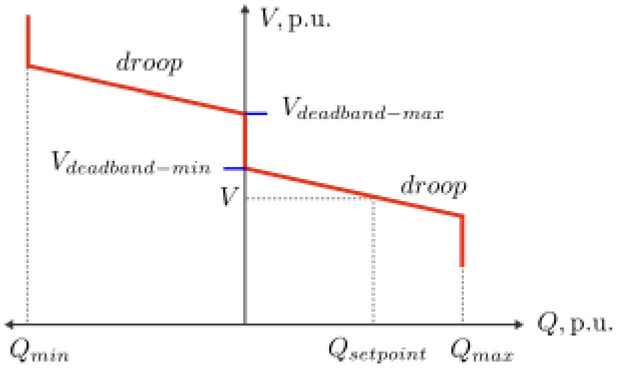
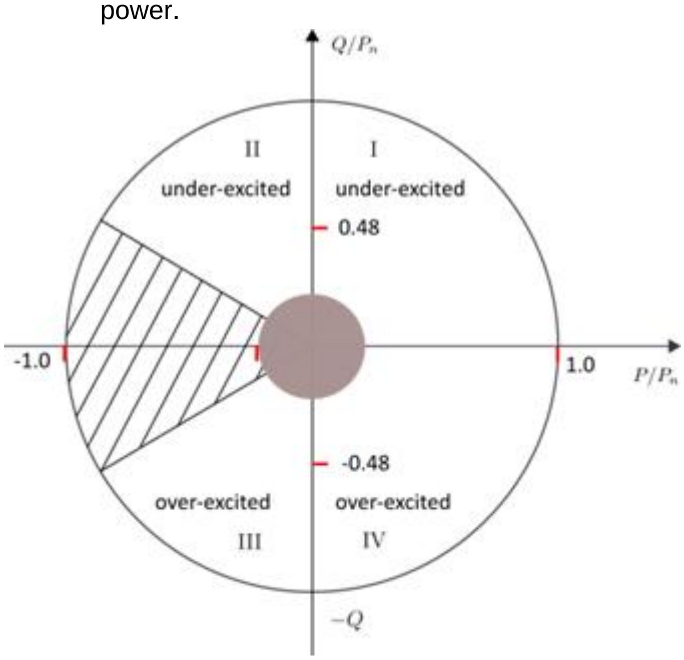
Test Case 8

Author: Tran The Hoang, Quoc Tuan Tran (CEA)
Version: 2
Project: Erigrid 2.0
Date: 01/12/2020

Name of the Test Case	Evaluation of voltage control in distribution grids
Narrative	With an ever-increasing penetration of renewable energy sources (RES), especially photovoltaic (PV systems), into distribution grids, the grid voltage may fluctuate in unacceptable ranges. The level of voltage fluctuation depends on grid topology, different operating conditions as well as level of RES penetration. Therefore, voltage control in distribution grids has become an essential task. Indeed, effective voltage control strategies have a number of benefits: ▪ Reduce voltage fluctuation ▪ Improve quality of power supply ▪ Maximize the penetration of PV into the grid ▪ Participate in ancillary services ▪ Increase the flexibility of operation ▪ Reduce PV curtailment There are a variety of voltage control strategies for distribution grids such as centralized, decentralized, or distributed. This Test Case is proposed to evaluate the distributed voltage control for distribution grids with high integration of single- and three-phase PV systems under different operating conditions.
Function(s) under Investigation (*FuI*) “the referenced specification of a function realized (operationalized) by the object under investigation”	▪ MAS-based distributed voltage-var control ▪ Reactive power capability of PV systems and their reactive power control modes for voltage control support The amount of reactive power absorbed/injected by the PV systems can be controlled following the characteristic below (ENTSO EN 50438:2013 or ENTSO EN 50549-1:2019 *“Requirements for micro-generating plants to be connected in parallel with public low-voltage distribution networks”*):  In addition, the reactive power exchange capability of the PV systems must meet these requirements:

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

- follow a characteristic curve provided by the DSO (see 4.4) within the active factor cos ϕ = 0,90-under-excited to 0,90-over-excited when the active power output of the PV plants is more than or equal to 20 % of its nominal active power;
- not exchanging more reactive power than 10 % of the PV plant’s nominal active power when the active power output is less than 20 % of its nominal active power.

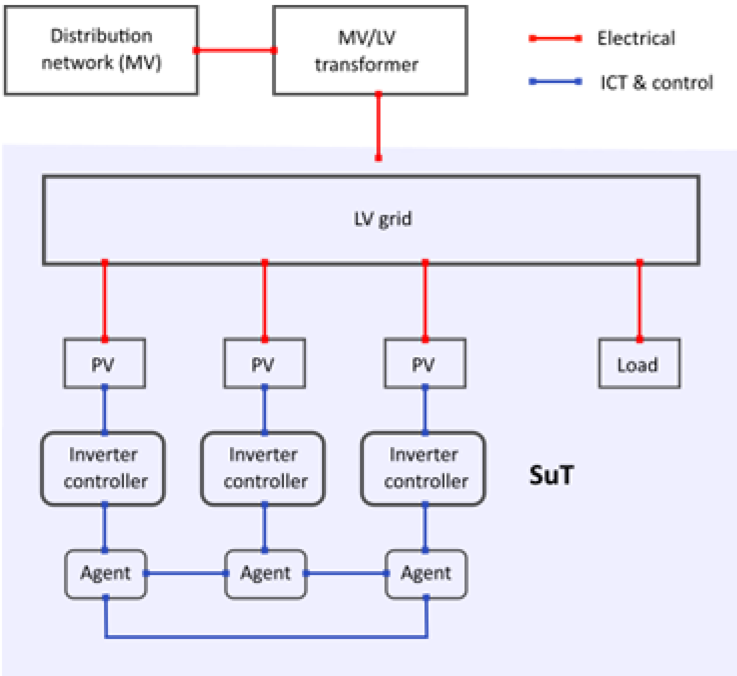


</td></tr>
<tr><td>Object under Investigation (OuI)
"the component(s) (1..n) that are to be qualified by the test”</td><td>

- Single-phase and three-phase PV inverters
- Multi-agent system (MAS)
</td></tr>
<tr><td>Domain under Investigation (DuI):
“the relevant domains or sub-domains of test parameters and connectivity.”</td><td>

- Electrical and electronic domains
- Control and ICT (time delays in sending/receiving controlling signals)
</td></tr>
<tr><td>Purpose of Investigation (PoI)
The test purpose in terms of Characterization, Verification, or Validation</td><td>

- To validate the performance of the MAS and PV systems for providing voltage control in a distributed manner
- To verify that the MAS and PV systems are able to maintain the grid voltage within the grid code requirement (±10% for LV distribution networks) under different operating conditions
</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td>System under Test (SuT):
Systems, subsystems, components included in the test case or test setup.</td><td>In the Test Case, a distribution grid with a high penetration of single-phase and three-phase PV systems is taken into consideration. Below is the single-line diagram illustrating the interaction of the main components.</td></tr>
</table>

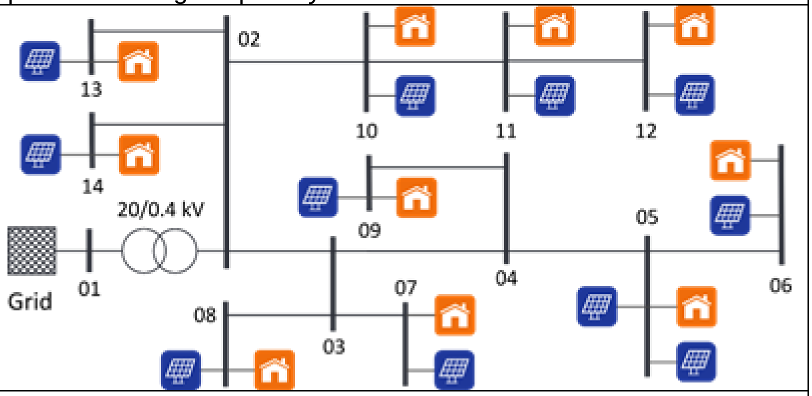
	 ▪ Single-phase and three-phase PV inverters ▪ Single-phase load and three-phase loads ▪ Multi-agent system (MAS) ▪ Communication of MAS
Functions under Test (*FuT*) Functions relevant to the operation of the system under test, including FuI and relevant interactions btw. OuI and SuT.	▪ MAS-based distributed voltage-var control ▪ Communication functionality between the agents with-in the MAS ▪ Reactive power exchange capability and reactive power control modes of PV systems
<u>Test criteria</u> *(TCR)* Formulation of criteria for each PoI based on properties of SuT; encom-passes properties of test signals and output measures.	▪ Voltage deviation must be maintained within limits (i.e., ±10% for LV networks) under different operating conditions ▪ Power losses ▪ The operating conditions of PV inverters must fulfil the protection requirements.
Target Metrics *(TM)* Measures required to quantify each identified test criteria	For PoI1: ▪ Reaction of MAS to grid voltage variation ▪ Information exchanged between agents of the MAS system ▪ Reaction of PV inverters to the controlling signals sent by their respective agents ▪ PV power characteristic according to the specifica-tions For PoI2: ▪ Voltage deviation ▪ PV curtailment ▪ Power losses

Variability Attributes *(VA)* controllable or uncontrollable factors and the required variability; ref. to PoI.	▪ Grid topology ▪ Main grid impedance ▪ PV penetration rate ▪ PV production ▪ Load consumption ▪ Influence of communication and control
Quality Attributes *(QA)* threshold levels for test result quality as well as pass/fail criteria.	▪ Voltage deviation within ±10% ▪ Reduction in power losses ▪ Increase of PV penetration

Qualification Strategy

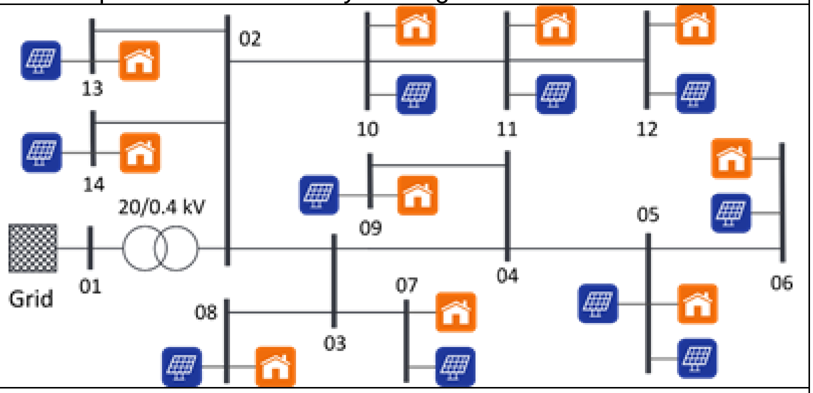
Two aforementioned PoI can be addressed by implementing two respective Test Specifications indexed TC8.TS01 and TC8.TS02. In our TC, a LV network whose topology is unchanged with realistic parameters is selected. Different input variables can be varied during the test such as PV installed capacity (or PV penetration level), solar irradiance, load consumption, communication time delay in order to evaluate the performance of the proposed distributed voltage control scheme.

Test Specification TC8.TS01

Reference to Test Case	TC8
Title of Test	Validation of the performance of a MAS and PV systems in providing grid voltage control functionality
Test Rationale	The test allows us to evaluate the ability of a MAS and PV systems to provide the functionalities of voltage control when the variation of grid voltage happens. How the agents receive measurement signals, communicate with each other, process received signals, and return the output controlling signals should be evaluated. Moreover, the performance of PV systems in responding to the controlling signals imposed by their respective agents should also be taken into account and to what extent they meet the reactive power exchange capability characteristic.
Specific Test System (graphical)	
Target measures	▪ Communication signals between agents ▪ Active and reactive power outputs of PV inverters ▪ Voltage on different nodes
Input and output parameters	<u>Input parameters:</u> ▪ PV active and reactive output powers ▪ Grid voltage ▪ Load consumption <u>Output parameters:</u> ▪ Signals exchanged between agents

	▪ PV active and reactive output powers ▪ Grid voltage
Test Design	Vary the PV output power and also load consumption until the voltage deviations at several locations in the studied grid go beyond the permissible ranges
Initial system state	Voltages at all nodes in the grids are closed to 1 p.u.
Evolution of system state and test signals	The voltages on various nodes increase or decrease as a result of the variation of PV production and load consumption
Other parameters	n/a
Temporal resolution	ms to seconds
Source of uncertainty	• Accuracy of measuring units • Communication delay
Suspension criteria / Stopping criteria	Detection of abnormal operating conditions, communication failure of MAS

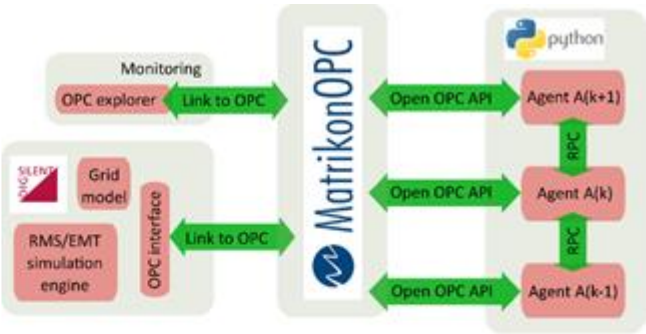
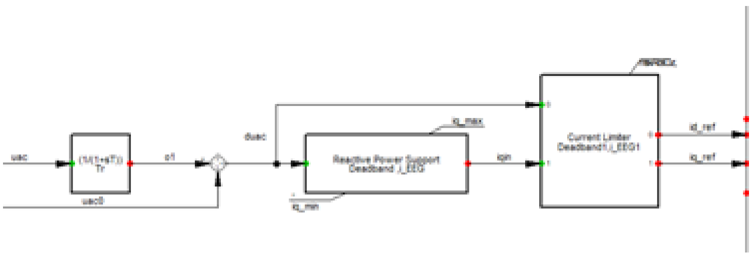
Test Specification TC8.TS02

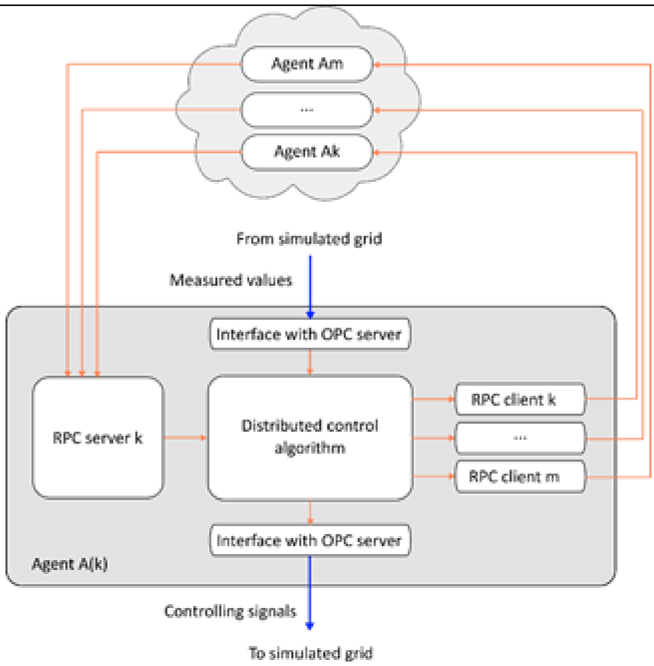
Reference to Test Case	TC8
Title of Test	Verification of the MAS-based distributed voltage control scheme in regulating the grid voltage
Test Rationale	The test is to evaluate the performance of the MAS-based distributed voltage control scheme to maintain the grid voltage within the permissible ranges imposed by the grid regulations under different operating conditions such as high PV production with light loading, low PV production with heavy loading.
Specific Test System (graphical)	
Target measures	▪ Voltage deviation ▪ PV curtailment ▪ Load curtailment ▪ Losses
Input and output parameters	<u>Input parameters</u> ▪ Grid frequency ▪ Grid voltage ▪ PV penetration level ▪ Solar irradiance ▪ Load consumption <u>Output parameters</u> ▪ Grid voltage deviation ▪ PV inverter AC terminal current and voltage (to derive PV active and reactive power outputs)
Test Design	• First, the distributed voltage control algorithm (FuT) is deactivated. PV production and load consumption are varied in order to create unacceptable voltage deviation scenarios. The patterns of PV production, load consumption and grid voltage are recorded. • Then, the FuT is activated. Repeat the variation of PV

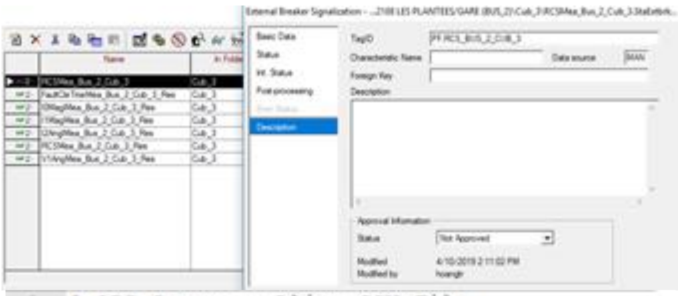
	production and load consumption according to those patterns recorded in the first step in order to evaluate the performance of the FuT.
Initial system state	• The percentage of PV penetration is 20% • The nominal grid voltage is 400 V • The nominal grid frequency is 50 Hz • PV systems are operating at most at 50% of their inverter rated powers • Load consumption is at 50% of the peak value • Communication between agents is established
Evolution of system state and test signals	Vary the load consumption and PV production according to the daily load curves and solar irradiance. In particular: • Load curves: for different types of days, for instance: ▫ Working days ▫ Weekends ▫ Holidays ▫ Summer and winter days • PV penetration ratios ▫ From 20% to 100%
Other parameters	n/a
Temporal resolution	ms to seconds
Source of uncertainty	• Accuracy of measuring units • Communication delay
Suspension criteria / Stopping criteria	Detection of abnormal operating conditions, communication failure of MAS

Mapping to Research Infrastructure

Experiment Specification TC8.TS01.ES01

Reference to Test Specification	Validation of the performance of a MAS and PV systemsin providing grid voltage control functionality
Title of Experiment	*Pure co-simulation: Validation and evaluation of the voltage control functionality of a MAS-based distributed voltage control system*
Research Infrastructure	CEA/INES (France)
Experiment Realisation	The experiments is realized by performing a co-simulation setup between PowerFactory and Python via OPC server. The MAS is developed and modelled in a Python environment. A realistic LV network with high penetration of PV systems is modelled in PowerFactory and is run in RMS mode. The PV inverter controllers are also embedded in PowerFactory. The control and measured signals that are exchanged between PowerFactory and Python are carried out via OPC server.
Experiment Setup (concrete lab equipment)	The diagram of the co-simulation setup is shown in the figure below  The PowerFactory model of PV inverter controller  Agent structure and its RPC (remote-procedure call) mechanism is presented as the following:

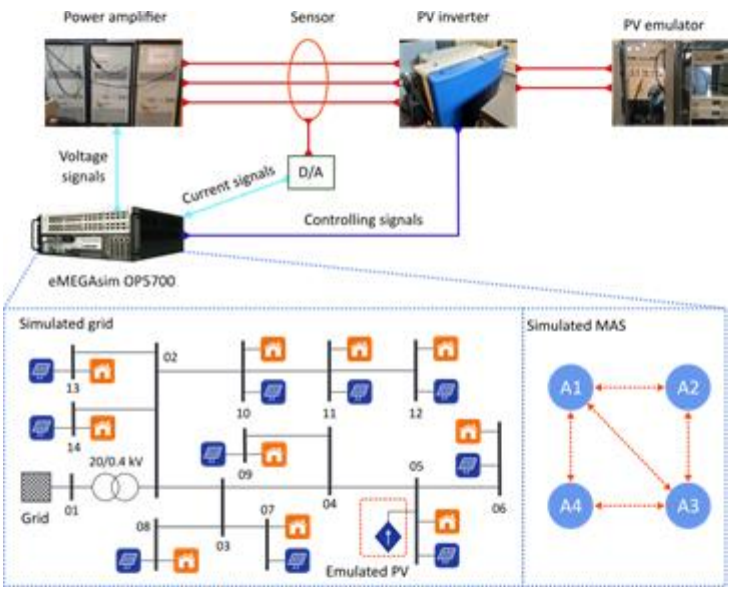
<table>
<tr><td></td><td>


Item tag names in PowerFactory for communicating with OPC server


```
# OPC Server - Alias CSV File
#
PF,MODE,,2,0,0,0,0
PF,RCS_BUS_2_CUB_3,,2,0,0,0,0
PF,RCS_BUS_2_CUB_3_RES,,2,0,0,0,0
PF,RCS_BUS_3_CUB_1,,2,0,0,0,0
PF,RCS_BUS_3_CUB_1_RES,,2,0,0,0,0
PF,RCS_BUS_4_CUB_2,,2,0,0,0,0
PF,RCS_BUS_4_CUB_2_RES,,2,0,0,0,0
PF,RCS_BUS_5_CUB_1,,2,0,0,0,0
PF,RCS_BUS_5_CUB_1_RES,,2,0,0,0,0
```
</td></tr>
<tr><td>Experimental Design and Justification</td><td>There are two different types of simulation will be carried out:
a. Different operating conditions with high PV generation will be generated in order to evaluate the performance of the distributed voltage control and the voltage support capability of the PV systems by regulating their reactive power exchange
b. Different time delay and packet loss will be created to test the signal exchange capability of the agents within the proposed MAS and also their performance under circumstances of lack of input data</td></tr>
<tr><td>Precision of equipment and measurement uncertainty</td><td>▪ OPAL-RT simulation time step: Ts = 5e10^{-6} s</td></tr>
<tr><td>Storage of experiment data</td><td>Matlab files and csv files</td></tr>
</table>

Experiment Specification TC8.TS01.ES02

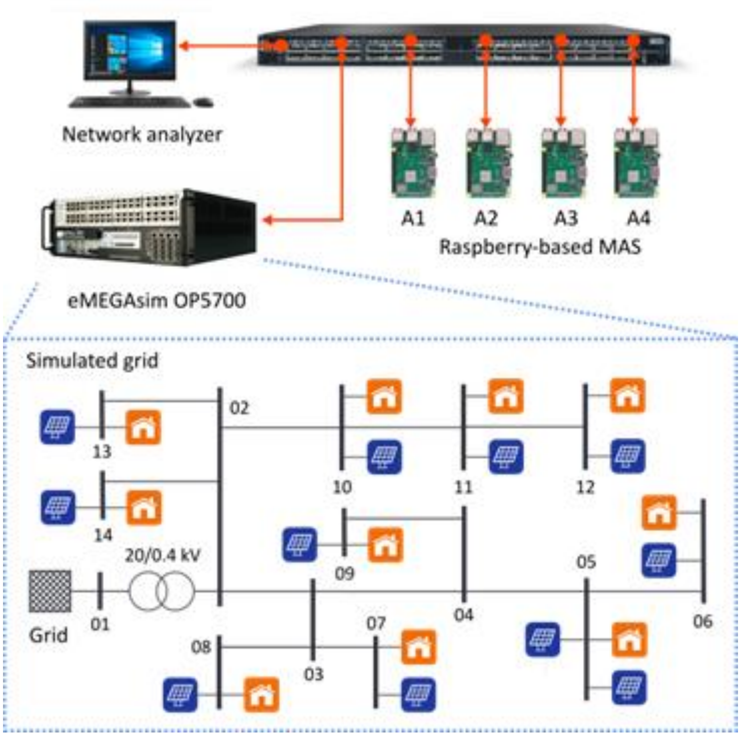
Reference to Test Specification	Validation of the performance of PV systems in providing grid voltage control functionality
Title of Experiment	*PHIL test: validation of PV systems functionality of participating in voltage control*
Research Infrastructure	CEA/INES (France)
Experiment Realisation	The experiments require testing PV inverter hardware connected to a grid simulated in a real-time simulator via power amplifiers. Other PV systems and the MAS-based distributed voltage control scheme are also implemented and embedded in the real-time simulator along with the studied grid. The currents of the PV hardware inverters are measured by sensors and sent to the real-time simulator. The control signals generated by the PV inverters' agents that are simulated in real-time simulators are directed to the PV hardware inverters

Experiment Setup (concrete lab equipment)	The experimental setup is as shown in the figure below.
	
	
	Overall, following are the lab equipment included in the experiment:
	▪ OPAL-RT eMegaSim OP5600 (or OP-5700)
	▪ Desktop for RT-LAB installation
	▪ 150 kVA grid simulator
	    ○ 3-phase 120V – 690V
	    ○ 0-2500 Hz fundamental/Up to 50 kHz harmonics
	    ○ PHIL simulation
	▪ 25 kW PV inverter
	▪ 15 kW DC programmable source for PV emulation
	▪ 45 kVA out – 15 kVA in Power amplifier
	▪ Power hub 64 A
	▪ Sensor
	▪ I/O cards

Experimental Design and Justification	Different operating conditions will be applied in order to generate under/over voltage issues within the simulated grid. Consequently, the MAS will react to these voltage violations and therefore generate control signals to the hardware-PV inverter and other simulated ones. The reactive power exchange capability of the PV inverter hard-

	ware can be observed and validated by monitoring their reactive power absorption/injection as well as the improvement of voltage levels at their PCCs. Another objective of the experiment is to analyze potential issues that may arise from the dynamics of the PV inverter hardware when they respond to the voltage variation of the grid.
Precision of equipment and measurement uncertainty	▪ OPAL-RT simulation time step: Ts = 5e10^{-6} s ▪ Packet losses due to the limitation of transmission rate of network cards ▪ Sensors and associated ADC
Storage of experiment data	*Matlab files and csv files*

Experiment Specification TC8.TS02.ES01

Reference to Test Specification	Validation of the performance of PV systems in providing grid voltage control functionality
Title of Experiment	*CHIL: MAS-based distributed voltage control*
Research Infrastructure	CEA/INES (France)
Experiment Realisation	The experiments require testing Raspberry-based MAS communicating to a grid simulated in a real-time simulator via power amplifiers. All PV systems are implemented and embedded in the real-time simulator along with the studied grid.
Experiment Setup (concrete lab equipment)	The experimental setup is as shown in the figure below.  The following lab equipment are included in the experiment: ▪ OPAL-RT eMegaSim OP5600 (or OP-5700) ▪ A cluster of Raspberry PI 4 Model B 4GB ▪ Ethernet switch
Experimental Design and Justification	Different operating conditions will be applied in order to generate under/over voltage issues within the simulated grid. Consequently, the MAS will react to these voltage violations, process the

	measurement input and then communicate with each other to generate appropriate controlling output signals to their corresponding PV inverters simulated inside the real-time simulator. The time delay and packet loss will be also created to test the performance of the proposed MAS and the implemented distributed voltage control under different communication scenarios. The ability of the MAS-based distributed voltage control system with a lack of information has an advantage over the centralized voltage control strategy.
Precision of equipment and measurement uncertainty	▪ OPAL-RT simulation time step: Ts = 5e10^{-6} s ▪ Packet losses due to the limitation of transmission rate of network cards
Storage of experiment data	*Matlab files and csv files*