inaccuracy of data exchange between the controller and the power converter, as well as inaccuracies of the internal measurement system of the converter.
Suspension criteria / Stopping criteria	Stopping criteria: • Reach to the predefined end of the test Suspension criteria • Reach to the system limits If stable operation has not been reached after predefined end of test

- **Test Specification TS.4**

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 setting. 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 Output: Q and P values from converter
Test Design	**Step#1**: Run the test for the base case scenario with normal loading scenario **Step#2**: Run the test for variable load and PV output and record the change in voltage **Step#3**: Introduce harmonics at the PCC point and check if the converter controller will filter it out.
Initial system state	
Evolution of system state	

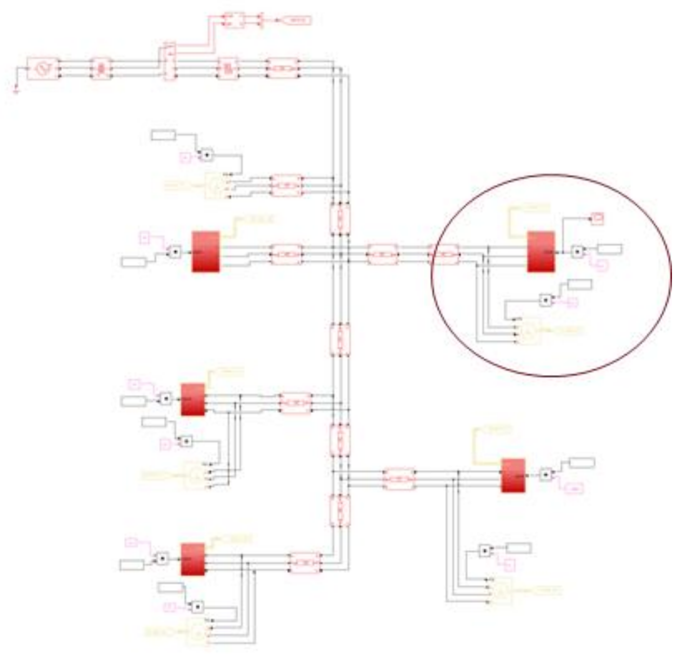
and test signals	
Other parameters	
Temporal resolution	120 µSec
Source of uncertainty	Sources of unstable system can be from the controller or from the PHIL setup itself. Needs careful baselining.
Suspension criteria / Stopping criteria	

Mapping Strategy

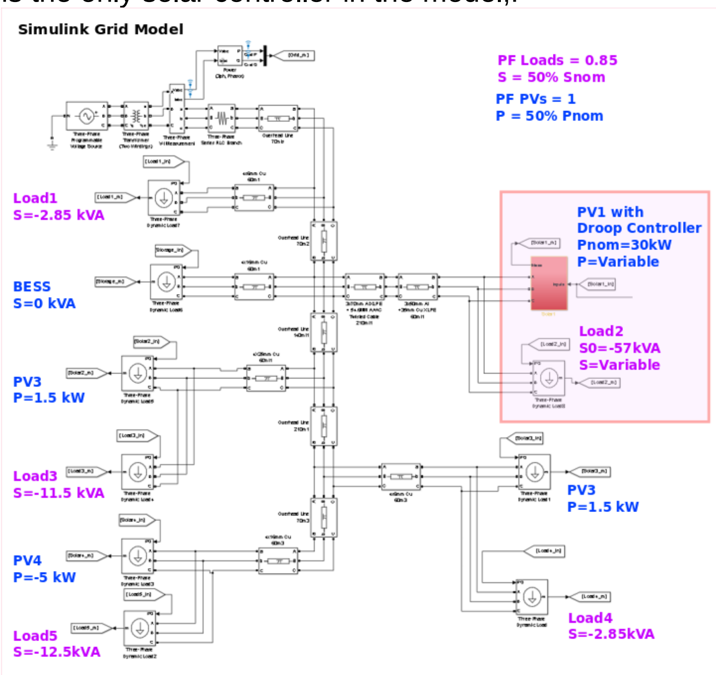
i.e. how is it planned to distribute (map) and execute the specified test (from test specification) in different RIs? (free text)

- **Experiement specification TC.S.1_1.1a**

Reference to Test Specification	Test Specification TS.1 Characterize and tune converter controller in simulated environment
Title of Experiment	Pure simulation droop controller test
Research Infrastructure	TEC
Experiment Realisation	Step 1. Integration of the controller as part of the PV model in the CIGRE MV Grid Step 2: Implementation of three different "reference disturbances" to the grid in stable initial conditions with reference profiles considered as inputs for the system: D1: Step in P generated by PV1 D2: Step in active power P of Load 2 D3: Step in reactive power Q of Load 2 Step 3; Test recording of measurements of interest: P and Q response of the controller, V and f in the grid at the connection point. Step 4: Calculation of the KPIs (Test Criteria) and validation of the test

Experiment Setup (concrete lab equipment)	 The converter controller has been integrated as belonging to the PV panel, while the rest of panels and the Battery Energy Storage System (BESS) have been modeled as dynamic PQ-controlled loads
Experimental Design and Justification	The CIGRE MV benchmark is a widely known test grid. However, it only have static data that does not allow the testing and comparison to a reference when testing dynamic controls. Due to this, common PQ load patterns as well as generation profiles have been settled for standarizing the test conditions between different RIs and thus allowing a comparative validation of results. For the single validation of the controller, two additional test setups have been considered in TECNALIA: the test of the controller only linked to the mains (avoiding the interaction with other dynamics that could mask the behaviour of the controller itself) and the test of multiple controllers integrated in the grid (to evaluate the dynamic response of the controller when acting in presence of other controllers). These tests are undoubtedly useful for tuning the parameters of the controller. However, for sake of comparison with the foreseen CHIL/PHIL implementation, the Experimental Setup abovementioned has been selected as reference setup for the TS.
Precision of equipment	N/A
Uncertainty measurement	Associated to the models
Storage of data	Matlab workspace

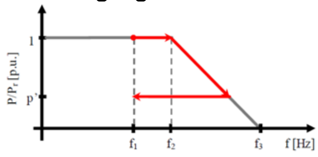
- **Experiement specification TC.S.1_1.1b**

Reference to Test Specification	Test Specification TS.1
Title of Experiment	Pure simulation droop controller test
Research Infrastructure	OFFIS
Experiment Realisation	As a pure simulation test, it was fully implemented in a Matlab Simulink model. Simulink was used because it offers the possibility of exporting afterwards the model to other equipment and perform experiments with hardware. The model consists in a modified version of the benchmark CIGRES LV Microgrid Network. The modifications correspond to the grid used by [Montoya, et al, Asynchronous Integration of a Real-Time Simulator to a Geographically Distributed Controller through a Co-Simulation Environment] and included the doubling of line distances, the substitution of all Distributed Energy Resources by PVs and a Battery Energy Storage System, using a three-phase network. An OLTC transformer was not included.
Experiment Setup (concrete lab equipment)	The experiment consisted in the simulation of a grid modelled in Matlab Simulink. The droop controller to characterize operates in PV1 Inverter and is the only solar controller in the model,: 

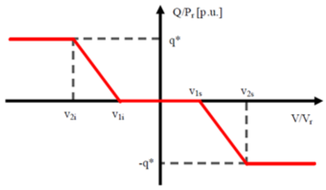
Experimental Design and Justification	

To see directly the effects of changing parameters in the system, only active and reactive power profiles of Load2 (the closest load) and PV1 inputs are varied.
The function of the droop controller was analysed in order to define the simulation cases. The function correspond to the P/f and Q/V parameters as defined by Italian standards for DGs connected to the low voltage (LV) distribution system, as in the following figure:

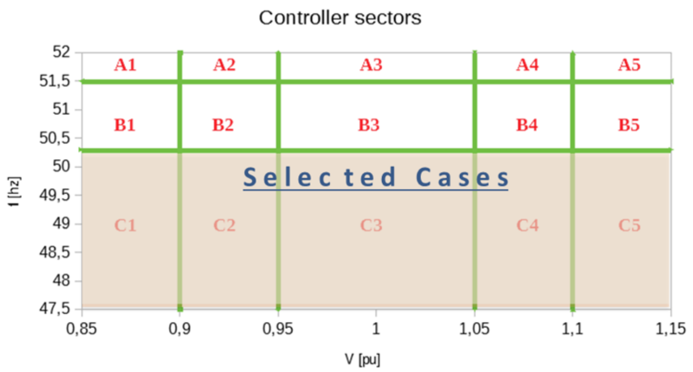
$$P_{ref} = \begin{cases} 1 & f \leq 50.3 \\ -0.833 * f + 42.915 & 50.3 \leq f < 51.5 \\ 0 & f > 51.5 \end{cases}$$



$$Q_{ref} = \begin{cases} 0.4843 & V < 0.9 \\ -9.686 * V + 9.2 & 0.9 \leq V < 0.95 \\ 0 & 0.95 \leq V < 1.05 \\ -9.686 * V + 10.17 & 1.05 \leq V < 1.10 \\ -0.4843 & V \geq 1.10 \end{cases}$$



The main interest is to characterize the effect of the controller in voltage and frequency at the connection point. The model includes a swing three-phase programmable voltage source, which represents a highly reliable main grid, which has a good reaction to frequency stability. In consequence, the selected cases are representative of the voltage increase and drop in the connection point, as seen in the following figure.



An iterative process was implemented in order to identify the values of the parameters that make the system reach a steady state corresponding to each of the selected cases. The values varied in this iterative process was Load 2 P&Q, with a PF of 0.85. For PV1 P, two constant cases were used: 15 kW and 30 kW (P max).
All other loads and DER inputs were modelled as three-phase dynamic loads, with constant input values corresponding to 50% of their aggregated nominal value according to the grid definition in [Papathanassiou, et al, A BENCHMARK LOW VOLTAGE MICROGRID NETWORK]. DER were implemented with a PF of 1 and a negative sign for power generation, and as suggested in the previous paper, Loads where implemented with a PF of 0.85 and a positive sign for power consumption. The values are indicated in the experimental setup figure.
Finally, a case without controller was implemented.

Precision of equipment	According to the model and Simulink. The time step utilized was of 0.1 ms
Uncertainty measurement	N/A
Storage of data	Matlab and Simulink files. Output plots and tables.

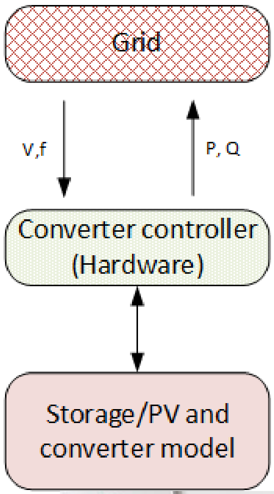
- **Experiment specification TC.S.1_1.2**

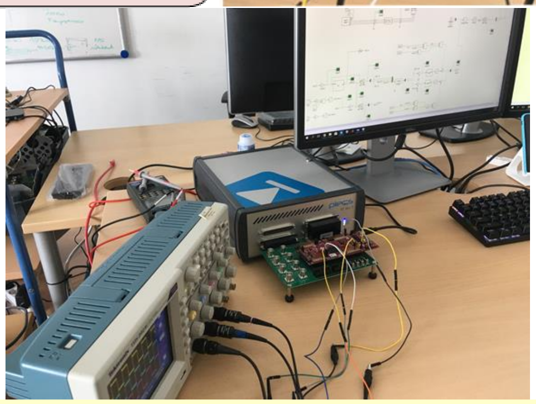
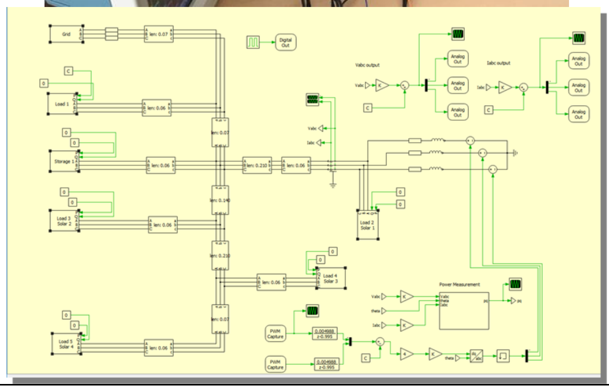
Reference to Test Specification	Test Specification TS.2
Title of Experiment	CHIL droop controller test
Research Infrastructure	IEE and AIT
Experiment Realisation	The experiment is realized in Controller Hardware- in-the-Loop (CHIL) setup. The grid (CIGRE LV network model) is emulated in real-time and the real converter controller is connected to the simulator.

<table>
<tr>
<td>Experiment Setup
(concrete lab equipment)</td>
<td>
In the following the CHIL setup at AIT is described; it contains the following elements:

PLECS-RT Box – runs a simplified(*) model of the CIGRE LV grid with time step Ts = 50µs
(*) cable models are reduced to simple RL impedances (mutual coupling between phases is not considered)
Texas Instruments C2000 F28379D LaunchPad control card

the RMS controller is deployed as C code to the card
Voltage and current measurements are provided via analog inputs of the control card
Voltage references are provided via the digital outputs of the control card

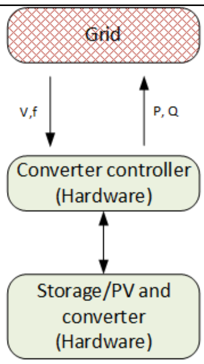


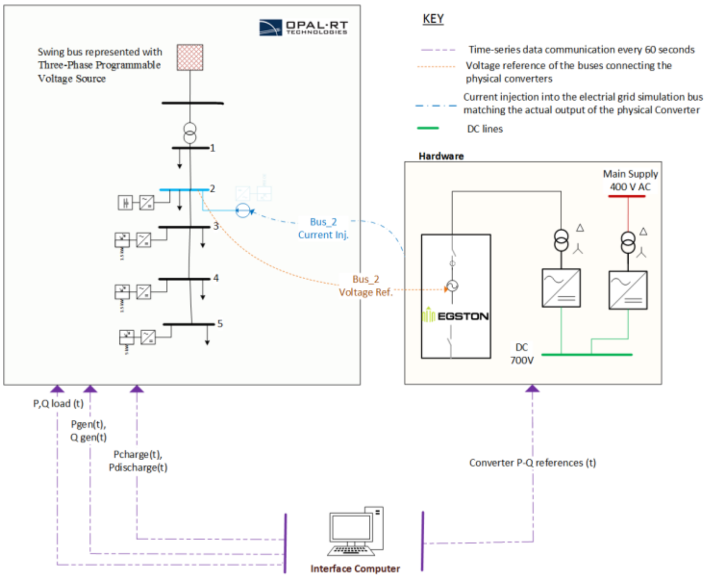



</td>
</tr>
<tr>
<td>Experimental Design and Justification</td>
<td></td>
</tr>
</table>

Precision of equipment	n/a
Uncertainty measurement	Associated to the models
Storage of data	Grid model in PLECS, controller code in C language, output plots and tables.

- **Experiment Specification TC.S.1_1.3**

Reference to Test Specification	Test Specification TS.4
Title of Experiment	PHIL test of droop controller
Research Infrastructure	SIN
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.

<table>
<tr>
<td>Experiment Setup
(concrete lab equipment)</td>
<td>


Equipment used in the network include:
• OPAL-RT platform (OP5600 5 core activated)
• A 200 kW power converter operating as a grid emulator
• A 60 kW two level converter
• Interfacing computer


</td>
</tr>
<tr>
<td>Experimental Design and Justification</td>
<td>
For testing the P-f droop characteristic:

Converter response to ramping to frequency at the source from 50 Hz to 52 Hz.

For testing the Q-V droop characteristic and dynamic behaviour of the converter:

Converter response to stepping-up PV1 output
Converter response to stepping-down of PV1 output
Converter response to stepping-up of P and Q of Load2
Converter response to stepping-down of P and Q of Load2

(For testing the PHIL stability:

Converter response to introduction of harmonic voltages in the PCC.

)
</td>
</tr>
</table>

Precision of equipment	
Uncertainty measurement	
Storage of data	RT-lab blok ‘opwriteFile’ triggered when needed and file stored in Matlab .dat file format in the model folder