STORE&GO

Innovative large-scale energy storage technologies and Power-to-Gas concepts after optimisation

D6.7

Final report "PtG grid integration experiments"

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Executive Summary

The project STORE&GO aims to investigate all the aspects regarding the integration of large-scale Power-to-Gas (PtG) at European level, by exploiting it as means for long-term storage. One of the aspects that should be properly addressed is the beneficial impact that the integration of PtG plants may have on the electricity system.

In the project framework, WP6 devoted its activities to investigate different aspects of the integration of PtG in the electricity grid, with the previous delivered reports.

This Deliverable focused in particular on how to integrate the information about the facilities replicating the real world condition into a simulation environment. For doing this, the concept of remote Physical Hardware-in-the-Loop (PHIL) has been used and exploited.

Remote simulation with physical hardware appears to be an effective means for investigating new technologies for the energy transition, with the purpose of solving the issues related to the introduction of new Renewable Energy Sources (RES) into the electricity system. These solutions are making the overall energy systems to be investigated much more complex than traditional ones, introducing new challenges to research. In fact:

- The newly integrated technologies deal with different energy vectors and sectors, thus

- Require interoperability and multidisciplinary analysis;

- The systems to be implemented often are large-scale energy systems leading to enormously complicated simulation models;

- The facilities for carrying out the experiments require huge investments as well as suitable areas where to be properly installed.

This may lead to the fact that a single laboratory with limited expertise, hardware/software facilities and available data has not the ability to secure satisfactory outcomes. The solution is the sharing of existing research infrastructures, by virtually joining different distant laboratories or facilities.

This results in an improvement of simulation capabilities for large-scale systems by decoupling them into sub-systems to be run on distant targets. This approach avoids the replication of existing facilities by exploiting the remote hardware in the loop concept for testing of remote devices.

Also confidential information of one lab, whose sharing may be either not allowed or requires long administrative authorization procedures, can be kept confidential. This is realized by simulating models locally and exchanging with the partners only proper data and simulation results through the co-simulation medium.

Thanks to the realized method [1] it is possible to analyse renewable devices in real time at remote power plants and place them in the loop of a local network simulation.

The results reported show that the architecture developed is strong enough for being applied also at new renewable power plants. This opens the possibility to use the data for research purposed, but also to act in remote on the infrastructure in case of particular tests (for example the acceptance test).

Acronyms

AC	Alternate Current
AVR	Automatic Voltage Regulator
CCGT	Combined-Cycle Gas Turbine
CHIL	Control Hardware-in-the-loop
CHP	Combined Heat and Power
CoE	Centre of Expertise
DC	Direct Current
DPS	Distributed Power System
DPS	Distributed Power System
DSO	Distribution System Operator
DSP	Data Signal processor
DUT	Device Under Test
ES	Electricity System
EtherCat	Power switch(es) accessible with address over Ethernet
FPGA	Field Programmable Gate Array
FTR	Financial Transmission Rights
HIL	Hardware-in-the-loop
HMI	Hardware Machine Interface
HPC	Hardware Power Control
HuT	Hardware under Test
HV	High Voltage
HW	Hardware
IEC	International Electro technical Commission
InetDistSim	Internet Distance Simulation
IP	Internet (address) Protocol
ISO	Independent System Operator
L	Coil
LC	Coil Capacitor
LCL	Coil Capacitor Coil
LV	Low Voltage
MV	Medium Voltage
OCGT	Open-Cycle Gas Turbine
OSL	Operational Security Limits
PA	Power Amplifier

PTG	Power-to-Gas
PC	Personal computer
PFD	Process Flow Diagram
PHIL	Power Hardware In the Loop
PM50F70	Power Module 50 KW
PoliTo	Power lab Torino
PtG	Power to gas
PV	Photovoltaic
PWM	Pulse Width Modulation
RES	Renewable Energy Sources
ROS	Rest of the System
RT	Real Time
RTT	Real Time Target
Sim2Sim	Simulation to Simulation
SNG	Synthetic Natural Gas
SW	Software
TCP	Transmission Control Protocol
UDP	User Diagram Protocol
VPN	Virtual Private Network

1 Power Hardware In-the-Loop method from local experiment to distributed co-simulation

1.1 Introduction to hardware in the loop

New technologies or approaches are being widely developed and proposed to be deployed in real energy systems to improve some desired objectives; however, supporting decision making processes to select best solutions in terms of performance and efficiency following cost-benefit analysis require some sort of scientific evidence based tools. These tools should be reliable, robust, and capable of demonstrating the behaviour and impact of newly developed devices or algorithms in different pre-defined scenarios. Therefore, new approaches and technologies need to be tested and verified using a safe laboratory test bed.

In real-world systems, both device or approach under test and the rest of a system are physical and naturally coupled. In the laboratory tests, the rest of a system as the study environment is replaced with its mathematical model to simulate its behaviour. In order to couple the hardware or software under test with the virtual model of the rest of system, we need a simulation platform which guarantees the synchronization, accuracy, and stability of the overall system. To achieve this, performing real-time simulations is inevitable. Real-time simulation is the most reliable simulation solution mainly based on electromagnetic transient analysis, which can capture dynamic behaviour of the systems in a realistic way respecting the timeline according real time occurrences.

To test and to validate the performance of a device prototype or to tune or characterize a newly manufactured hardware like an electrolyzer before installing in the system (e.g. connecting to the power grid), a so-called hardware-in-the-loop is often carried out using digital real-time simulators. In case when the device is a controller which retrieves some measurements or alarms and produces some command signals as feedback to the rest of system, there is no need to exchange power; hence an off-the-shelf digital real-time simulator can be directly coupled with the device, performing Control Hardware-in-the-loop (CHIL).
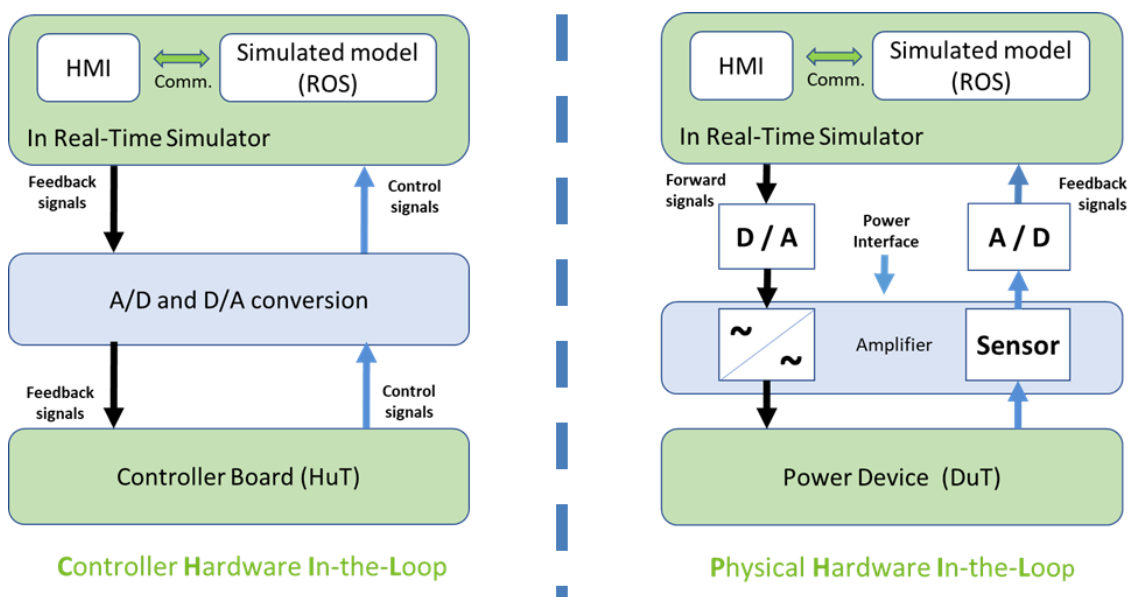
Figure 1-1: Two types of hardware in the loop

In cases when the device is a source of energy (e.g. solar panel, wind turbine connected generator, fuel cell, etc.) or sink of energy (i.e. loads), an interface is needed to enable power exchange. In

such cases, a power amplifier is exploited to perform a Power Hardware-in-the-loop (PHIL). Figure 1-1 illustrates CHIL and PHIL.

The power interface is the key element in PHIL experiments. The power interface is made of a power amplifier and a set of sensors which monitor the hardware under test (HuT). The power amplifier acts as a source or sink in order to respectively generate or absorb power. From the simulated grid it is possible to extract the values of voltage or current to control the output of the power amplifier in order to feed the HuT. If we equip the load with current or voltage sensors, we can extract the load required current or voltage quantity and they are sent as feedback to the software grid to close the simulation loop. Moreover, a high quality of the supplied voltage to the device under test can be obtained if the frequency bandwidth of the power interface is higher. The wider is the output bandwidth of the Power Amplifier, the better the Power Amplifier can reproduce the fast voltage oscillations (at high frequency). A narrow bandwidth means that signals at higher frequency cannot be reproduced and so they are filtered out by the power interface [2],[3].

1.2 Remote Hardware In-the-Loop Experiment

Integrating new technologies to energy systems and interfacing different energy vectors and sectors to provide new opportunities of energy storage and management makes the new systems more complex than traditional ones. Multidisciplinary analysis is needed to ensure the right performance of a newly developed technology (e.g. prosumer, micro-grid controller, electrolyzer, etc.) in the overall system. This directly introduces new challenges to the hardware-in-the-loop experiments due to the following reasons:

•   New devices or technologies require interdisciplinary studies among different expertise areas;

•   Interoperability analysis of newly integrated technology is crucial;

•   The rest of the system (i.e. simulated model of the grid) could be a large-scale energy system;

•   The rest of the system may be a "system of systems" with variant geographical and energy behavioural (e.g due to social or cultural habits) characteristics;

•   Interaction of OPAL[4] and Triphase[5] or Cinergia [6] power amplifiers / inverters;

The remote hardware-in-the-loop system for global measurement that we established for prosumer characterization is based on the so-called "geographically distributed real-time co-simulation" [7]. This approach enables interconnecting distant laboratories to create an integrated simulation and experiment laboratory. Such a laboratory provides a number of benefits. The first benefit is the virtual sharing of software and hardware facilities for remote testing of devices, both by integrating (power) hardware in the loop and remote software-in-the-loop. The target model itself is simulated in a different lab. Other benefits are: enhancing simulation capabilities for large-scale systems through the coupling of sub-systems; and keeping susceptible data/model/algorithm confidential.

Since the vision of this approach is not limited to only remote laboratory (hardware/software) access, "Internet-Distributed hardware-in-the-loop (HIL)" has attracted many researchers for the last twenty years. We intend to implement and use such an internet-distributed HIL in two steps: firstly to enable a laboratory (PoliTo's) to access the Real-Time Target of the other laboratory (Hanze's, see Figure 1-3). Then we load Simulink [8] models through the internet, and run a PHIL remotely, provided the hardware set-up is done (Figure 1-2 (B)). The next phase is to decouple the "rest of the system" (i.e. the virtual model of the grid and behavioural scenarios) to be concurrently run on simulators located in both distant laboratories (Figure 1-2 (C)).
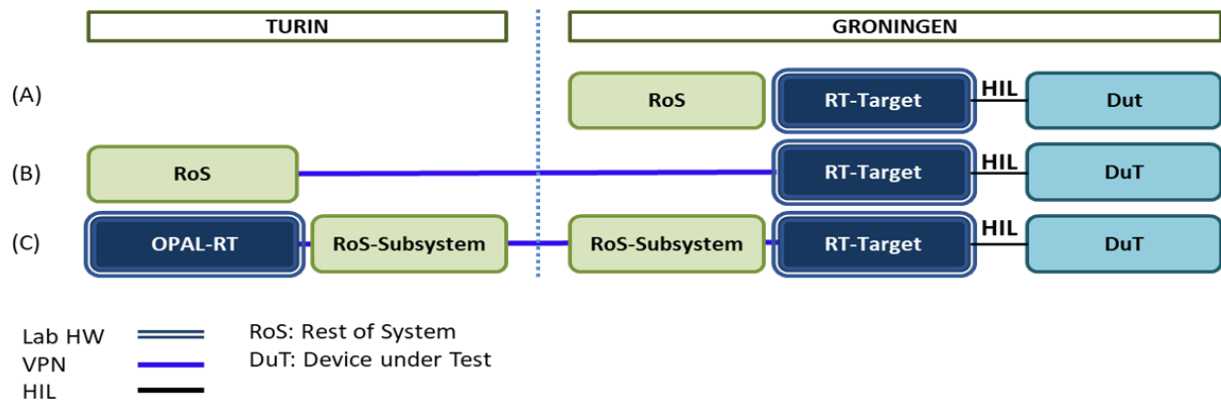
Figure 1-2: General overview of tested PHIL by PoliTo (Turin) and Hanze (Groningen) [4]

Figure 1-3: RTS-lab Politecnico di Torino   Entrance / Hanze Facilities

2 Hanze's Entrance facilities description and integration

2.1 Aim of the laboratory

The Real-Time Micro-Grid laboratory, situated at the Energy Transition Centre building of the Hanze University of Applied Sciences (Groningen, the Netherlands) is a test site that has been designed and built for the purpose of energy transition- and PtG grid integration experiments. The laboratory setup comprises new energy transition sources and all the additional components necessary to investigate the integration of hydrogen production by water electrolysis with renewable energy sources (Figure 2-1). The research method is based on the characterization of these sources, comprising electrolyzer, PV panels, wind turbines, fuel cells, and others, through the acquisition of appropriate data in order to produce mathematical models based on the real-time and dynamic measurements.
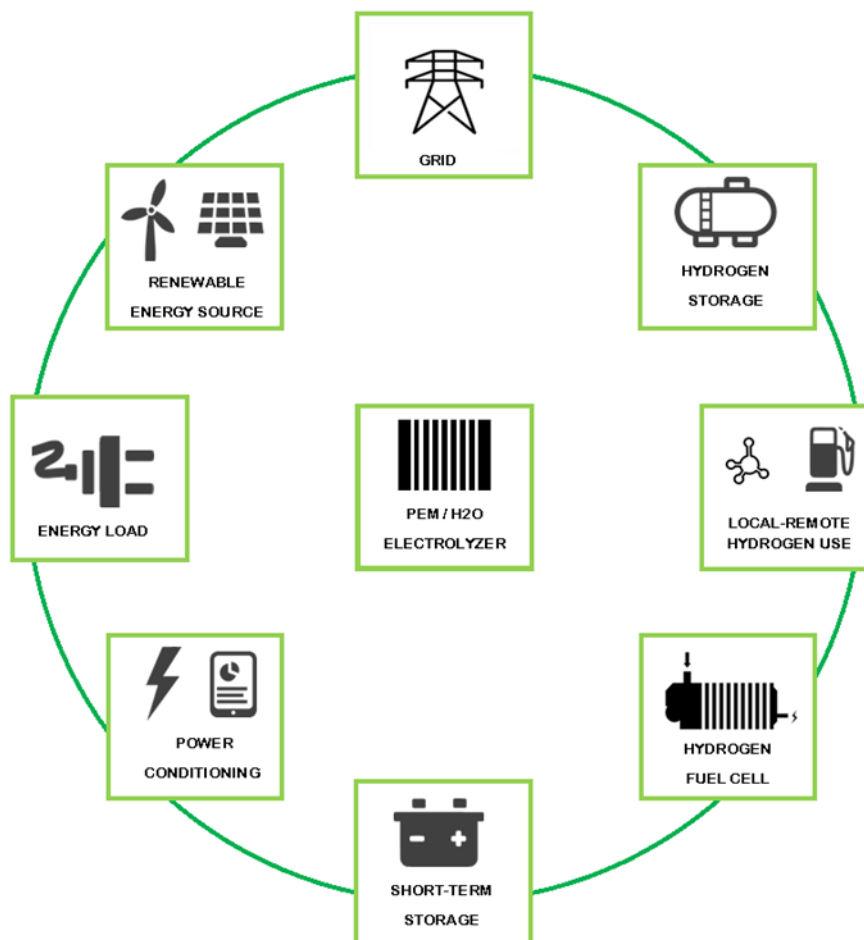
Figure 2-1: Components for the integration of hydrogen production with renewable energy sources

Another important aspect is that the complete setup has now been configured to be accessible through a low latency data connection by remote use. This allows to establish a communication between the micro-grid laboratory and the Global Real-Time Simulation Lab (G-RTSLab) located at the Politecnico in Torino. In this way, the laboratory equipment in Groningen can be accessed from Turin for the purpose to remotely collect real-time data to use into large-scale grid models and with the final aim to realize a distributed real-time co-simulation. The various subsystems and both the physical and virtual connections between them are schematized in Figure 2-2

Figure 2-2: The real-time micro grid setup installed in Hanze

2.2   Grid facilities

In the lab environment, two portions of grid can be distinguished. On one side, the one called local grid is the prolongation of the main external grid and extends from the supply po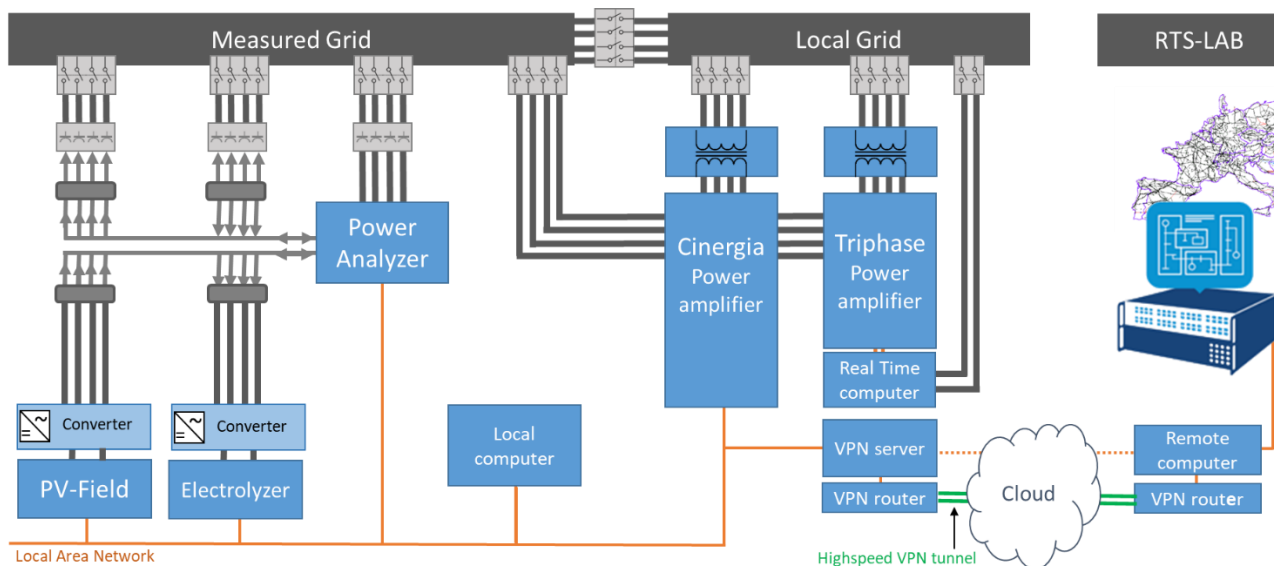int of the cabin to within the laboratory room. On the other side, the one called measured grid is a main-grid independent and galvanic separated grid and occupies the main part cabin. The measured grid is configured as a three-phase with neutral conductor (3PH+N) and is functionally equivalent to the most common European three-phase AC networks. The setup is fitted with a locked switch to bypass the local grid to the micro-grid environment. After closing this switch, it is possible to connect prosumers with loads > 15 kW (Triphase) or loads > 32 kW (Cinergia) so that they can use and store energy from or send energy to the local grid. Connections of the single subsystems to both local and measured grid are realized and measurements are performed safely through the interconnected junction box.

2.3   Triphase power amplifier hardware

The creation of a controllable grid (in terms of both voltage and frequency) needs a power amplifier which is able to replicate in the grid the requested condition. In our setup, a Triphase power amplifier (PA) [9] is used. This system is able to realize a scalable, flexible and open platform for prototyping and power hardware-in-the-loop testing of power conversion and power system applications. Thus, with this system a complete controlled micro-grid is obtained.

The PA consists of a 15 kW bidirectional isolated power module with 6-channel output, suited for bidirectional energy flow between the supply grid and single or three-phase AC or DC loads and sources. It includes power amplifiers, power converters, measurements, connection contactors, safety features, signal processing units and software libraries for high-end real-time control. For virtual operation, the PA power module is connected over a real-time communication bus, called XC real-time Network, to a powerful PC-based real-time control unit. This PC is able to run the models for all kind of customized sources or loads in real-time. In fact, the PA can be configured as either 'voltage source' - 'grid generator' or 'current source' – 'load', with a specific load pattern, harmonic signature, independent phase shift angle, etc.
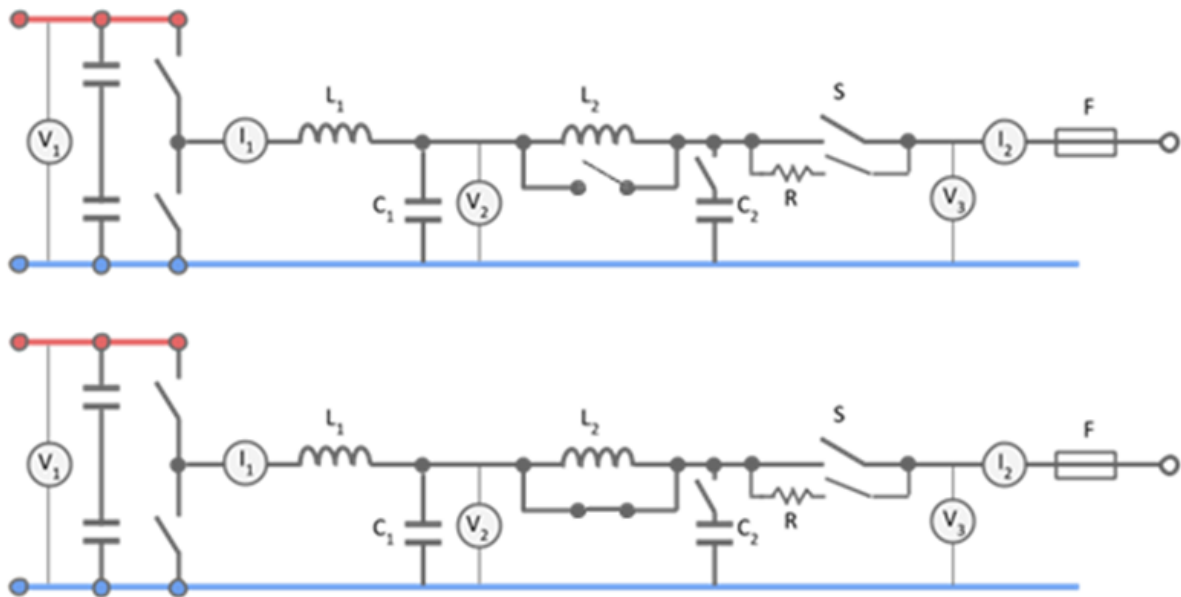
Figure 2-3: Triphase power amplifier operation diagrams

Table 2-1: Diagram reference

V_1	DC Bus voltage measurement
I_1	Inverter current measurement
L_1	Primary inductor
C_1	Primary capacitor
V_2	Primary capacitor voltage measurement
L_2	Secondary inductor (bypass able)
I_1	Output current measurement
S	Output contactor
R	Precharge

This is possible by switching over numerous internal switches with many inductive and capacitive configurable components. In particular, with a specific load model, it is possible to analyse what is needed to eliminate grid disturbances, which can affect the power quality of the supply. For instance, when a certain prosumer creates a capacitive phase, the virtual model can create an inductive load that is capable of fully compensating the grid disturbance. Figure 2-3 shows the two simplified switch diagrams. At the top The LCL model for current injection / rejection into a stable voltage source (grid). The bottom diagram shows the Inductor (L_2) bypass use for LC operation used to generate a high dynamic voltage source.

2.3.1 Triphase power amplifier mathematical models

The real time simulated grid of the Triphase PM15F70 application is created with a mathematical compiled Simulink model. After compiling, the code is programmed into the power amplifier's gate arrays. For the first experiments we have realised and modelled a complete virtual model by the use of a compiled Matlab Simulink model . The development and applied tests of this model is described and explained in the D6.2 [10] and the D6.5 reports. Figure 2-4 shows the frontend model of a complete simulated PM50F70 within a Matlab/Simulink model environment. With this model it is possible to virtually run the PM50F70 on an engineering pc.
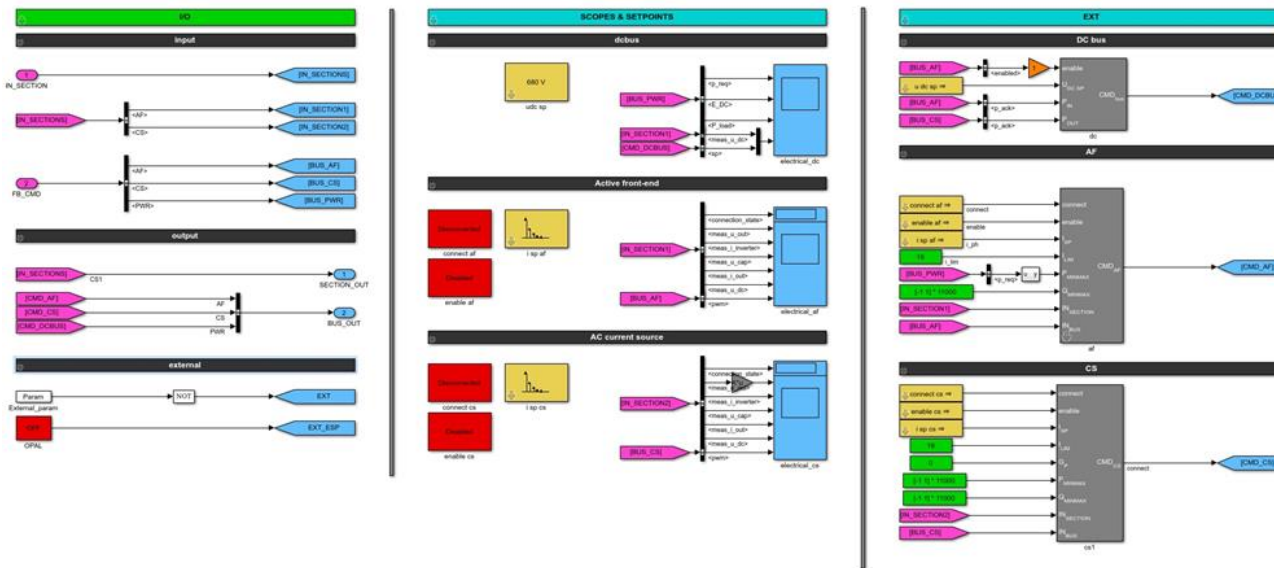
Figure 2-4: Simulink command centre control

2.4   Cinergia power amplifier

The Cinergia power amplifier is a device that combines the functionalities of a 32 kW Grid Emulator, Electronic Load and Bidirectional DC Converter in a single cabinet. The Grid Emulators are power electronic devices designed to emulate an AC electrical grid in normal condition as well as in disturbed conditions (voltage dips, frequency and voltage fluctuations, flicker, and harmonics).
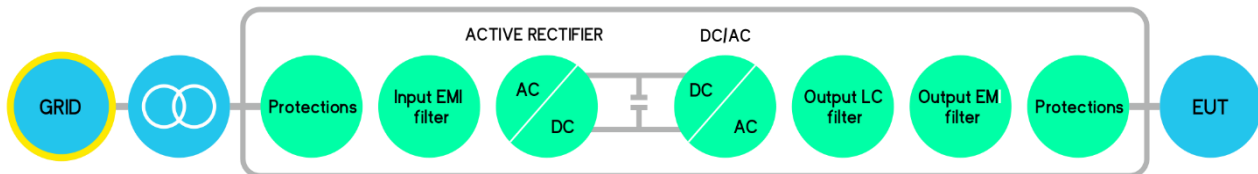
Figure 2-5: Schematic of the Cinergia's model

The hardware platform is based on a Back-to-Back power conversion topology, formed by two IGBT-based power stages. The grid side stage is an Active Rectifier which produces clean sinusoidal currents with very low harmonic distortion and power factor close to one. The EUT side stage can be configured for AC voltage source or AC current source or DC output. In AC, voltage/current are controlled by using state of the art digital proportional-resonant controllers. In DC, the three independent buck-boost bidirectional legs enable the separate control of three different DC voltages or current.

Figure 2-6: Cinergia's hardware overview.

The power analyzer has the following operation states:

- **Initialization** During the initialization, the power supply control system checks the presence of all internal compone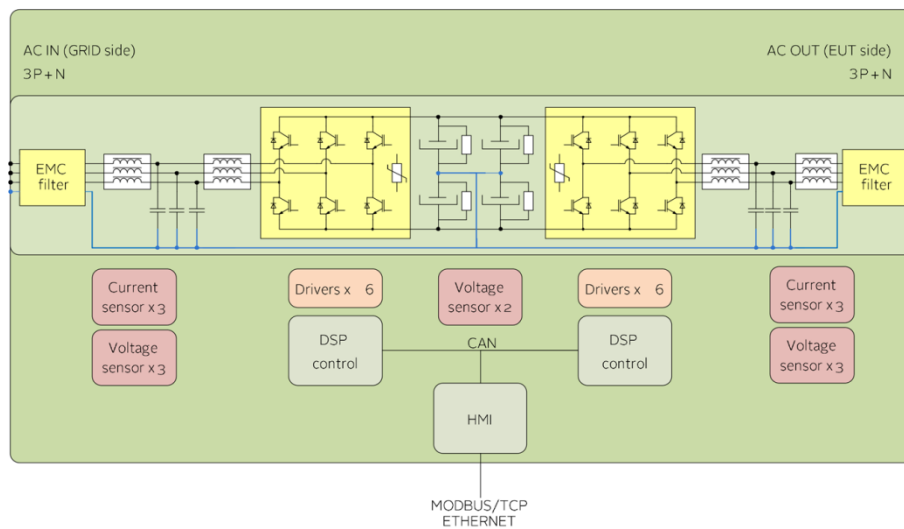nts, and the embedded PC loads the operating system. No voltage is present at the DC bus, and the IGBTs PWMs are completely stopped. The transition from Initialization state brings the power supply to the Standby state as long as the emergency stop is deactivated (equipment armed).

- **Standby** It keeps the power supply in low power mode until an Enable signal is received. While the power supply is in standby, only the internal power supplies are energized. In particular, this means that there is no voltage in the DC link and no voltage/current is applied to the output of the power supply

- **Precharge** This state is an internal transition state between Standby and Ready. During this state, the DC link is gradually charged through resistors until the rated DC link voltage is reached. The transition will finish successfully as long as, in less than 10 seconds of precharge, the DC link has reached the specified voltage.

- **Ready** The power supply is ready to operate but no PWM signal is sent to IGBTs. The DC bus is charged to the rectified voltage and there is no voltage/current applied to the output.

- **Run** In this state, the power supply is completely operational. Due to the power supply architecture, the grid side converter (Active Rectifier) will make the transition first while it stabilizes the DC link voltage. After that, the inverter will start the control algorithms and PWM.

- **Alarm** In this state, the power supply is stopped and kept in a safe condition: the DC link is discharged and the PWM signals are stopped.

Cinergia has a specific AC panel to configure independently the output voltage waveform, the transition ramps and the distortion of each phase of the generated grid. In this panel, each phase can be independently configured: rms current magnitude, phase delay, harmonics content, free-frequency harmonic and transition ramps.

Figure 2-7: Cinergia's AC configure panel

2.4.1   Cinergia communication

Cinergia's power amplifier can be operated and supervised remotely through an Ethernet communications bus. An internal embedded PC, with Cinergia's proprietary software, allows the exchange of information between the internal SPI bus and the external Modbus TCP/IP (Ethernet). In this way, we have developed specific Matlab Simulink model by using Cinergia's power amplifiers Modbus

TCP/IP protocol for communication. In order to write/read to this Cinergia power amplifier we used Matlab Simulink "mmodbus' functions to read and write using the Ethernet [11] Modbus/FTU Protocol [12].

2.4.2 Cinergia power amplifier mathematical models

For our tests we have developed a set of Simulink sub models to be able to set up a stable grid and change or set grid parameters during local or remote network simulations.
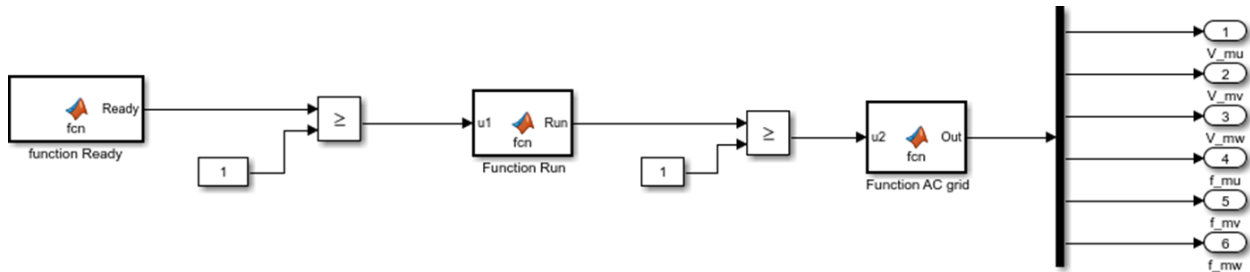

Figure 2-8: Simulink model subsystem InitGrid

Figure 2-8 shows the Matlab Simulink functions needed to initialize a stable local grid. The parameters for a stable European main grid to start are already preloaded into the Cinergia's registers. We define three Matlab functions for initializing the Cinergia's functions in or Simulink sub model to set up a stable grid:

- **Ready:** Set the ready bit, enabling the grid emulators ready state.

- **Run:** Set the run bit, enabling the grid emulators output

- **AC GRID:** Setting configuration to accept AC-grid parameters

Additionally, there are two relational operators for the transition from one state to another, which will not be instantaneous. For example, between the enable and ready states there is a Precharge phase, and when the device is ready, a bit is set in the respective register. For this reason, the output of the first two functions is compared before continuing to the next step
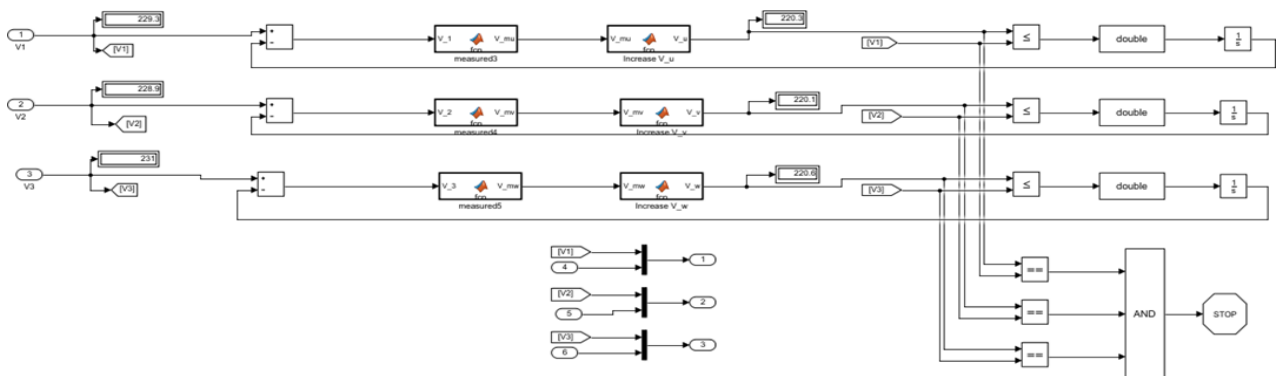
Figure 2-9: Simulink model sub system VolCntr

The voltage control Figure 2-9 is useful to set the Cinergia's voltage to the reference value, namely which of the main grid, this value is is measured by the PPA. In fact, "the PPA read V" function allows measuring the rms voltage from the main grid. Inside the loop, there are two other Matlab functions. The first one measured the output voltage of the Cinergia, the second one increases this value by

one unit until the set-value. The simulation will stop when the voltage achieves the set value, to connect the device in synchronism with the main Grid.
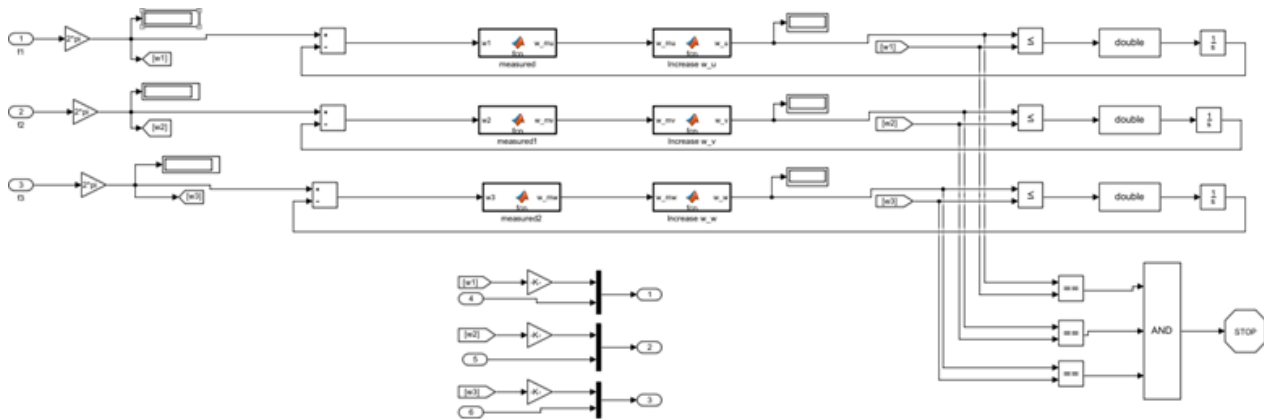

Figure 2-10: Simulink model subsystem ChgPar

The Simulink subsystem model in Figure 2-10 to control any grid parameter follows the same logic of the VolCntr. The real value is monitored during runtime to obtain the same settings during a full simulation run. Figure 4-8 shows the combined sub systems in the model we have used in the test sessions we have completed (Chapter 4).

2.5 Electrolyzer

The electrolyzer we used is a fully automated Proton Exchange Membrane (PEM) based water electrolysis system of 8 kW (1 m^3 hydrogen (STP) per hour) [13]. It is dedicated for stationary applications and can produce hydrogen continuously when supplied with power and deionized water. It is designed for indoor operation only, thus is located in a container that consists of two separated rooms. One of them contains the Power Logic Controller (PLC) and the water preparation system (where tap water is treated by reverse osmosis and ion exchange filters to create suitable water for electrolysis), whereas the other room contains the "electrolyzer system", composed of:

•   An electrolysis cell stack

•   Auxiliary equipment, necessary for regulating electrolysis operations (circulating water, drying hydrogen, pressurizing hydrogen and shutting down the system)

•   Sensors and control board for monitoring performance.

Furthermore, in the same room where the electrolyzer is located, a system of valves and two 5-litre tanks for storing the produced hydrogen is also installed. The tanks can be emptied afterwards by venting the contained hydrogen outside of the unit. Produced hydrogen can also be directly vented during operation, without filling the tanks.

Figure 2-11 shows the process flow diagram of the hydrogen production and the fragment inside the unit.
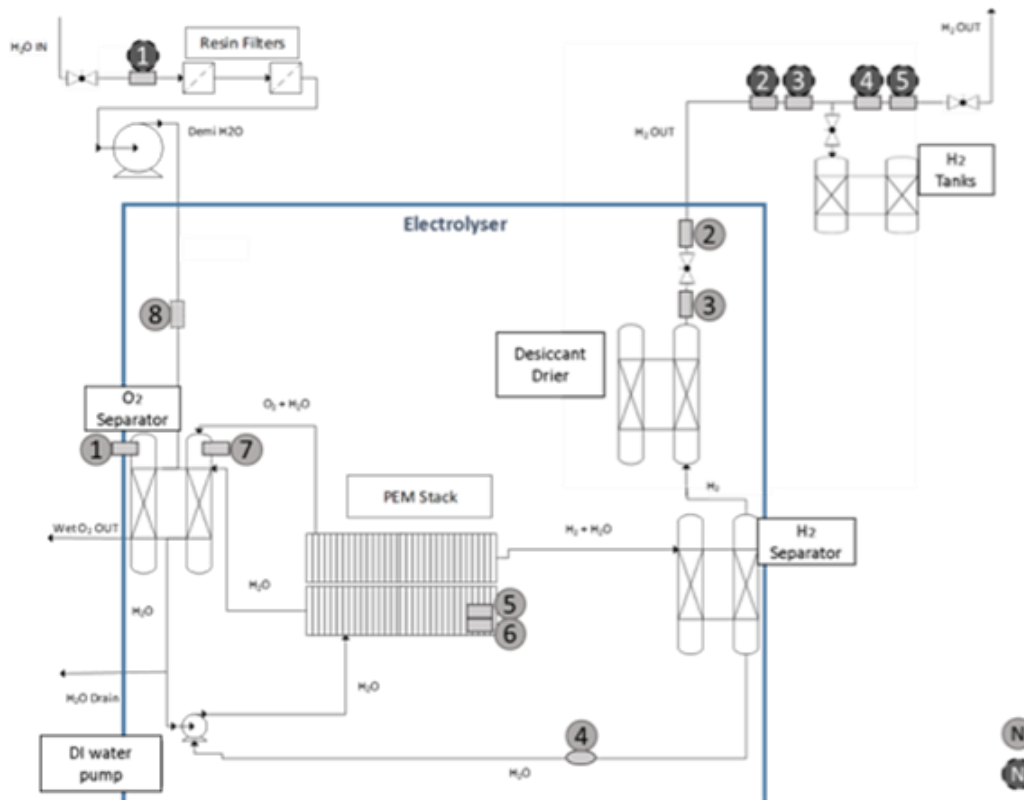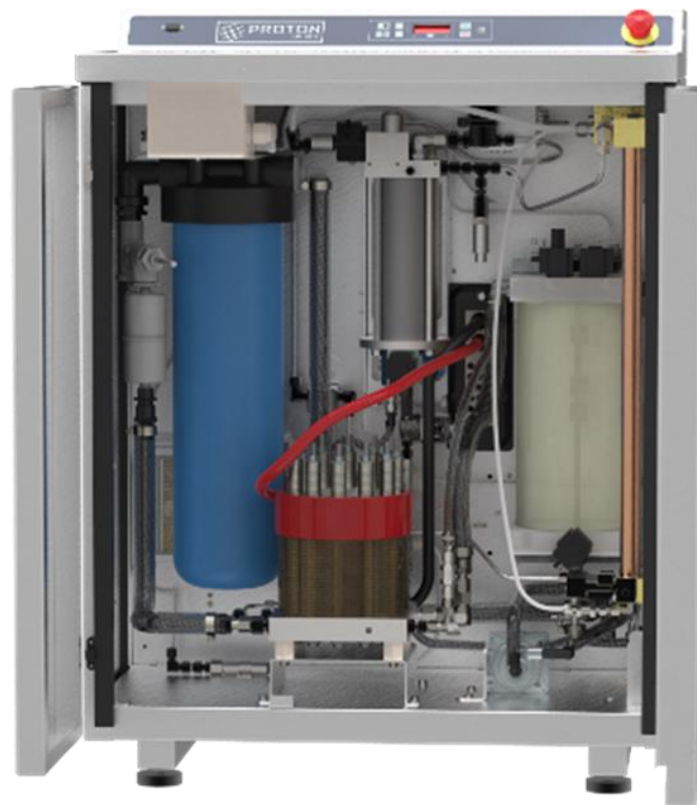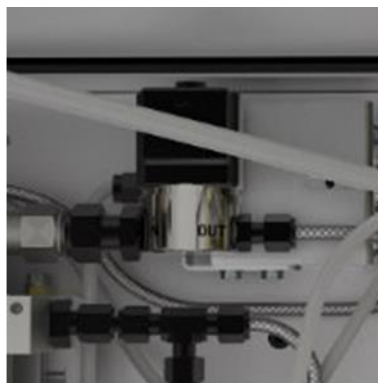
Figure 2-11: Process flow diagram of the electrolyzer

The electrolyzer has the following operating states:

- *Pre-Start:* The state begins when the main power switch is closed. The system flushes itself out if water quality is below the required resistivity. Water levels in the two separators (i.e., H_2/water and O_2/water) are adjusted if they are low. When Pre-Start operation is completed, it is possible to maintain this idle state or moving into the next state.

- *Generate-Vent:* In this mode, the circulation pump is started up and the system verifies the process values of water flow rate and water quality. Full current is applied to the stack after 120 seconds and hydrogen generation is started. The system checks the levels of both separator levels (i.e., H_2/water and O_2/water), voltage conditions in the stack and rectifier operation, and vents hydrogen and oxygen outside during this operation. If the process values pass all checkpoints, the electrolyzer will stop venting and start to build up system pressure, leading to the next state.

- *Pressurize Storage:* In this state, the hydrogen circuit in the system is pressurized up to the pressure regulator setpoint (approximately 15 bar). Once this pressure value is reached, the process goes into steady-state.

- *Steady-State:* The electrolyzer produces hydrogen that flows intermittently out of the system through the product hydrogen port. In fact, the hydrogen is produced and delivered only when the pressure of it in the tank (called product pression) is below the set point. Once the setpoint is reached, the electrolyzer stops the production of hydrogen, remaining in hot stand-by. It is worth to note that if the hydrogen is not stored in the tank but only vented into the air, the electrolyzer continues to produce hydrogen indefinitely.
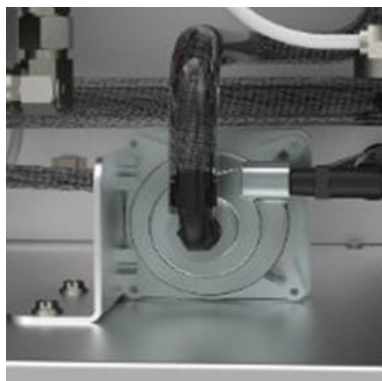
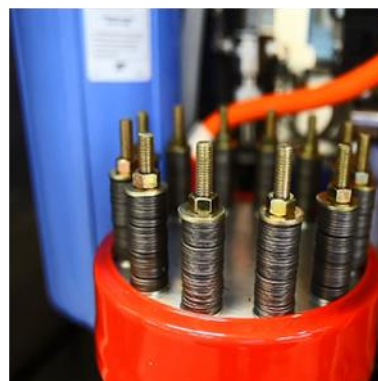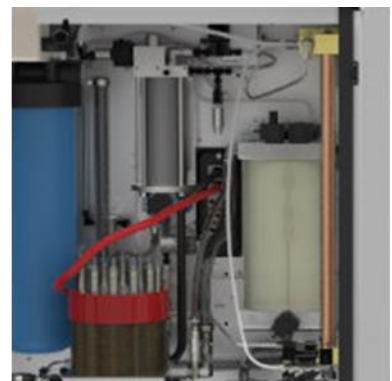|		
D.I. Water Polishing Bed	Combustible Gas Detector	Hydrogen Phase Separator
Circulation Pump	Cell Stack	Oxygen Phase Separator

Figure 2-12: Process flow diagram of the electrolyzer

2.5.1 Flow controller

A flow controller has been recently added on the output product pipe, and its communication channel has been connected to the laboratory LAN. In this way, the instrument allows both to control and measure the amount of produced gas flowing through it. All its data and settings can be accessed through the Modbus TCP/IP protocol by a computer connected to the same LAN (being directly or via VPN, as for the other instruments already installed). In particular, this device has been installed for allowing studies on the electrolyser dynamic behaviour. In fact, the hydrogen production rate can be considered roughly proportional to the electrical current of the stack, and this affects the overall (AC) electrical consumption of the unit. It follows a step change in the setpoint of hydrogen. The output flow produces a sudden change of electrical power consumption of the entire system.

2.5.2 Measure of electrolyser-related variables

The values related to the hydrogen production and the system variables (e.g., water inlet) can be monitored and logged in two separate ways, i.e., by downloading from the PLC located in the container, or directly from the electrolyser by using a commercial software via RS-232 connection. With reference to Figure 2-11, Table 2-2 and Table 2-3 show the measurement devices in the system, their location in the process flow diagram, and whether their data can be accessed either from the PLC side or from the electrolyser side.

Table 2-2: PLC monitored variables

N	PLC monitored variables	
1	H_2O inlet volume flow	[ml/min]
2	Produced H_2 volume flow (upstream of the tanks)	[m^3/h]
3	Produced H_2 pressure (upstream of the tanks)	[bar]
4	Produced H_2 volume flow (downstream of the tanks)	[m^3/h]
5	Produced H_2 pressure (downstream of the tanks)	[bar]

Table 2-3: HOGEN monitored variables

N	HOGEN monitored variables	
1	Gas detect	[%LeL]
2	Product pressure	[psi]
3	System pressure	[psi]
4	Water quality	[MΩ]
5	Stack voltage	[V]
6	Stack current	[A]
7	System temperature	[°C]
8	Water flow rate	[lpm]

*Other variables related to the converter monitoring such as:
3.3 V DC sense, 24.0 V DC sense, +5.0 V DC sense, 2.5 V reference,
-5.0 V DC sense, board temperature, spare thermistor

3 Communication methods.

Realizing a remote hardware-in-the-loop needs a special infrastructure. In fact, besides the real time grid setup, it is also required a reliable low latency network: for reaching a latency lower than 50 ms, a high-speed internet connection is necessary. Furthermore, a good security for ports and connection is mandatory.
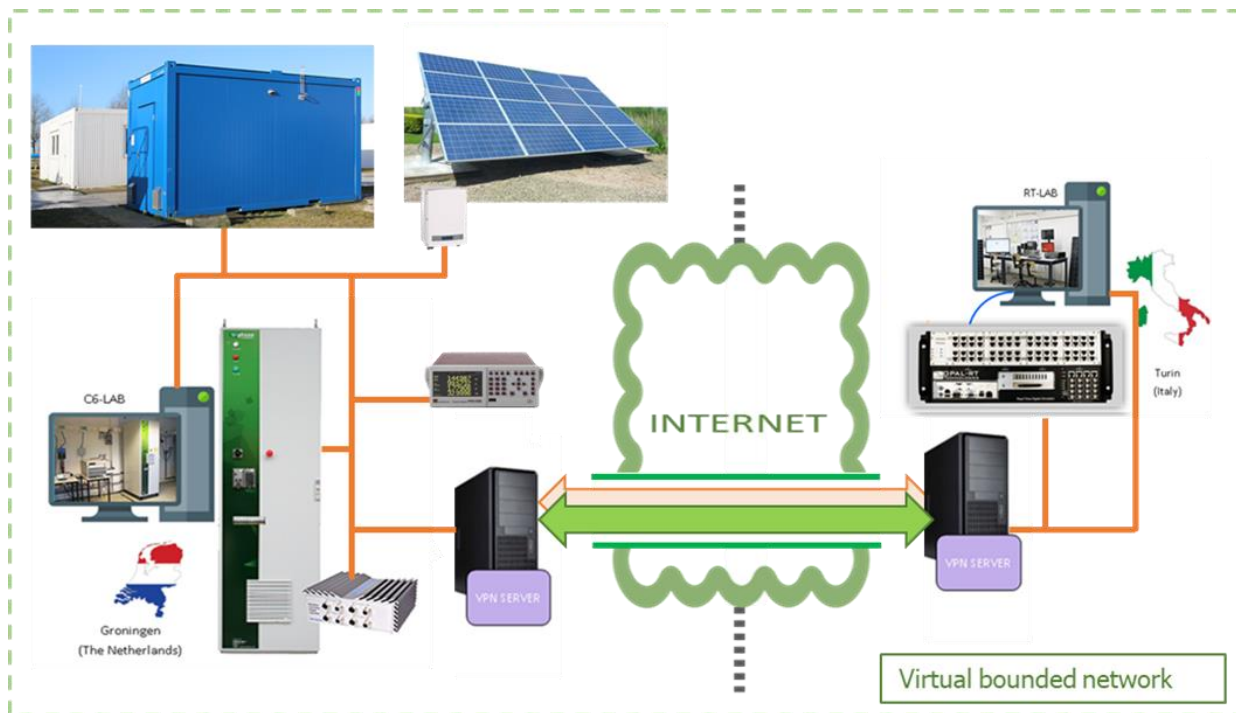

Figure 3-1: Virtual bounded network

Figure 3-1 shows the two physically separated local area networks (LAN), one placed in Groningen and the other one in Turin. They connect together different LANs, and are merged into a single segment via a layer 2 Ethernet bridge connection. [11] Figure 3-2 shows the configuration created in this test bed: Groningen is the main LAN; there is created a virtual hub on the OpenVpn server and a local bridge connection is realized to the network adapter on the specific LAN. The side of Turin represents the sub-LAN; in that side a PC connected to the Opal/RT LAN is equipped with a virtual OpenVpn server and hub, which is bridged to the LAN connection. When a connection is initiated from Turin, a cascade connection is made between Turin and Groningen. At this moment, the two separated network segments are converted into a single segment, whose two sides can communicate with each other. This fact leads to a connection between devices that seem to operate in the same network segment. So every remote or local device can be accessed and configured in the same LAN.

Software tools or math models for directly controlling real time devices (such as electrolyzers, power inverters, power analyzers, and so on) use additional security protections for LAN use. These methods are usually based on the MAC-addresses or the identification number of the processor of the computer on which the tool or model is compiled or installed.
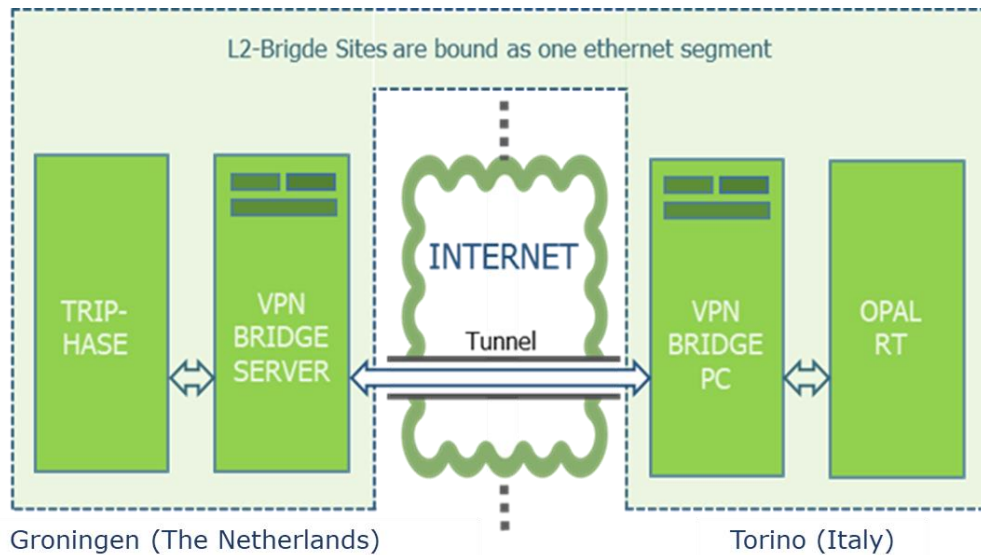
Figure 3-2: Communication structure

The security of the software tools mostly is related to having a valid license for the installation of the software on a specific computer. In the math models of the Triphase power system, the MAC-address referring to the real-time computer is used in a combination with the identification of the workstation which uploaded the model. This security method ensures that only the user who up-loaded and built the model on the real-time system can execute it. The Triphase uses a special script to realize the onetime identification of a new workstation / compiler on the real time PC. Most electrolysers and measurement equipment are communicating with the Modbus protocol. These devices are also direct accessible with the Modbus Ethernet Protocol [12] in the same network.
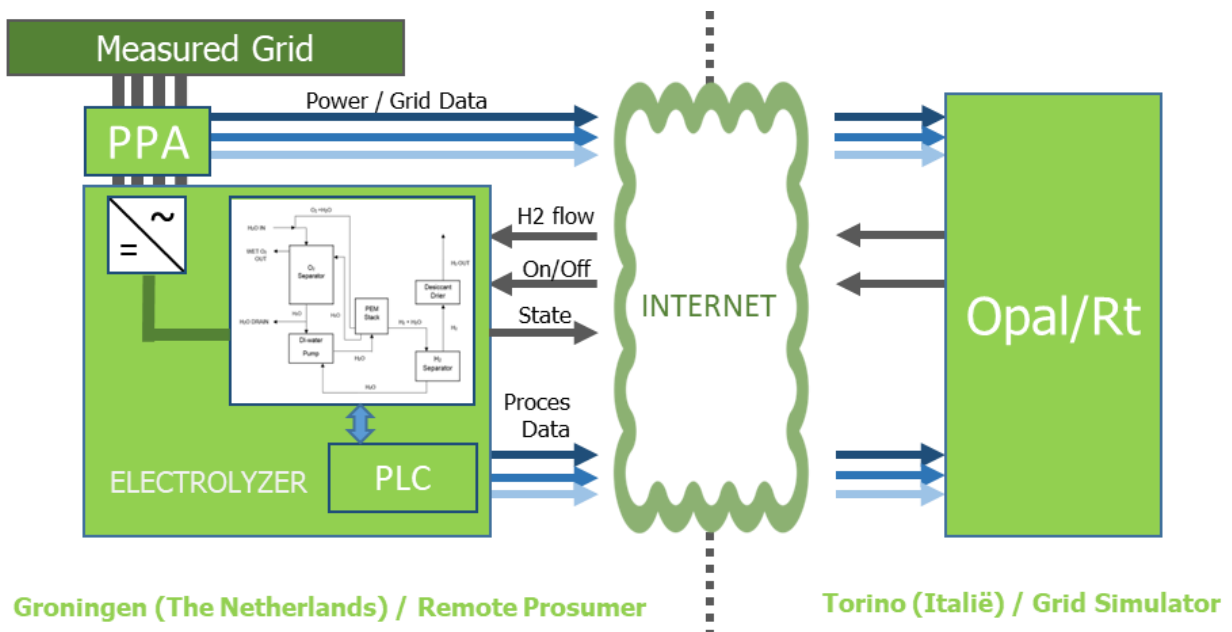

Figure 3-3: Electrolyzer control connections

The connected electrolyzer in Figure 3-3 facilitates the RTS simulation model to interact and modify process parameters and hydrogen production settings.

4 Physical hardware in the loop measurements

With the realized network configuration (chapter 3), the hardware installed on site is fully and safely controllable from the remote side (Figure 3-3). With this setup and the interoperability of the Cinergia grid emulator it will be possible to connect the electrolyzer as HIL into remote running simulations, finally realizing the so-called distributed real-time co-simulation. This chapter describes the method and results of remote physical hardware in the loop. With the implementation and use of the previously described connection:

- Enables the remote access from PoliTo to the hardware and software resources located at Entrance grid setup, achieving the objective of the share of research infrastructures;

- Offers the possibility to remotely monitor and control the setup from within running simulations, which constitutes the first step towards a co-simulation involving RPHIL tests on the electrolyzer.

- The two experimental tests described in the following section were aimed at proving the feasibility of these two aspects.

4.1 Interoperability of hardware, software and VPN

The first test set was intended to demonstrate the functioning of the VPN [14] [15] communication for retrieving measurements from and sending control signals to the instruments, with a special attention payed to the data transmission delay. On this basis, two identical tests were performed by acting on the control and measurement equipment of the electrolyzer, first locally from Groningen and then remotely from Turin. Specifically, the following operations were performed:

- Control and measurement of the hydrogen flow rate (output) by means of the flow controller

- The setpoint given to the flow controller in both cases was as follows: the electrolyzer was started up with the flow controller set to 25% of the maximum flow rate. This value was kept constant for 7 minutes to make sure that the electrolyzer had been correctly started and the steady state had been reached. Then 3 subsequent steps of 1 minute duration increased the setpoint of 25% at a time (1 minute at 50%, 1 minute at 75% and finally 1 minute at 100% of the maximum flow rate). The control was done by means of the Modbus controller setpoint software, while the data logging and saving were possible for both setpoint and real signals by using the implemented Matlab code.

- Measurement of the active and reactive power (electrical input on the AC side) by means of the PPA power analyzer

- The electrical inputs to the electrolyzer were measured by means of the power analyzer, interfaced with its data logger software. The instrument was set by enabling High-Speed Mode and loading the same settings configuration already used during all the previous experiments [10] at 20 ms time step.
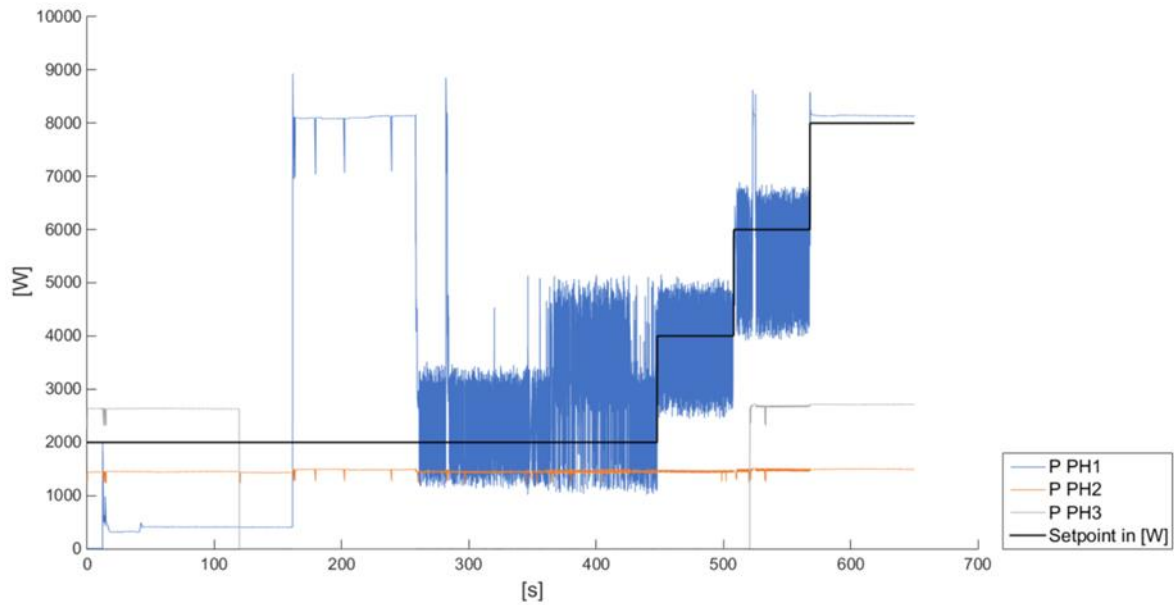
Figure 4-1: Active power withdrawn by the electrolyzer – local measurements
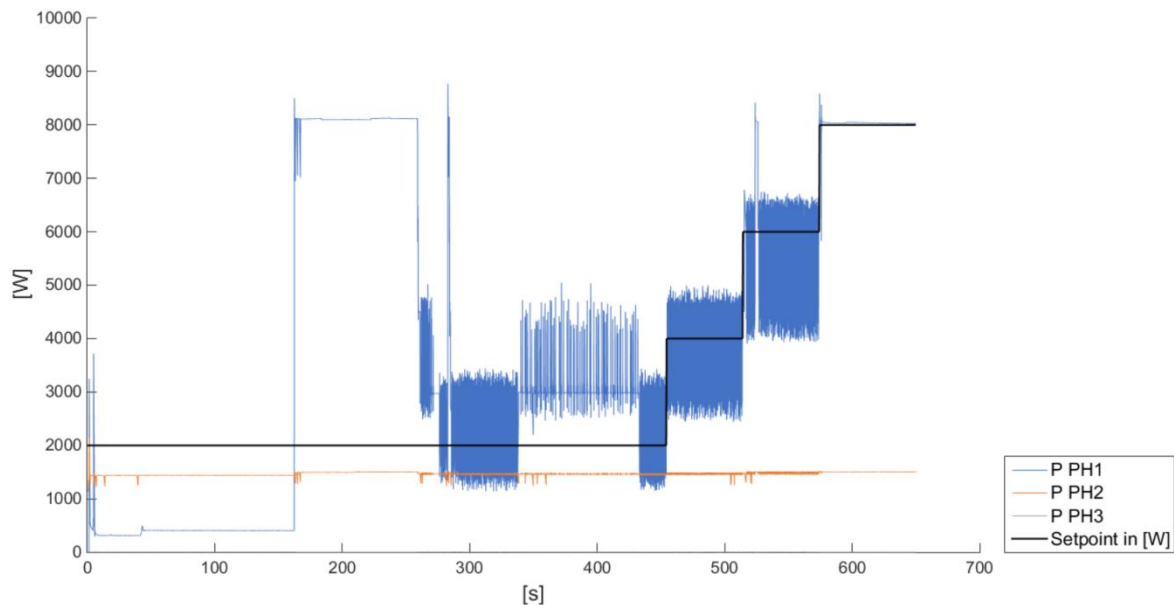

Figure 4-2: Active power withdrawn by the electrolyzer – RHIL measurements

Figure 4-1 illustrates the active power for all three phases with measurements performed locally from Groningen, while Figure 4-2 depicts the same parameters with data logging carried out in remote from Turin. By looking at the graphs and focusing on phase 1 (which is the most important one as the only phase used for rectifying the DC voltage), no big differences are visible between the local and remote measurements. In both cases, the electrical behavior of the electrolyzer passing through the same operating states is captured: the generating-vent mode with a low power consumption (around 400 W); the pressurize-storage state during which full power is applied to the stack (8 kW); the steady state at three partial load conditions (25, 50, 75%), in which the power profile variates around a mean value roughly equal to, respectively, 25, 50 or 75% of the maximum power consumption; at last, the steady state at full-load, in which the power is maintained constant and equal to the maximum value (8 kW). This is the well-known dynamic behavior of the electrolyzer: the simple visual

comparison of the results has shown it can be captured from a remote location in the same way as on-site. In fact, the slight discrepancies emerging by comparing the two cases do not appear to be due to communication delays, but only to the fact that the electrolyzer behavior is not perfectly re-producible at subsequent start-ups. (For instance, the generating-vent mode can last longer depending on the initial water quality; the waveforms representing the power consumption at a certain time can be shifted depending on the switching control initial instant and so on.)
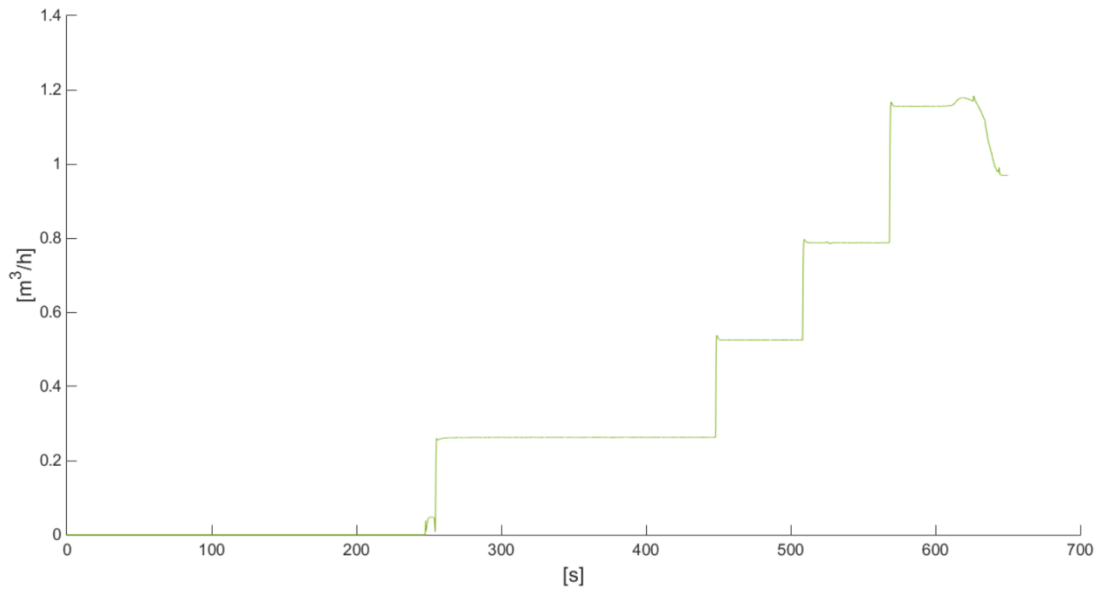

Figure 4-3: Production of H_2 – local measurements
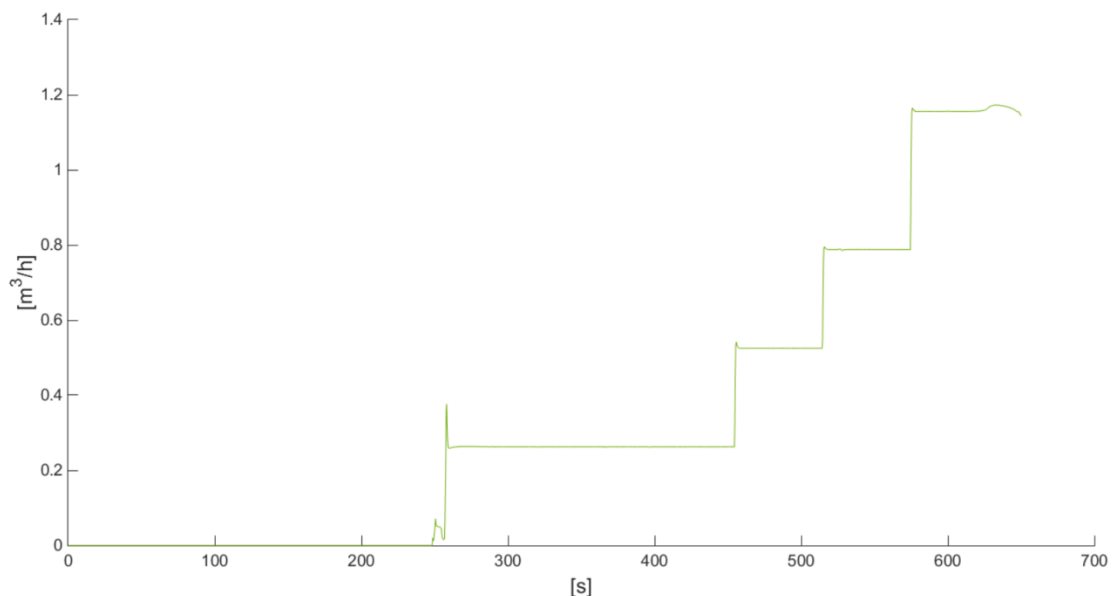

Figure 4-4: Production of H_2 – RHIL measurements

The hydrogen output flow measured both from Groningen and from Turin is presented in Figure 4-3, whereas the same parameter measured from Turin is shown in Figure 4-4. In both cases, it can be

seen that the dynamic behavior of the flow passing through the steady state at the four load conditions (25, 50, 75, 100% of the maximum output flow – averaged to 1.05 m^3/h) with a dynamic between the steady states that lasts no more than 1 s. Here again, it is possible to say that the two graphs are very similar, the dynamic of the flow can be captured without any visible difference between the remote and the local measurements.

Since the delay due to the data transmission via VPN between the two laboratories could not be inferred from a comparison of the graphs, it was necessary to pay attention to the logging time of the instruments and, for a further analysis, to look deeply into the packets exchange by using WireShark [16] software for network protocol analysis. From such analysis, it emerged that:

Power analyzer: the minimum sampling time handled locally is 20 ms. It can be respected on average when the instrument is read in remote. This is due to the way in which the High-Speed measurement mode is implemented [16]: the power analyzer is able to sequentially send the data packets to the PC without any need for query. It follows that, since the speed of the forwarded data is higher than the latency of the communication link, the packets are queued and then received at irregular intervals.

Flow controller: the minimum transaction time for the control through the Modbus interface equals 30 ms from Groningen and rises to about 100 ms from Turin. The minimum sampling times for the measurements through the implemented code in Matlab are 50 ms from Groningen and 14 0ms from Turin. This slight delay is because the communication of the instrument is based on a normal Modbus TCP/IP protocol, so that the request from the remote PC must be received before the instrument could send back the reply.

In conclusion, the latency introduced by the VPN communication only slightly affects the remote measurements in terms of regularity of the time step for the power analyzer and minimum sampling time for the flow controller. Also the transaction time for the remote control of the flow controller setpoint is marginally influenced. Nevertheless, the delays introduced in the entire control chain are minimal and do not prevent the use of the multi-site set-up for research purposes.

4.2 Test: Mathematical model inter-operability

This series of tests was aimed at carrying out the control and measurement of electrolyzer data from within a Matlab Simulink environment, both locally and remotely, in order to demonstrate the possibility of integrating the hydrogen production unit into co-simulations based on RHIL concepts. A Simulink model was created for this purpose, which is composed of three different conceptual parts:

- Flow controller Modbus writing: used to read the measured data of H$_2$ flow from the flow controller;

- Flow controller Modbus reading: used to write the setpoint of H$_2$ flow from the flow controller;

- Power analyzer TCP reading: used to read the three-phase active and reactive power from the power analyzer.

- Cinergia power amplifier Modbus reading/writing used to read and write the characterisation parameters of the grid;

Each part contains Matlab functions implemented on purpose either for writing or reading the data of the respective instrument, taking into account the protocol requirements and also the necessary translation (may be ASCII, binary, decimal or hexadecimal). The component parts of the Simulink models which are used for the device communication are shown in Figure 4-5, Figure 4-6, Figure 4-7, and Figure 4-8.
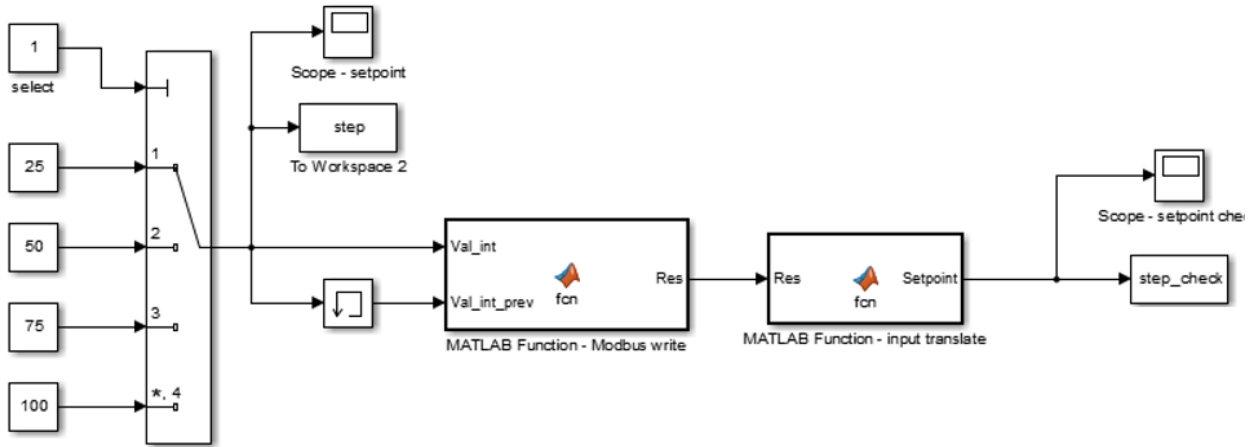
Figure 4-5: Simulink model subsystem: flow controller Modbus writing
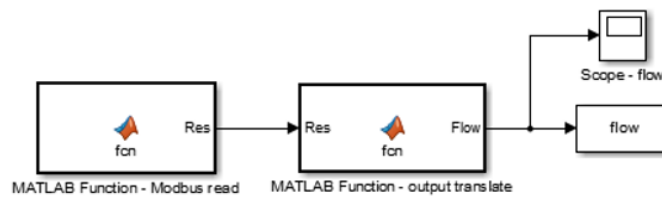
Figure 4-6: Flow controller Modbus reading
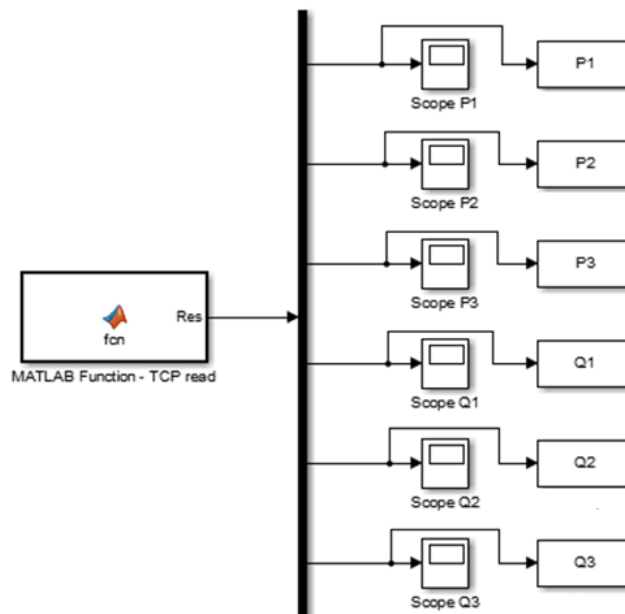
Figure 4-7: Simulink model subsystem: power analyzer TCP reading

Figure 4-8: Simulink model subsystem: Cinergia TCP / Modbus read/write

With this model, two identical tests were performed by giving the flow controller the same set points already described in the previous section, first locally from Groningen and then remotely from Turin.

Figure 4-9: Active power withdrawn by the electrolyzer – Local measurements

Figure 4-10: Active power withdrawn by the electrolyzer – RHIL Simulink measurements

The results obtained for the three-phase active power are shown in Figure 4-9 (model run from Groningen), and in Figure 4-10 (model run from Turin).
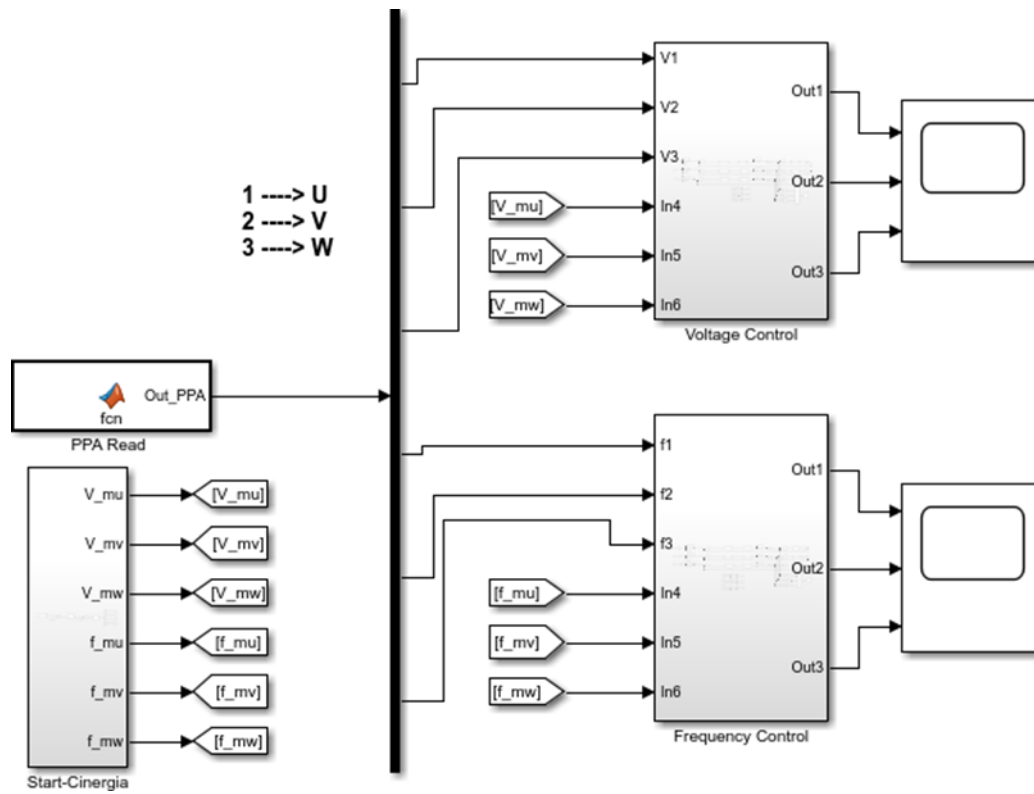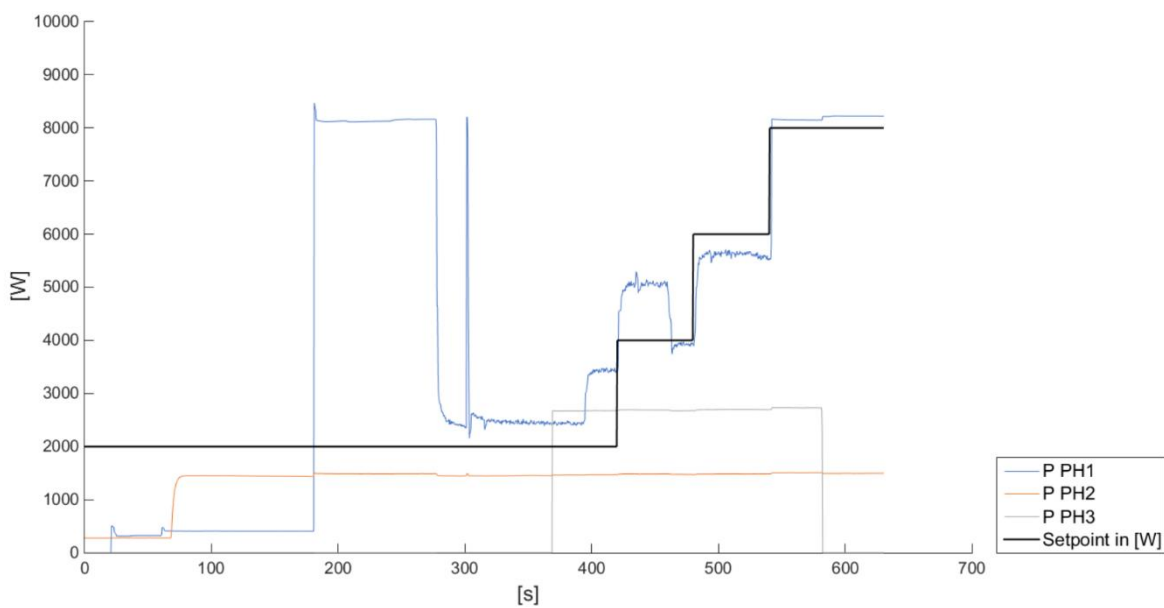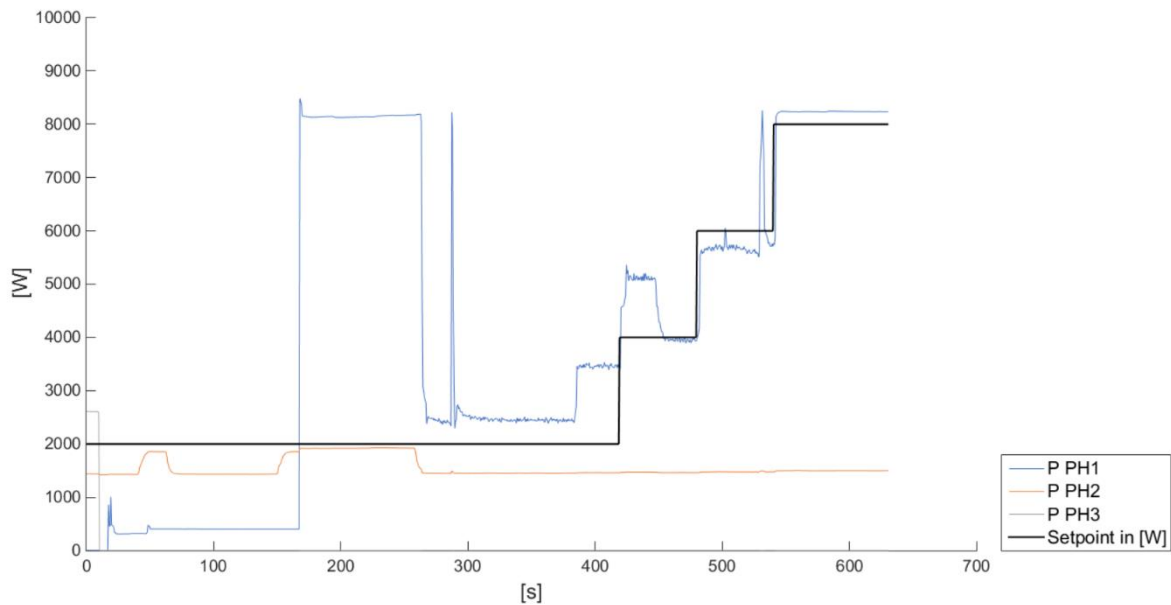
All the considerations on the electrolyzer dynamic behavior presented in the above section are still valid here. From both graphs, by focusing on phase 1, it can be observed the the electrolyzer start-up phase comprises generating-vent and pressurize-storage states; then the steady states at 25, 50, 75 and 100% of full-load, with an almost step change in between them. The only main difference highlighted in these cases is that the ranges of power variation are consistently reduced if compared with the results of the previous experimental set. The measured values at each time step appear to be the only an average of the real data within the considered interval.

This is due to the fact that, within the Simulink environment, the instruments cannot be read at the minimum sample time available as in the first cases, but this has to be necessarily higher because of the further latency introduced by the simulation. In fact, it is worth to notice that the Simulink block Matlab Function works by interacting with Matlab while running the simulation. At each simulation time step the model is shortly paused, the Simulink blocks interface with the respective Matlab file that runs the code to read/write data from and to the instruments. Finally, when the values are received, they are transferred from Matlab to Simulink and the simulation starts again moving to the subsequent time step.

This increased the minimum simulation time step to 400 ms when the model was run from Groningen. When the same model was run from Turin, the latency due to the communication Matlab-Simulink in addition to the delay due to the VPN communication further raised the minimum simulation time step to 600 ms. In both cases, this is the minimum fixed-step time that was possible to set. In fact, since the simulation time step also identifies the time period in which new values are requested and received from the instruments, a lower value would create too much data traffic which would slow down the communication and eventually lead to failure in the instruments and simulation crash.
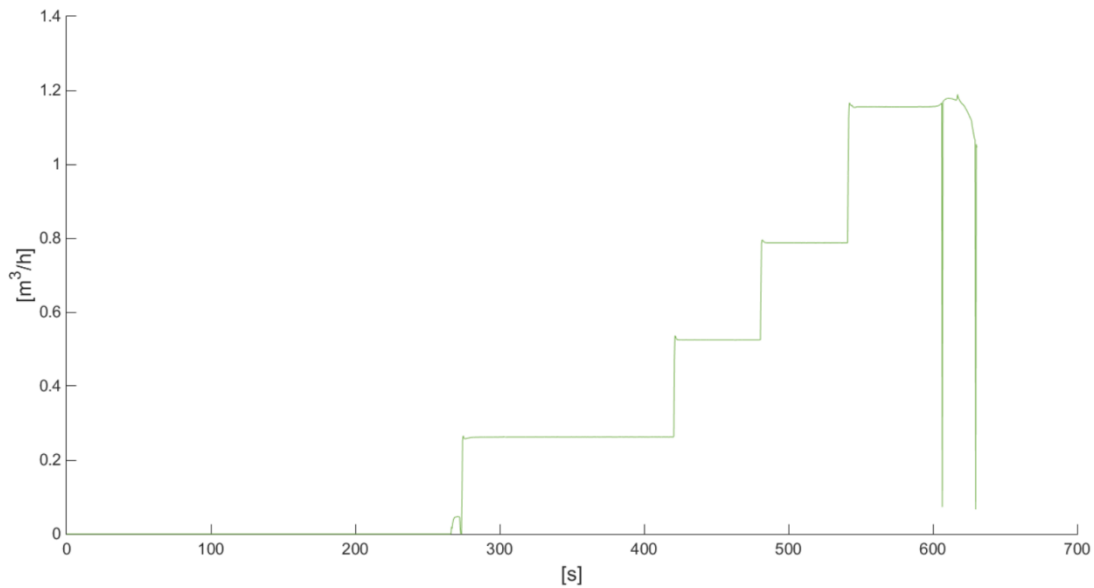
Figure 4-11: Simulink model subsystem: flow controller Modbus writing

The measurements of hydrogen output flow are presented in Figure 4-11 (model run from Groningen) and in Figure 4-12 (model run from Turin). The two graphs are barely distinguishable from the respective graphs obtained during the previous test case. In fact, unlike the power read from the power analyzer, the H_2 flow obtained from the flow controller is generally not influenced by the huge increment in time step due to the simulation latency. This is because the flow is constant during the steady states and does not present the variation typically analysed for the power. Only the accuracy in capturing the flow dynamic, lasting less than 1 s, might be influenced by the higher time step
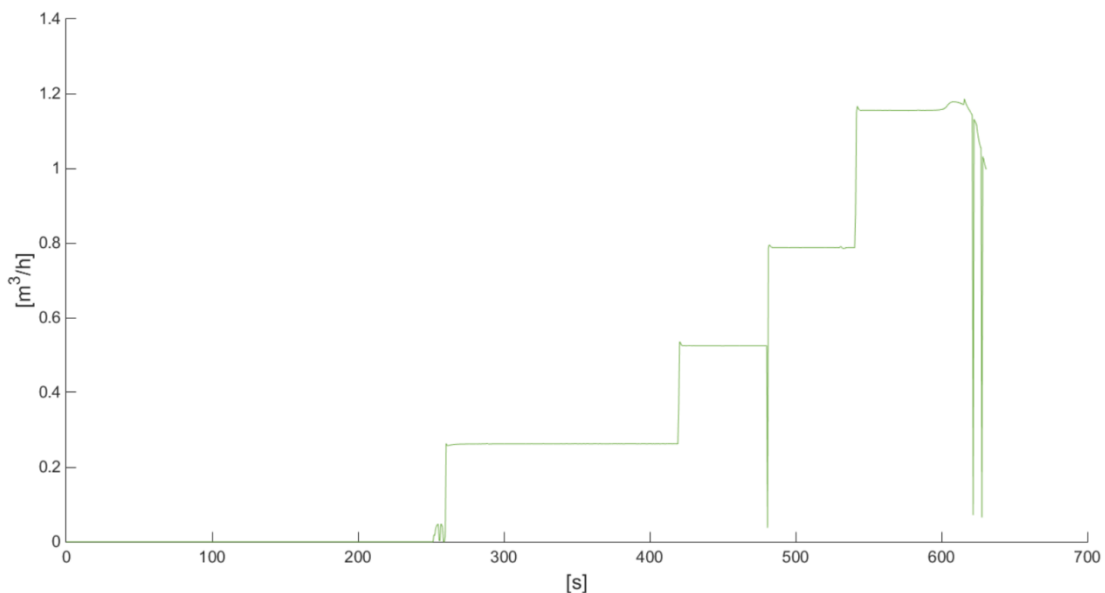
Figure 4-12: Production of H_2 – RHIL model measurements

At last, we presented the measurements of the grid alteration initiated from the model we have developed for the Cinergia grid emulator. In this test, the voltage increase is simulated while measuring with the complete setup. Figure 4-13 shows the local simulation of the generated three phase grid. The grid parameters in this simulation are measured with the power analyzer. The test is also run

from the remote location while we keep track of the latency between the simulation from the RTS lab at Politecnico Torino and the hardware facilities at Entrance Groningen. Because of zero latency, the local simulation shows a very quick responding when comparing voltage and set values.
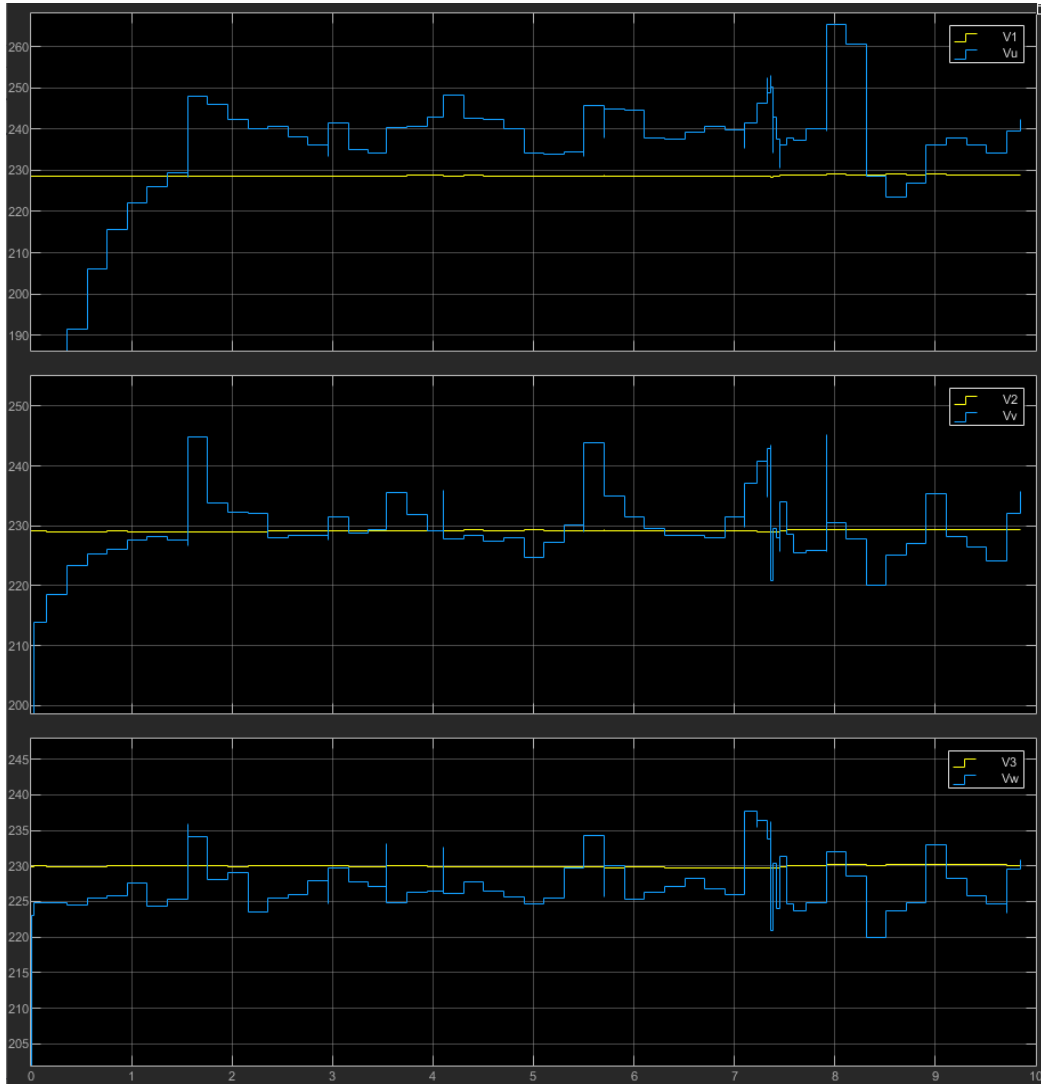
Figure 4-13: Voltage control – Local model measurements

Analysing Figure 4-14, the RHIL simulation has a high latency because the model interacts with the power analyzer and power amplifier sequentially. The RHIL results shows that higher latency leads to a reduction of the voltage adjustment corrections of the power amplifier. However, reducing the number of corrections leads to corrections with a smaller deviation, so that the result remains accurate.

Figure 4-14: Voltage control – RHIL model measurements

In conclusion, it is possible to manage the measurement and control chain of the electrolyzer and the grid within a simulation running locally and – what is more important, remotely, but this leads to limits in terms of minimum sample time for reading the instruments and minimum simulation time step. In particular, this influences the accuracy in reading the power from the power analyzer while the reading of the flow controller is marginally affected only with regard to the capture of the flow dynamics. Improvements in the method of integrating the measuring and control devices in Simulink may lead to a lower simulation time step (for example by developing appropriate Simulink S-function blocks for interacting with the instruments without need to interface with Matlab).

5   Conclusions

This report explained in detail all the technical aspects concerning the methods of the physical infra-structure for remotely acting on remote process devices at the Entrance facility, both in terms of control and measurements. The activities involved installing and testing the different infrastructure parts, as well as their connection(s). In particular, the main systems developed so far consist of:

- Local electrical grid, which can be managed either connected to the main grid or as an island. This infrastructure allows the connection of different components, aiming to replicate the "prosumer" environment, considering both loads and generation

- Measurement infrastructure, mainly composed of the power analyser, able to properly meas-ure with high sampling rate electrical variables (i.e., active and reactive power, current and so on), in such a way that the dynamic behaviour of the electrolyzer could be captured and used later in simulations

- Communication infrastructure, for sending in quasi-real time the collected measurements, but also for sending the control signals for changing the operative conditions of the remote connected device(s)

- Control system acting on the flow controller and power amplifiers. This control allows to mod-ify the production of hydrogen, i.e., analysing how the system reacts in case of change of the production and grid alterations. The power amplifiers will act also directly on the electrical inputs (AC side), for replicating the network conditions simulated in another platform (i.e., real time simulator). The modification of the electrical inputs is reached through the supply of the entire system through the Cinergia power amplifier.

The method and test field developed and tested is, up to know, applied to a small scale plant, but it demonstrates the possibility to use the same of infrastructure to collect information (in real time) also from larger plants, such as the ones installed at the demo sites. This opens the possibility to use the data for research purposes, but also to act remotely on the infrastructure in case of particular tests (for example the acceptance test).

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[4]   "OPAL is a trademark of OPAL technologies." .

[5]   "Triphase is a registered trademark of National Instruments." .

[6]   Cinergia, "GE – Grid Emulator GE – Grid Emulator," pp. 1–6.

[7]   M. Stevic *et al.*, "Virtual integration of laboratories over long distance for real-time co-simulation of power systems," in *42nd Annual Conference of IEEE Industrial Electronics Society*.

[8]   Simulink, Mathlab Simulink developed by MathWorks, is a graphical programming environment for modeling, simulating and analyzing multidomain dynamical systems. Its primary interface is a graphical block diagramming tool and a customizable set of block libraries. It offers tight integration with the rest of the MATLAB environment and can either drive MATLAB or be scripted from it. Simulink is widely used in automatic control and digital signal processing for multidomain simulation and Model-Based Design Mathlab, Simulink are registered trademarks . https://nl.mathworks.com/products/simulink.html.

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6 Appendix 1: PoliTo's global real time simulation Lab

This section presents the Global Real Time Simulation Lab (G-RTSLab): in the follow, the mission of the lab is briefly introduced together with the use for the project STORE&GO. Then, the hardware and software facilities are presented. Finally, a set of systems already implemented with this philosophy is shown, for clarifying the multi-purpose role of this tool for studying the electricity (and more in general, the energy) sector.

6.1 Mission and use in the project STORE&GO

The G-RTSLab, located at Politecnico di Torino, is an internationally interconnected laboratory of real-time simulation.

Its aim is the study of the role of electricity in the energy transition, as well as the investigation of new features for allowing the implementation of smart grids and super grids.

The activities of the G-RTSLab are integrated into the Energy Center Lab (EC-Lab), where interdisciplinary studies related to different energy sectors (e.g., electricity, gas and heat) can be studied entirely. The modelling of the above systems can be effectively made through extensive use of real hardware, for the correct characterisation of the different devices. Thanks to the possibility to connect through internet devices located in different physical places, the use of RTS results a winning approach for developing a unique distributed laboratory running the same experiment at the same time. This fact provides different advantages:

- The possibility to share facilities all around the world: the share allows the efficient use of different facilities, by avoiding replication. Furthermore, the share of knowledge becomes easier, due to the engagement of different researchers at the same project

- The possibility to not share data, but only input and outputs. An example is the possible use of results coming from the elaboration of confidential data, which should not be shared with the partners (e.g., modelling of National transmission network), but can be used on another platform (belonging to third part) synchronised with it.

In the project STORE&GO, the presence of different facilities in Hanze led to consider the possibility of characterising the behaviour of a "global prosumer" (i.e., producer and consumer of both gas and electricity) connected to a distribution network.

The choice to characterise the prosumer comes from the size of the facilities there, which are suitable for this kind of purpose.

An overview of the lab is provided in Figure 6-1. In the following, its features will be explained, by relating them with the components installed

Figure 6-1: Overview of G-RTSLab at Politecnico di Torino

6.2 Hardware and software configuration

The core of the laboratory is the Real Time Simulator OPAL-RT 5600, shown In Figure 6-2.

Figure 6-2: Real Time Simulator OPAL-RT5600

The characteristics of it are summarised in the list below:

• OP5600 HIL Box Real-Time Computer 3.46 GHz, 12 cores (Spartan 3 Platform)

• Red Hat Linux Intel C compiler

• Intel EXPI9404PTL PT Quad Port Ethernet Server Adapter 10/ 100/1000 Mbps PCI-Expres 4 x RJ45 (for IEC 61850 and other Ethernet based protocol)

• Digital Output Card (32 Channels, Push-Pull, galvanic isolation 5 V to 30 V)

• Digital Input Card (32 Channels, Opto coupler, 4.5 V to 30 V)

• Analog Input Card (16 Channels, 16 bits, 2.5 us, ±16 V)

• Analog Output Card (16 Channels, 16 bits, 1 us, ±16 V)

• RT-LAB Host/Workstation License - Professional

Two software configurations are installed:

• eMEGAsim

• ePHASORsim (Up to 2000 nodes)

Table 6-1: Table Characteristics of the two software configurations available

Features	eMEGAsim	ePHASORsim
Simulation type	Electro Magnetic Transient (EMT) domain	Phasor domain
Typical time step	Network solution: 10 – 100 µs Switches and converters: 200 ns – 2 µs	1 ms – 10 ms
Compatible modelling environments	Simulink, Simscape Power System	Simulink, Excel, PSS®E, CYME, Power Factory, FMU (Open Modelica)
Maximum real-time network size	300 3-phase nodes (900 nodes)	30,000 nodes
Maximum non real-time network size	1,500 3-phase nodes (5,000 nodes)	100,000 nodes
Additional characteristics	Dedicated SSN solver Application Programming Interfaces: Python, C, Java, LabVIEW Multi-physical domain simulation	10,000 nodes @ 10 ms

6.3 Networks

For the features of the hardware described above, the idea is to connect it to a node of a low voltage (LV) network. Currently, a working version of a network sample composed of both MV feeder and LV networks is already implemented on RTS, and shown in Figure 6-3**Fehler! Verweisquelle konnte nicht gefunden werden.**. The main characteristics of the network are given in Table 6-2

Table 6-2: Main network characteristics

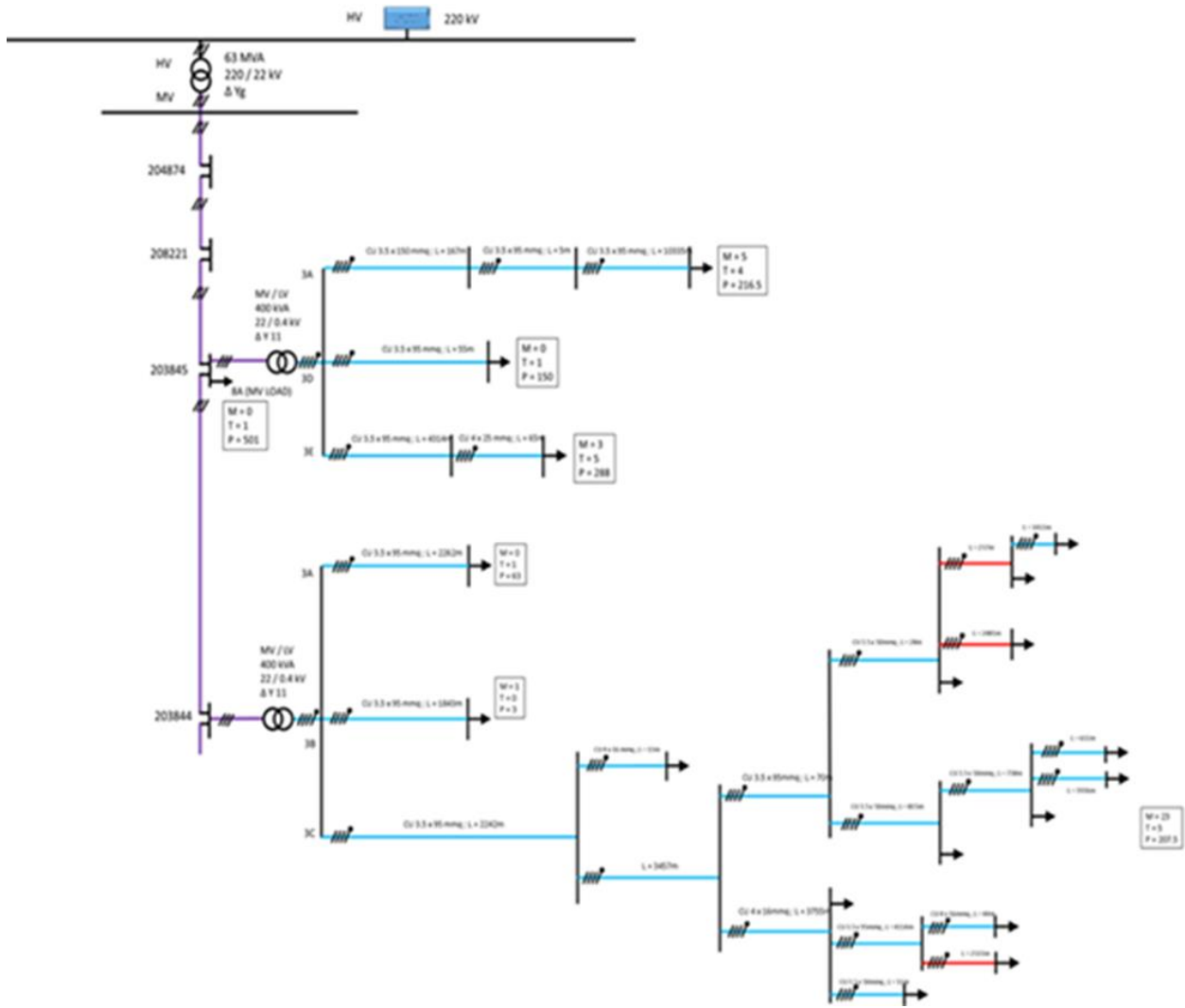|	
Number of LV networks	2
Total number of buses	33
Total number of lines	29
Total length of MV feeder	5,32 km
Total number of 1-phase customers	32
Total number of 3-phase customers	17
Total load installed	1429

Figure 6-3: LV network implemented in OPAL RT