POLITECNICO DI TORINO

Collegio di Ingegneria Elettrica

Tesi di Laurea Magistrale

Remote Hardware In-The-Loop for PtG Integration

Supervisors

Prof. Ettore BOMPARD

Prof. Enrico PONS

Dr. Andrea MAZZA

Ir. Harm LOK

Candidate

Giuseppe MIANO

Luglio 2020

Acknowledgements

Prima di procedere con la trattazione, mi è doveroso dedicare questo spazio del mio elaborato alle persone che mi sono state vicine in questo percorso di crescita personale e professionale.

In primis, un ringraziamento speciale al mio relatore Prof. Andrea Mazza, per la sua immensa pazienza e disponibilità, per i suoi indispensabili consigli, per le conoscenze trasmesse durante tutto il percorso di stesura dell'elaborato.

Vorrei ringraziare anche il Prof Harm Lok e Marvin, per avermi accolto a braccia aperte nel laboratorio dell'Hanze University of Groningen e per tutto il tempo dedicatomi durante i mesi di permanenza nei Paesi Bassi.

Ringrazio infinitamente mio Padre e mia Madre, senza di loro tutto questo sicuramente non sarebbe stato possibile. Grazie per esserci sempre, grazie per tutti i sacrifici che avete fatto e per avere sempre sostunuto le mie scelte. Grazie veramente di TUTTO.

Ringrazio i miei nonni, per il vostro immenso amore, per gli insegnameti e i valori che mi avete trasmesso.

Grazie a Emanuele, Tony, Sara, Marco, Ciccio, Peppe Gullo per tutti i momenti passati in questi anni unversitari, facendomi sentire parte di una grande famiglia.

Un grazie particolare va Fabiana, che in questi mesi sei sempre stata presente supportandomi e sopportandomi nei momenti in cui ho avuto più bisogno, trovando sempre la parola giusta per risollevarmi e andare avanti. Grazie, senza di te tutto sarebbe stato molto più difficile.

Grazie ai miei amici d'infazia Antonio, Mirko, Peppe Giulio, Peppe Calca e Alessandro per esserci sempre stati e per tutti i momenti di spensieratezza.

Infine rigrazio i miei colleghi Tano, Chiara, Antonio e Andrea per avermi sempre incoraggiato fin dall'inizio del percorso universitario.

"All progress takes place outside the comfort zone"
Michael John Bobak

Summary

Power-to-Gas (PtG) is a technology that uses electricity to produce hydrogen through a process of electrolysis. This one can be used directly or, after appropriate conversation into syngas or methane, it can be used as chemical raw materials, burned to produce heat, or converted to electricity by means conventional generators or gas turbines.
The presence of generation from renewable sources is becoming larger and larger in our electrical systems, and this often causes the production higher than the demand. In this context, the proper use of PtG represents an alternative energy storage to reduce the renewable curtailment.
The study conducted in this thesis aims to improve the knowledge on the impact of a PtG inserted in a distribution network with the presence of photovoltaic generation, using the test technique known as Power-Hardware-In-the-Loop (PHIL).
Power-Hardware-In-the-Loop aims to replicate real-world conditions for carrying out meaningful tests on device prototypes and new technologies, like PtG, which be deployed in real energy systems. The purpose is tuning, validating and verifying the system performances or collecting data with the objective to create realistic device models – all this avoiding to deploy the device directly into the grid, which may be harmful for the grid itself, or when the device needs to be tested under uncommon conditions that may be hard to reproduce.
PtG is a load, which consumes energy: for this, an interface is needed to enable power exchange. This interface is composed of a power amplifier and a set of sensors monitoring the load; the power amplifier acts as a source or user. From the simulated grid, the extraction of the values of voltage or current to control the output of the power amplifier is allowed. If a load is equipped with current or voltage sensors, it is possible to extract the current or voltage required by the load and sent them as feedback to the software grid to close the simulation loop.
The first step was to develop a Simulink model that well represents the distribution network considered in the STORE&GO roject, considering the load and generation profiles of a generic October day.
Furthermore, before connecting the PtG to the simulated network, it was necessary to design the control of the power amplifier, so that the PtG can be powered at

the same voltage and frequency as the simulated network. The designed control is a closed-loop type. In each cycle, this control increases the output voltage and frequency of the power amplifier until the reference values are reached.
The PtG and the Power Amplifier considered in this thesis are placed at Hanze University in Groningen (NL), but thanks to a Virtual Private Network (VPN) connection, the Global Real-Time Simulations laboratory of Politecnico di Torino can remotely control these devices through proper Simulink models.
The aim was to connect the electrolyser, situated at Hanze University, to the simulated network, but this was not possible due to the Covid-19 emergency, which forced the closure of the Hanze University laboratory. As a consequence, a Simulink model of a PtG was reproduced, complete with electrolyser, storage system and methanator, by analyzing the impact of the PtG system on the network. The results obtained are considered very satisfactory. In fact, it can be said that the addition of PtG systems in a distribution network can improve grid operation even for very high photovoltaic penetrations, by increasing its ability network to host a higher penetration of generation non-programmable, giving more flexibility to the electrical system.
Also, the integration of PtG solves grid problems, i.e. reverse power flow, overcurrents and overvoltages. In conclusion, the research results show that PtG can be a good solution both as a storage system and as a means to improve grid conditions with a large amount of installed renewable energy.
The interconnection between the two laboratories, together with the set-up of the power amplifier, will allows to reproduce the simulations results by using a real device. Thus, this thesis has provided all the tools for future collaborations between the two institutes and all the models required to verify the effectiveness of the approach based on PHIL.

Table of Contents

List of Tables

List of Figures

Acronyms

RES
: Renewable Energy Sources

PtG
: Power to Gas

SNG
: Synthetic Natural Gas

CO_2
: Carbon Dioxide (chemical compound)

H_2
: Hydrogen (chemical compound)

O_2
: Oxigen (chemical compound)

H_2O
: Water (chemical compound)

O^{2-}
: Oxigen Ion (chemical compound)

H^+
: Hydrogen Ion (chemical compound)

CH_4
: Methane (chemical compound)

KOH

Potassium Hydroxide (chemical compound)

NaOH

Sodium Hydroxide (chemical compound)

OH^-

Hydroxide Ions (chemical compound)

PEM

Protn Exchange Membrane

SOEC

Solid Oxide Electrolysis

MEA

Membrane Electrode Assembly

HIL

Hardware In the Loop

PHIL

Power Hardware In the Loop

RPHIL

Remote Power Hardware In the Loop

HuT

Hardware Under Test

RoS

Rest of the System

RTS

Real Time Simulation

G-RTSLab

Global Real-Time Simulation Lab

EnTranCe
Energy Transition Centre

RMS
Root Mean Square

LAN
Local Area Network

USB
Universal Serial Bus

CSV
Commma Separated Values

PLC
Programmable Logic Controller

RO
Reverse Osmosis

AC
Alternative Current

DC
Direct Current

EUT
Early User Test

PWM
Pulse Width Modulation

IGBT
Insulated Gate Bipolar Transistor

FFT
Fast Fourier Transform

CF

Capacity Factor

THD

Total Harmonic Distorsion

TCP/IP

Transmission Control Protocol/Internet Protocol

HMI

Human Machine Interface

SPI

Serial Peripheral Interface

RTT

Real Time Target

VPN

Virtual Private Network

HV

High Voltage

MV

High Voltage

LV

Low Voltage

PV

Photo-Voltaic

SD

Secure Digital

UDP

User Datagram Protocol

Chapter 1

PtG: To Increase the Efficiency of Electrical System

1.1 Introduction

In recent years, the energy sector is undergoing substantial changes in order to promote better efficiency, increase the use of Renewable Energy Sources (RES), reduce carbon emissions and develop new technologies, which allow a fair balance between costs and benefits. One of the principal problems of RES production is its variability. Indeed, when the generation exceeds the electrical demand, it is necessary a RES curtailment. In this context, one of the main challenges is the necessity of introducing more flexibility to the existing system in order to reduce the RES curtailment. In this framework, Power to Gas (PtG) technology represents a suitable solution for the long-term storage of the electricity produced by RES-based plants. Actually, PtG is able to give more flexibility to the electrical system and it allows to convert electricity into gas. In particular by providing a certain amount of electricity it is possible to obtain, by means of the electrolysis process, Hydrogen (H_2) and, subsequently, using a methanation process Synthetic Natural Gas (SNG). Thanks to the transformation of excess electricity into gas, the PtG represents a strategy alternative energy storage in times of surplus. The H_2 and/or SNG produced, therefore, represent a strategy to accumulate energy at times (or possibly in places) when there is a surplus of production compared to demand. SNG and H_2 can be subsequently used for the production of electrical and thermal energy (through the use of cogeneration engines and/or fuel cells) for transport (considering both methane and hydrogen powered vehicles) or directly fed into the gas distribution network for domestic use.

1.2 Technological overview of PtG

In order to carry out the functions in support of the electricity grid, a PtG plant needs an amount of energy, which is taken from the electrical system to which it's connected and controlling the electrolyser, so it's possible to change the power required by the PtG, so it can participate actively in the operation of the system.

A PtG plant is composed of the following parts:

- An electrolyser, which produces H_2;
- A methanation process;
- A Carbon Dioxide (CO_2) source, necessary for the methanation step;
- Storage facilities;

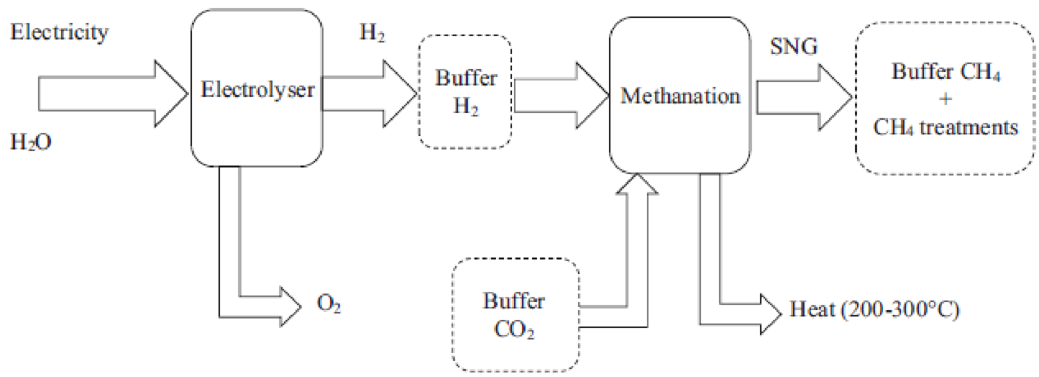

Figure 1.1: Scheme of a Typical PtG Installation [1]

From Figure 1.1, it's possible to see both the input, i.e. electricity, Water (H_2O), CO_2, and outputs, i.e. SNG, Oxygen (O_2) and heat. A further energy input is required to supply the auxiliary services, like the energy for pumping the H_2O, for pressuring the H_2.

1.2.1 Electrolyser

The electrolyser is a device that allows the production of H_2, absorbing energy from the grid, through the split of H_2O. That is, it converts electrical energy into chemical energy, according to endothermic Reaction 1.1:

$$H_2O_{(l)} + energy \leftrightarrow H_2 + \frac{1}{2}O_2 \tag{1.1}$$

The elementary electrolysis cell consists of two metallic electrodes, an anode and a cathode, immersed in a liquid electrolyte. A thin electrolytic layer, consisting of a diaphragm impregnated with the electrolyte, is placed between the electrodes and acts as an electric isolator. Because the reaction is non-spontaneous, electrical work is applied to the cell in order to dissociate H_2O molecules into its constituents and generate gaseous hydrogen.
Specifically, direct current passes between the two electrodes, where the charge carriers are the electrons, and then flows through the electrolyte, with the charges being carried by the mobile ions. This current flow provides the necessary energy to split the H_2O molecules into their constituent elements. The diaphragm serves as an electric isolator and maintains the evolving gas streams separated, to prevent their spontaneous chemical recombination by diffusion in the interpolar area. As a result of the process, O_2 is formed at the anodic (positive) terminal and H_2 at the cathodic (negative) terminal, the production being directly proportional to the current flowing through the electrodes. Since individual cells are of limited production capacity, they are stacked together to obtain the production capacity most appropriate for the process requirements.

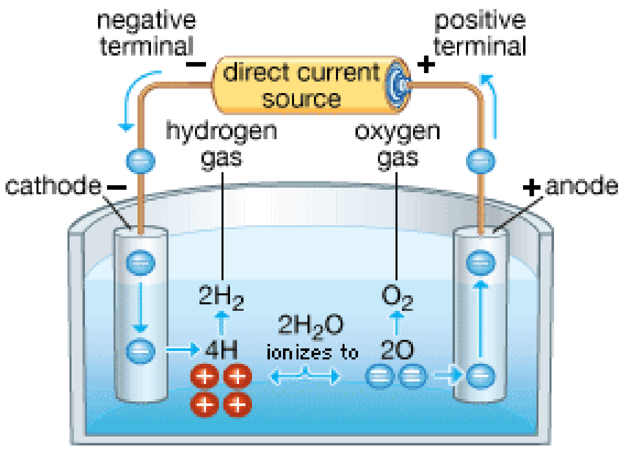

Figure 1.2: Electrolysis Cell [2]

The consumption of energy for the reaction depends on the technology, that is used, the temperature and the pressure of the process.
The principal technology can be used are three:

- Alkaline Electrolysers;
- Proton Exchange Membrane Electrolysers (PEM);
- Solid Oxide Electrolysis (SOEC);

Alkaline Electrolysers

Alkaline electrolysis is a mature technology. Several megawatt industrial electrolysers are used in the industry for the large-scale production of H_2 in view of different end-uses. It is a type of electrolyser that is characterized of two electrodes operating in a liquid alkaline electrolyte solution of Potassium Hydroxide (KOH) or Sodium Hydroxide (NaOH). These electrodes are separated by a diaphragm, dividing the product gases and transporting the Hydroxide Ions (OH^-) from one electrode to the other.
The electrodes are typically separated by a thin porous foil (with a thickness between 0.050 to 0.5 mm), commonly referred to as diaphragm or separator. The diaphragm is non-conductive to electrons, thus avoiding electrical shorts between the electrodes while allowing small distances between them. The ionic conductivity is supplied by the aqueous alkaline solution, which penetrates in the pores of the porous diaphragm.
In alkaline electrolysis cells, H_2O goes into the cathode and here is divided into H_2 and OH^-. So, in an external separator, H_2 is separated from H_2O, while OH^- move to the anode producing O_2.

The process is described by Reactions 1.2, 1.3 and 1.4.

$$Anode : 2OH^{-} \rightarrow H_2O + \frac{1}{2}O_2 + 2e^{-} \tag{1.2}$$

$$Catode : 2H_2O + 2e^{-} \rightarrow H_2 + 20H^{-} \tag{1.3}$$

$$Overall\,cell : H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{1.4}$$

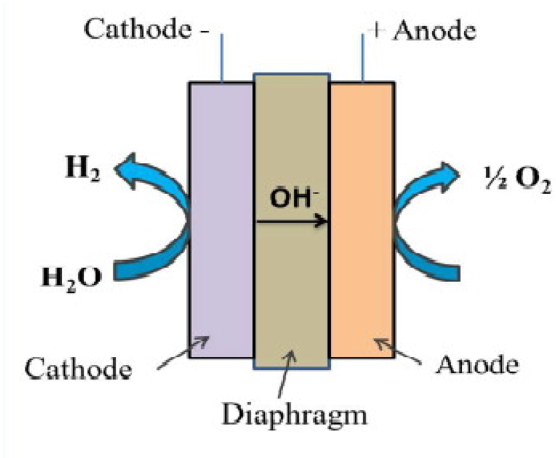

Figure 1.3: Schematic Working Principle of Alkaline Electrolysis [3]

PEM Electrolysers

The PEM technology for water electrolysers was developed in 1966 by General Electric. It takes its name from the use of a polymer membrane as an electrolyte. This membrane has the double purpose of acting both as cell separator, (to separate gas products and avoid recombination), and as electrolytic media, (to move ionic charges between the electrodes). The membrane surface is covered on both sides by two porous catalytic layers, on which current collectors are pressed to create electric contacts for the electrodes. The obtained structure is called Membrane Electrode Assembly (MEA). The final result is a cell without liquid electrolyte: the only liquid element is the de-ionized water feeding the electrochemical reaction. Therefore, it is possible to use acidic media avoiding the dissolution of metallic catalysts due to the highly acidic environment. For this, noble materials have been adopted as catalysts. This aspect significantly increases the cost, which is twice the cost of the alkaline technology. In PEM cells, H_2O goes into the anode and here is divided into O_2 and Hydrogen Ions (H^+). So, O_2 stays in the aqueous admixture, which is ejected from the anode, while H^+, across the membrane, goes to the cathode where are recombined with electrons to form H_2.
The process is described by Reactions 1.5, 1.6 and 1.7.

$$Anode : H_2O \rightarrow 2H^+ + \frac{1}{2}O_2 + 2e^- \tag{1.5}$$

$$Catode : 2H^+ + 2e^- \rightarrow H_2 \tag{1.6}$$

$$Overall\ cell : H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{1.7}$$

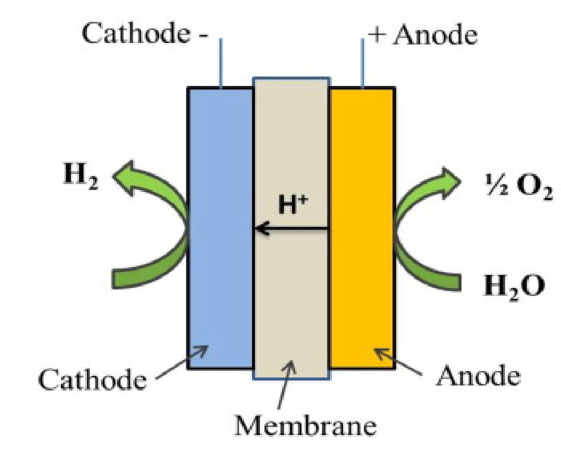

Figure 1.4: Schematic Working Principle of PEM Electrolysis [3]

PEM has different advantages compared to alkaline technology:

- Thinner and more compact cell, with excellent chemical properties and mechanical stability and durability;
- The absence of liquid electrolyte, that allows the operation at elevated current densities in the range 0.5-2 A/cm^2 as well as pressure differences between electrodes potentially up to 100 bar. In this way, highly compressed H_2 can be produced on one side, while simultaneously the feedwater and the O_2 produced can be kept at atmospheric pressure on the opposite side, thus reducing the risks associated with the handling of O_2 pressurized;

Table 1.1: Technical Parameters of the Major Technologies [4]

Type	**Alkaline**	**PEM**	
Rated Power	0.055 - 1.5	0.008 - 2	[MW]
Rated Production	0.4 - 760	0.53 - 400	[Nm^3/h]
Energy Consuption	7.5 - 5	5.8 - 6.7	[kWh/Nm^3]
Efficiency	47 - 70	48 - 61	[%]
Operating Pressure	1 - 30	10 - 30	[bar]
Operating Temperature	65 - 100	20 - 100	[°C]
Current Density	0.2 - 0.4	0.5 - 2	[A/cm^2]

Solid Oxide Electrolysis

Solide Oxide Electrolysis (SOE) is a high-temperature steam electrolysis technology. It was developed for the first time in Germany in 1970s and is still at the development stage. The SOE is alkaline and Oxygen Ion conductor (O^{2-}), so the reactions are similar to the ones governing the alkaline cell. The principal difference is that the reaction in SOE cellis carried out at high temperatures (approximately 700-1000 °C) with water steam instead of liquid.
Reactions governing the process are 1.8, 1.9 and 1.10.

$$Anode : O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^- \tag{1.8}$$

$$Catode : H_2O + 2e^- \rightarrow H_2 + O^{2-} \tag{1.9}$$

$$Overall\,cell : H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{1.10}$$

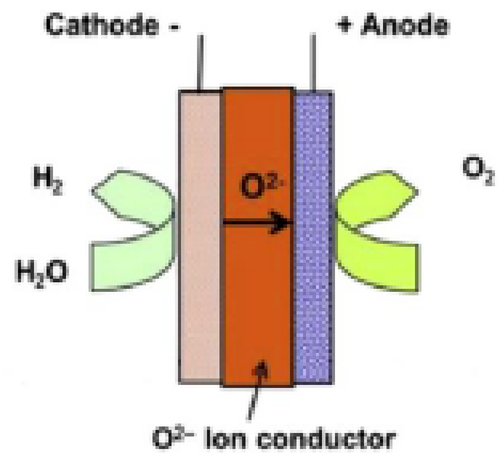

Figure 1.5: Schematic Working Principle of SOE Electrolysis [3]

1.2.2 Methanation Process, CO_2 Production and Storage

The PtG consists of an electrolyser, a buffer tank and a methane tank. The electrolyser has a very fast operating dynamics, able to respond practically instantly at the input set-point. On the other hand, the methanator is not able to respond so quickly, thus a tank is installed to decouple the two process. When the tank is full (the electrolyser can produce more hydrogen than the methanator can dispose of), the electrolyser is connected directly to the methanation unit (bypass). This fact means that the system will no longer work at maximum efficiency, but since the methanator will not be able to respond to the changes in the electrolyser, this will decrease, also the composition of the final SNG will be affected, in fact, the quality and purity of the methane produced will be lower. With it will also decrease the power absorbable by the PtG, because it is in a saturation situation.
The methanation process consists of the production of Methane (CH_4) or SNG by using H_2 and CO_2 as input and of releasing a consistent amount of heat. The final product is called renewable power methane and it could be a substitute of conventional natural gas because it can be used in the same applications without the limitations associated to H_2 usage.

The methanation reaction is an exothermic process in which CO_2 reacts with H_2, in the presence of a catalyst, producing CH_4 with H_2O as shown by Reaction 1.11.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{1.11}$$

Therefore, CO_2 is necessary for the methanation process. Possible CO_2 sources are:

- CO_2 from carbon capture;
- CO_2 from biomass;
- CO_2 from industrial processes;
- CO_2 from air;

Finally, proper containers are needed in order to store the gases involved in the process. Storage makes it possible to purchase and store gas in the summer months, when demand for gas and the cost of raw material are lower, and then use it in the winter months, when demand for gas and its cost increase.

During storage, the gas undergoes two processes: during the injection phase, the gas is compressed into the reservoir using the compressor stations, whose turbines push the gas volumes inside the wells until the reservoirs are filled according to the defined pressures (compression), while during the supply phase, the gas present in the reservoir is dehydrated to free it from water and hydrocarbons present in the formation and thus make it usable (treatment).

In the field of storage, a distinction is made:

- Strategic storage, aimed at making up for situations of lack or reduction in supply or crisis in the gas system;
- Modulation storage, aimed at satisfying the modulation of daily, seasonal and peak consumption trends;
- Mineral storage, which is necessary for technical and economic reasons to allow the optimal development of natural gas field cultivation in the territory;

The gas storage facility can be built using deep geological structures, suitable for receiving, storing and withdrawing gas. These structures are essentially of two types:

- Depleted or nearing depletion of gas production fields;
- Porous and permeable underground structures obtained from aquifer basins;

1.3 PtG in the Electrical Sector

This section describes the improvement that the integration of PtG can bring in the different sectors of electricity system.
The electrical system consists of:

- Generation side: through different types of power plants (thermoelectric, hydroelectric, nuclear, wind, photovoltaic, etc.). Generally, the electricity produced by the generators of these plants is Medium Voltage (MV) to avoid problems and very high costs for electrical insulation;
- Transmission side: at the output of the production plants, some transformers raise the voltage from MV to very high (15/30kV to 220/380kV). The main reason for raising the voltage to similar levels is to reduce line losses and the cost of conductors, to import large amounts of energy, without having too large currents and consequently conductors with high cross-sections. The transmission network is typically a meshed network to ensure operational reliability. The lines of this network are very long (even hundreds of km), so they allow a transfer of electricity over long distances. Connected to the transmission grid is the sub-transmission grid, which connects the transmission grid to the distribution grid. Between the transmission grid and the sub-transmission grid, there are lowering transformers to switch to High Voltage (HV), usually to 150/120kV;
- Distribution side: The distribution network is connected to the sub-transmission network via HV/MV lowering transformers (from 150/120kV to 20/15kV). System operation is radial. In most cases, these networks can be weakly meshed. Therefore, there are redundant connections kept open to ensure the operation of the radial network. The distribution network can be divided into two parts: the MV network with lines a few km long with a voltage between 20 and 15 kV and the Low Voltage (LV) part with 400V, typically the most common houses and loads are connected to this network (utilization side) . Between the two parts of the grid, there are MV/LV lowering transformers. The structure of the LV network is radial;

1.3.1 Generation Side

In this area, it is made a differentiation between dispatchable and non-dispatchable power plants. The first ones include plants with controllable generators (such as based on fossil), while the second ones are non-controllable generator, (like solar and wind plants).
The application of PtG to dispatchable plants allows:

- More flexibility, because of the increase in the energy-shifting possibilities from electricity to gas and vice versa. This is helpful for the system when variations in the electrical power injected into or drawn from the electrical network are needed for control purposes or to provide reserve services to the system;
- Arbitrage opportunity, in economic terms the possibilities to supply a system by power or fuel involves a careful economic assessment of the provision of services and the costs of selling and purchasing both energy vectors;
- CO_2 emission reduction, because of the possibility to employ the carbon dioxide resulting as a byproduct of the plant for the process of methanation;

On the other hand, the application of PtG to non-dispatchable plants can lead to:

- Reduce the RES curtailment; in fact, during peak power production periods, it is possible to store the energy by converting electricity into gas;
- Introduce an integrated energy system based on RES. The gas-electricity integration facilities can help in improving the dispatchability of these power plants;

1.3.2 Transmission Side

On the transmission side, the applications of PtG can be distinguished in ancillary services, energy storage RES integration and system management.

Ancillary Services

The ancillary services are necessary to ensure the security and the stability of the entire electricity system. The applications for which PtG can find a role are the following:

- Spinning reserve: PtG shows characteristics suitable for the substitution of conventional power plants in spinning reserve operations through demand response;
- Frequency and voltage regulation, because increasing the penetration of RES in the electrical system, the voltage and control is becoming more difficult to due the mismatch between the production and consumption;
- Load following and load levelling, because the integration of PtG can help to shape load and generation profiles;
- Unit commitment: PtG could cover the mismatch between the forecasted and actual renewable production;

Bulk Energy Storage and RES Integration

The PtG could be a good solution for energy storage, simplifying the achievement of the balance of power grid and the reduction of network congestion time. This results in a general improvement of the network flexibility, which represents a key factor for the integration of RES in the electrical system.

System Management

One of the principal advantages of the PtG is that it is a connection between the electrical and gas systems. The integration of these two systems would allow to simultaneously manage them on the basis of joint technical and economic assessments. The major results would be the alleviation of both gas and electricity network congestion caused by transfer limits, as well as the modification of gas and electricity prices in accordance to market trends.

1.3.3 Distribution Side

On the distribution side, there are many problems due to the increase of the RES penetration which is changing the traditional passive distribution network into an active network. When the production is higher than load, there will be problems related to the inversion of the power flow (the power starts flowing backward along the feeder).
The PtG, like for the transmission system could be a good solution to improve the voltage and frequency control and it can play the role of coupling facilities between the electrical and gas network also at the distribution level. The optimal management of the integrated system would likewise leads to improvements in the operation of both networks.

1.3.4 Utilization Side

On the utilization side, PtG applications can be according to the size of small, medium, and large scale applications. The user, who owns a PtG plant, is called prosumer, because is both producer and a consumer of electrical energy, so the prosumer identifies an entity capable to produce and consume both electricity and gas. Prosumer produces the energy it uses, accumulates it and exchanges it with the network, thus, reducing the cost of buying it and the pollution to transport and store it. The prosumer self-consumes, produces, accumulates in a modern way, and in the near future, it could potentially resell the excesses on the free market.

Chapter 2

The Real Time Micro Grid Laboratory

2.1 Introduction

The Real-Time Micro-Grid laboratory, situated at the Energy Transition Centre (EnTranCe) 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 H_2 production by water electrolysis with RES. The research method is based on the characterization of these sources, comprising electrolyzer, Photo-Voltaic (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. 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-RTS Lab) located at the Politecnico in Torino. In this way, the laboratory equipment at Hanze University can be accessed from Politecnico di Torino 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.

The laboratory setup is briefly represented in Figure 2.1, it is possible to distinguish two grids: the first one called Local Grid supplies the Micro-Grid Lab directly from the external grid, the second one called Measured Grid is an independent grid. 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 energy sources or loads, that can send, use or store energy from the local grid.

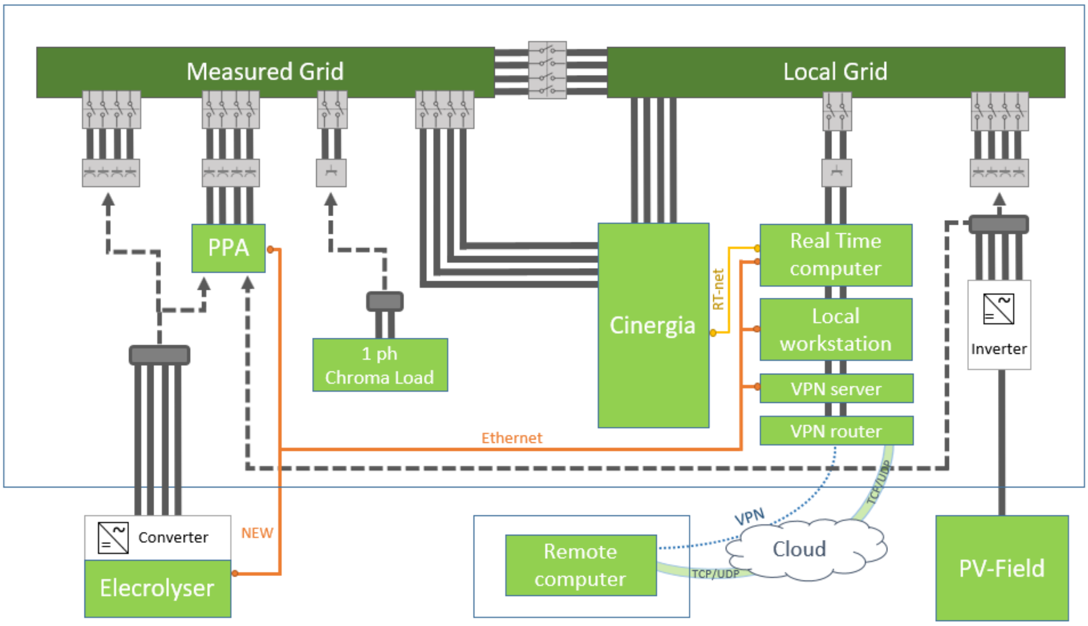

Figure 2.1: Real Time Micro Grid Laboratory Set-up [5]

2.2 Devices Used for the Experiments

2.2.1 Power Analyzer

The power analyzer (model: PPA1500, fabricated by Newtons4th Ltd) has been selected for its excellent properties in real-time analysis. It is capable of dynamically measuring electrical parameters over all three phases, performing the harmonic analysis, computing the power factor and real Root Mean Square (RMS) values, for a total of 60 data parameters logged in a one-time frame.

Figure 2.2: PPA1500

The Newtons4th Ltd's power analyzer is provided by the company with software programs for setting configurations, reading measurements and logging data directly on the user's laptop, namely PPA DataLogger. It is fitted with a graphical interface designed to be very simple and intuitive. Specifically, it allows to connect the Personal Computer (PC) to the power analyzer via RS232, Universal Serial Bus (USB) and Local Area Network (LAN) and comprises all measurement modes which reflect the instrument operating options. It also enables to export text files in Comma-Separate Values (CSV) format or directly to Microsoft Excel.

2.2.2 PEM Electrolyser

The electrolyzer under study is PEM water electrolysis system of 8 kW. When supplied with power and deionized water, it is capable of producing up to 1.05 Nm^3 of H_2 per hour with a continuous output stream. Its specifications are summarized in Table 2.1.

Table 2.1: Electrolyser Specifications [6]

Proton Energy Systems, S-series Hogen40 Hydrogen Generator	
Supply Voltage	200-240 [V_{AC}]
Number of Phases	1∼
Full Load Current	44 [A]
Frequency	50/60 [Hz]
Hydrogen Product Rate	1.05 [Nm^3/h]
Hydrogen Output Pressure	13.8 [bar]
Altitude	1520 [m]
Ambient Temperature	5-40 [°C]
DI Water Conductivity	>1 [MΩ cm]
Installation	Indoor

The unit is located in a container, shown in Figure 2.3, outside right next to the laboratory.

Figure 2.3: Electrolyser Container at the EnTranCe Test Site

The container is divided into two rooms. In the first one, there are the Programmable Logic Controller (PLC) and the water preparation system, where tap water is treated by means of a Reverse Osmosis (RO) unit and ion exchange filters to create suitable water for electrolysis (Figure 2.4). The deionized water then flows to the room, on the other side, where the electrolyser itself is situated (Figure 2.5). This room also houses a system of valves and two 5l storage cylinders for storing H_2 produced. The tanks can be emptied afterward by venting the contained H_2 outside. H_2 produced can also be directly vented during operation, without filling the tanks. The former production method will be further referred to as tanks filling mode, the latter as venting mode. A flow controller has been added at last to the setup to control the flow of H_2 while vented to the outside air.

Figure 2.4: PLC's room

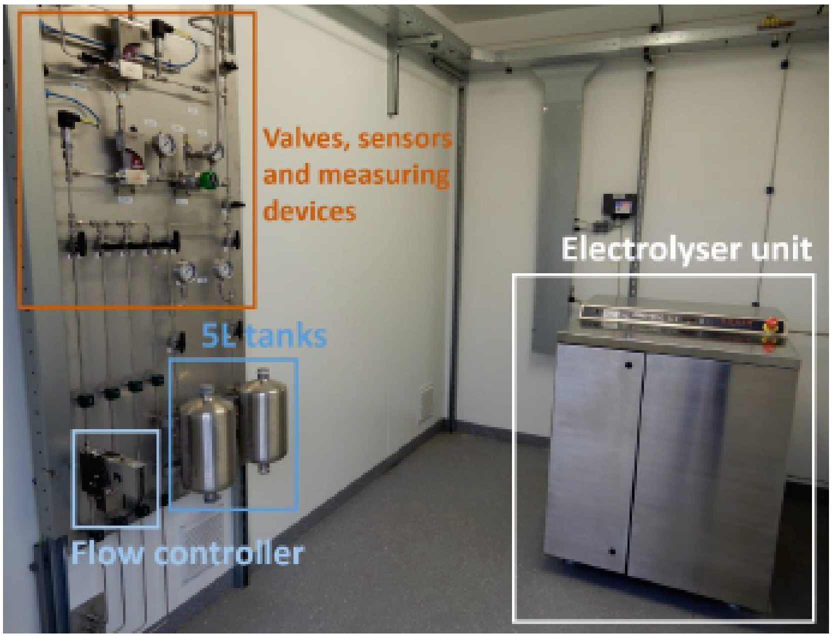

Figure 2.5: Electrolyser's Room

The electrolyser unit contains an electrolysis cell stack and auxiliary equipment, required for regulating electrolysis operations (circulating H_2O, drying and pressurizing H_2, performing safety operations and shutting down the system). The internal part of the unit and the functional elements included therein are illustrated in Figure 2.6.

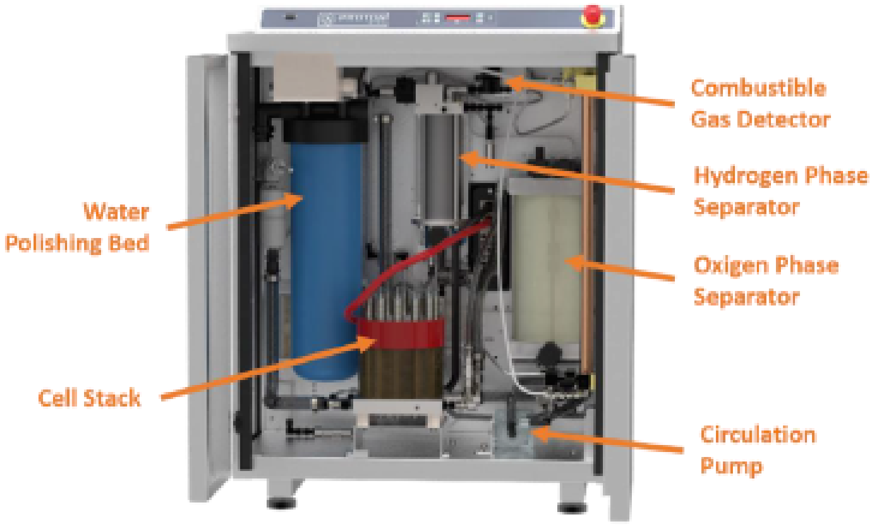

Figure 2.6: Inside of the Proton's Hogen40 PEM Electrolyser [6]

The electrolysis unit is internally controlled and fully automated in every state and process. The operator only has to start the system up at the beginning and shut it down at the end of operation. Throughout the electrolyser start-up and functioning, various operating states can be distinguished:

- PRE-START: it starts when the main power switch is turned on. The system flushes itself out of the water if water quality is below the required conductivity;
- GENERATE-VENT: in this mode, the circulation pump is started up and the system verifies the process values of H_2O flow rate and H_2O quality. Now the system checks both separator levels, voltage conditions in the stack and rectifier operation, venting H_2 and O_2 outside during this process. If the process values pass all checks, the electrolyser will stop venting and start to build up pressure, leading to the next state;
- PRESSURIZE STORAGE: in this state, the system pressure is increased up to the system pressure set-point while H_2 lines are pressurized up to the product pressure set-point. Once the set-point levels are reached, the process goes into steady-state;
- STEADY-STATE: the generator produces H_2 that flows out of the system through the H_2 product port. The full flow of gas is produced when the system pressure is below its set-point and, similarly, the full flow of gas is delivered when the product pressure is below the respective set-point. When the set-points are reached, the power used for H_2 generation is switched off and the electrolyser remains in idle state. When the pressure drops below the set-points, the generator will deliver full gas production until it reaches the pressure set-points again;

Initially, the parameters of H_2 production process and system input/output variables were monitored and recorded in two separate ways:

- By reading an Secure Digital (SD) card connected to the PLC, which could be extracted if the electrolyser was switched off, or by connecting the PLC to the laptop via USB cable and reading the card via the SD Card Suite program;
- Using a program called HOGEN40 and a USB-RS232 serial converter cable to make a laptop communicate with the system;

But at the beginning of this project, both the electrolyser and the PLC were prepared to be accessible via Ethernet connection, it is now possible to perform all the measurements directly through a computer connected to the laboratory LAN, without the need to use a serial cable.

By comparing Tables 2.2 and 2.3 with the numbers in Figure 2.7, it is possible to understand the type of measuring devices in the system and their position.

Table 2.2: PLC Monitored Variables

N (Dark Grey)	PLC Monotored Variables	
1	H_2O inlet flow	[ml/min]
2	Produced H_2 volume flow	[m^3/h]
3	Produced H2 pressure	[bar]
4	Produced H_2 volume flow	[m^3/h]
5	Produced H_2 pressure	[bar]

Table 2.3: HOGEN40 Monitored Variables

N (Pale Grey)	HOGEN4 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]

An additional measuring equipment is a flow control (letter C in Figure 2.7), installed on the product outlet pipe leading to the outside air and its communication channel connected to the laboratory LAN via Ethernet. In this way, the device allows both to control and measure the amount of product gas flowing through it, while all its data and settings are accessible from an engineering computer connected to the same LAN. The instrument is based on the Modbus Transmission Control Protocol/Internet Protocol (TCP/IP) communication, so it is possible to interact with it both through a software interface specifically designed for reading/writing Modbus registers and by implementing a code to perform the same task in Matlab.

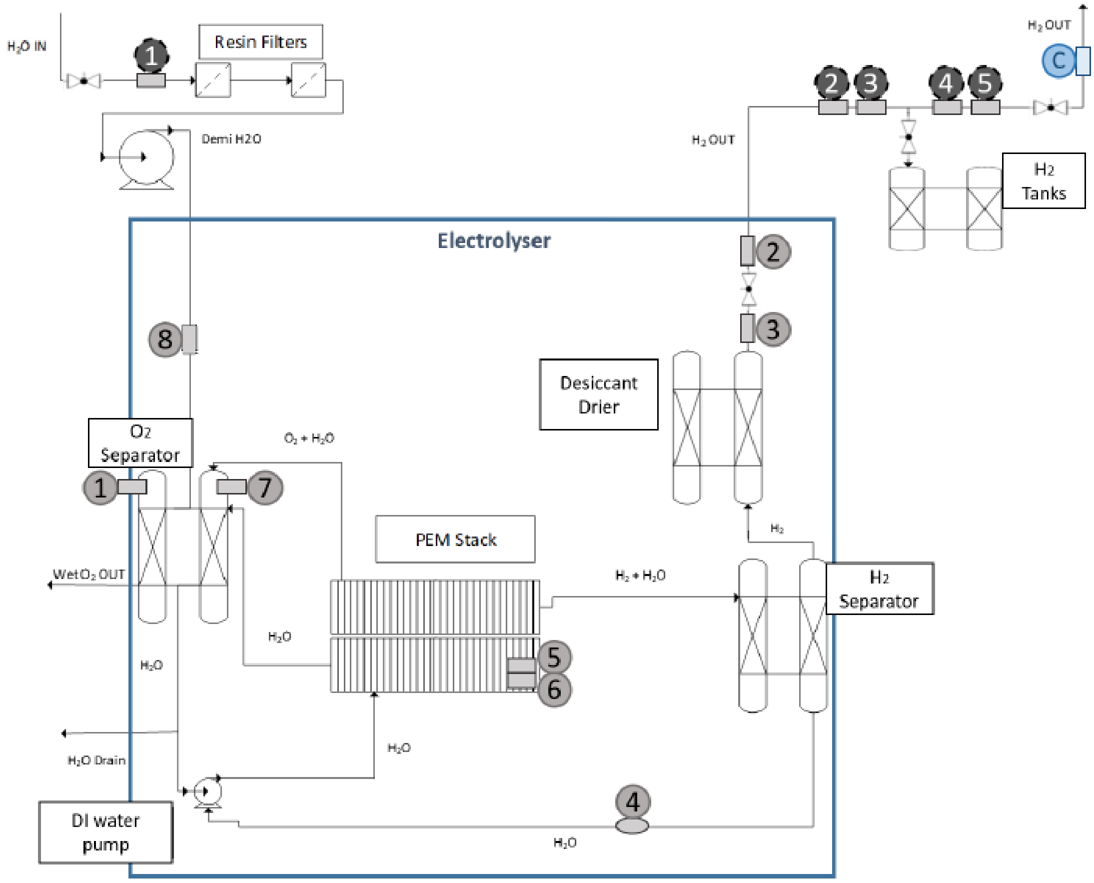

Figure 2.7: Measuring Equipment of the Hydrogen Production Process [4]

2.2.3 Power Amplifier: Cinergia GE & EL-20

Figure 2.8: The Power Amplifier Cinergia GE & EL-20

Cinergia GE & EL-20 is a device, that combines in a single cabinet all the functionalities of Grid Emulator, Electronic Load and Bidirectional Direct Current (DC) Converter. The Grid Emulators are power electronic devices designed to emulate an Alternative Current (AC) electrical grid in normal condition, as well as in disturbed conditions (by simulating voltage dips, frequency and voltage fluctuations, flicker, and harmonics). The hardware platform is based on a Back-to-Back power conversion topology, formed by two Insulated Gate Bipolar Transistors (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 Early User Test (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 separated control of three different DC voltages or currents.

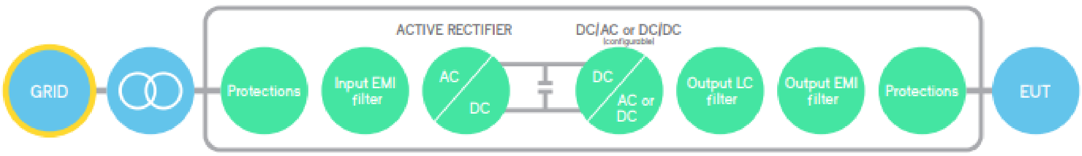

Figure 2.9: Schematic of the Cinergia's Model [7]

The operation of the power supply is based on six different states and six transitions. Each state defines the behaviour and the possible actions of the power supply:

- INITIALIZATION. During the initialization, the power supply control system checks the presence of all internal components and the embedded PC loads the operating system. No voltage is present at the DC-bus and the IGBTs Pulse Width Modulations (PWM) 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 outputs;
- 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 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 GE & EL-20 is equipped with a software, with which, through specific panels, it is possible to configure independently the output voltage waveforms, the transition ramps and the distortion of each phase. In this panel, each phase can be independently configured: RMS current magnitude, phase delay, harmonics content, free-frequency harmonic and transition ramps. A plot shows the expected real-time waveform, the Fast Fourier Transform (FFT) representation and the numeric data: RMS, peak, Capacity Factor (CF) and Total Harmonic Distorsion (THD). By a supervisory screen, it is possible to control the evolution time of voltage, current and active power of the output. Where S, R, T are the output phase, while U, V, W are the main grid's phase.

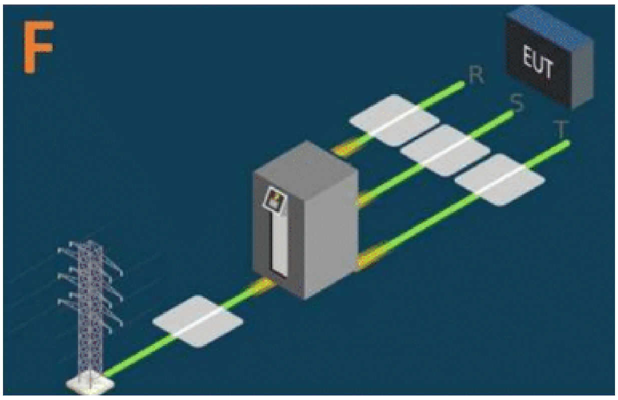

Figure 2.10: Power Amplifier's Phase [7]

2.2.4 Virtual Connection: Ethernet and VPN

The laboratory LAN consists of a router directly connected to the internet backbone of the Hanze University data center. This provides a reliable, high-speed Ethernet connection with a speed of 1 GB/sec and a latency of less than 50 ms. The Ethernet connection is by definition based on a TCP/IP protocol, so each interconnected device must be supplied with its own IP address. This allows information to be exchanged between the devices and the local engineering PC.
Also, for virtual operation, the power amplifier is connected via a real-time communication bus to the PC-based real-time control unit. This Real-Time Target (RTT) is responsible for running models for all types of custom sources or loads in real-time. The models are first implemented on the engineering workstation and then sent to the RTT via Ethernet. In general, with the network configuration described: the cams that regulate the function of the power amplifier can be sent from the local computer to the RTT and then to the power amplifier and meanwhile via the power analyzer, the connected devices can be monitored in real-time, while the data can be accessed and recorded from the local computer.

A server has been added to the described network topology to create an Internet connection with the remote computer at G-RTSLab and allow communication between the two laboratories. In particular, the server's task is to forward data between the remote instances, release invalid packets, collect communication link statistics and perform other arbitrary operations on data sent and received, if necessary. The protocol used by this device for data exchange is the User Datagram Protocol (UDP).
For security reasons, communication is carried out through a Virtual Private Network (VPN) tunnel. The solution is based on open-source VPN software called OpenVPN, which can establish a fully decentralized virtual network on the Internet and to allow point-to-point data exchange. This method is essential to protect all data and equipment from unwanted use. More details on VPN communication between the two laboratories for the creation of the multi-lab setup and the implementation of the related experiments can be found in Section 3.3.

Chapter 3

Remote Power Hardware in Loop

3.1 Introduction

Hardware-In-the-Loop (HIL) aims to replicate real-world conditions for carrying out meaningful tests on device prototypes and new technologies, like an electrolyser, proposed to be deployed in real energy systems. The aim is tuning, validating and verifying the system performances or collecting data with the purpose to create realistic device models – all this avoiding to deploy the device directly into the grid, which may be harmful for the grid itself or for the device. In fact, while in real-world systems both Hardware Under Test (HuT) and the grid are physical and naturally coupled, in the laboratory test environment the grid is replaced with its mathematical model, so-called Rest of the System (RoS). In order to safely couple the HuT with this virtual system and to realistically simulate the behavior of the real system, the model has to be implemented on a robust target simulation platform and a Real-Time Simulation (RTS) has to be performed. This is a simulation solution able to follow the dynamic behavior of the system by respecting the timeline according to the wall clock. In this way, it guarantees synchronization, accuracy, and stability of the overall system.

If the device is a controller that retrieves some measurement or alarms and produces some command signals as feedback to the rest of the system, thus is no need to exchange power. If the device is a source of energy or load, which respectively produces and consumes energy. An interface is needed to enable power exchange. In such cases, a power amplifier is exploited to perform Power Hardware In the Loop (PHIL).

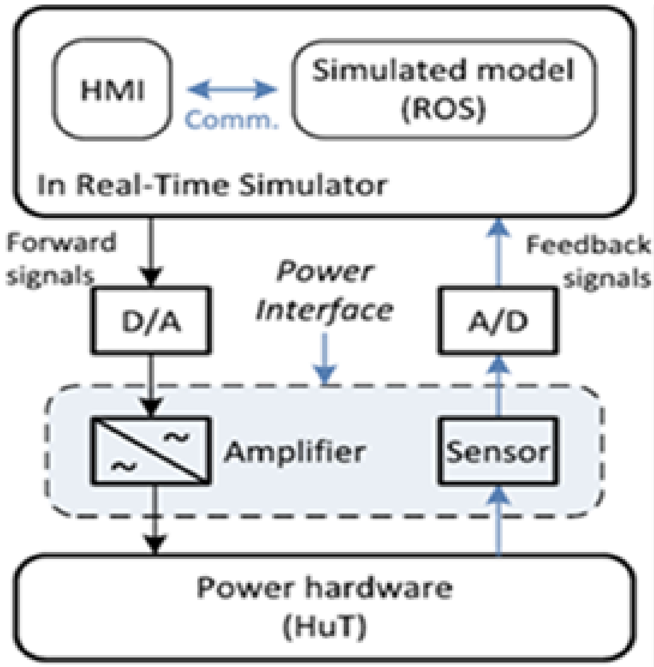

Figure 3.1: Scheme of PHIL [8]

The power interface is made of a power amplifier and a set of sensors which monitor HuT, the power amplifier acts as a source or load. 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 the load is equipped with current or voltage sensors, it is possible to extract the current or voltage required by the load and sent them as feedback to the software grid to close the simulation loop.
An advanced and recently developed approach for deploying PHIL is to interconnect different distant laboratories in order to create an integrated laboratory for remote simulations and experiments, realizing the so-called Remote Power Hardware In the Loop (RPHIL).

RPHIL is useful to investigate new technologies for energy transition, but this investigation is more complex than the traditional ones, because an interoperability and multidisciplinary analysis is required since the new technologies deal with different energy vectors and sectors. Another aspect is that the systems to be implemented are often large-scale energy systems, leading to complicate simulation models. This requiring high computation resources, these resources can be unavailable in a single laboratory. Then, the solution then lies in the share of existing research infrastructures by virtually joining different distant laboratories. This allows:

- Soft-sharing of expertise in a large knowledge-based virtual background;
- Soft-sharing of hardware and software resources;
- The confidentiality of data, models and algorithms;

3.2 Control and Connection of the Power Amplifier

In this experiment, the electrolyser is a load that consumes energy, hence an interface is needed to enable power exchange. In this case, the interface is the Power Amplifier Cinergia GE & EL-20. Before powering the electrolyser with the grid emulator, it was necessary to develop a control of the device so that the output voltages of the three phases and the frequency are the same as those of the main grid.
Cinergia's power converters 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 Serial Peripheral Interface (SPI) bus and the external Modbus TCP/IP (Ethernet). In this way, the customer can build specific Human Machine Interface (HMI) client software application, while Cinergia's power converter acts as a Modbus TCP/IP server. In order to achieve this target, it's necessary to use the Modbus data table D0270 [9], where there are the useful Modbus addresses to establish the connection between the laptop (with the Matlab/Simulink environment) and the device.

So, the first step is to establish the communication between Matlab and Cinergia's power amplifier by the Matlab's function *mmodbus*, using the TCP/IP address and door of the device. After this, it's possible to write or read data through the functions write and read. The respective syntax is below:

- $write(m, target, address, values)$;
- $read(m, target, address, count)$;

Where m is the Modbus object, $target$ is the type of the register, $address$ is where to read or write in the device, $values$ is the number wanted to write, $count$ represents the number of values to read. Using this function it was developed a Simulink model to control the output frequency and voltage.

Figure 3.2 shows the Simulink model to control the voltage and frequency of the power amplifier. The aim of the simulation is that the output voltage and frequency of the device reach the reference value provided by the main grid. This model is composed of:

- Function PPA Read;
- Start-Cinergia;
- Voltage Control;
- Frequency Control;

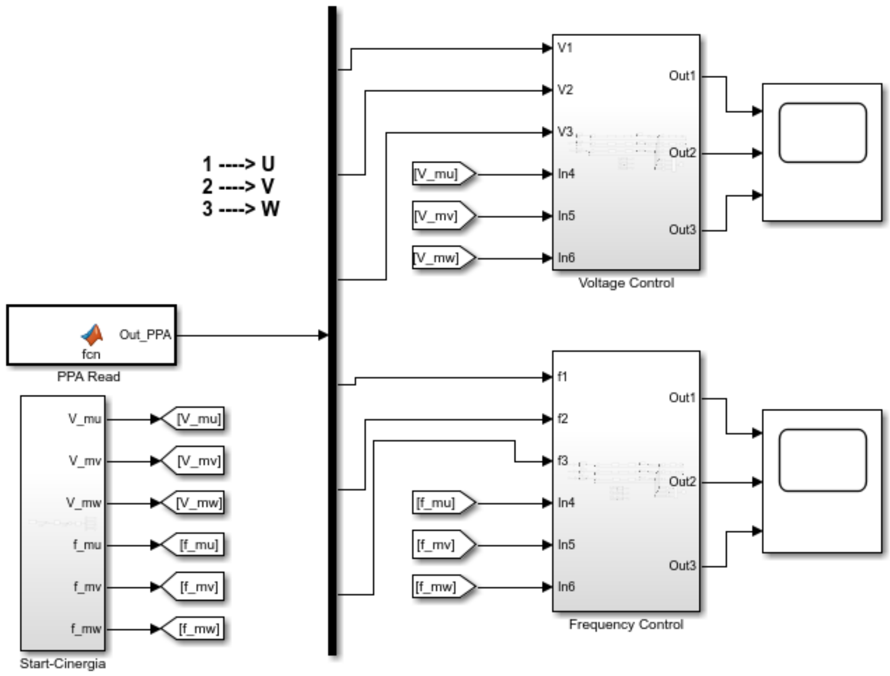

Figure 3.2: Simulink Model of Cinergia Control

3.2.1 Start Cinergia

The block “Start Cinergia” has a function to put in RUN state the power amplifier. Its architecture is in Figure 3.3.

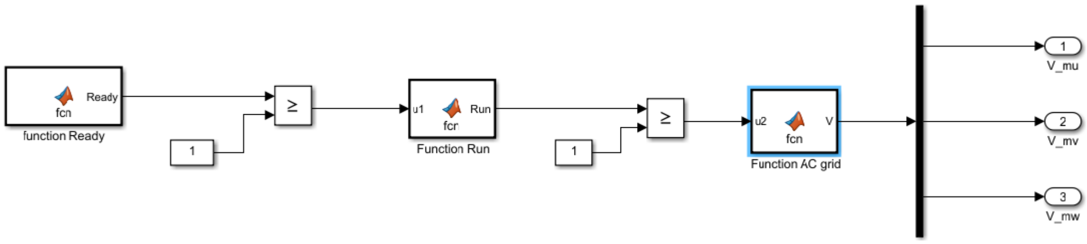

Figure 3.3: Model Start Cinergia

This block is composed by three Matlab function:

- **Function Ready**, to put in ENABLE and READY the power amplifier, this writing 1 in the respective addresses;
- **Function Run** has the same logic of the previous function, but to put the power amplifier in RUN ;
- **Function AC grid**, which allows to set any parameters to create AC grid. The outputs of this block are the power amplifier’s voltage and frequency, which must be compared with the reference values.

Additionally, there are two relational operators, this because the transition from one state to another is not instantaneous. For example, between the ENABLE and READY states, there is a PRECHARGE phase, and when the device is ready, a 1 is written in the respective addresses. for this reason, the output of the first two functions is the reading of the two registers and when it is read 1, the simulation goes to the next step.

3.2.2 Voltage Control

The voltage control is useful to set the power amplifier's voltage to the reference value, namely the one of the main grid, which is measured by the PPA. In fact "the PPA read V" function allows to measure the RMS voltage from the main grid. Inside the loop, there are other two Matlab functions, the first one measures the output voltage of the power amplifier, whereas the second one increases this value of 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. The Simulink model is shown in Figure 3.4:

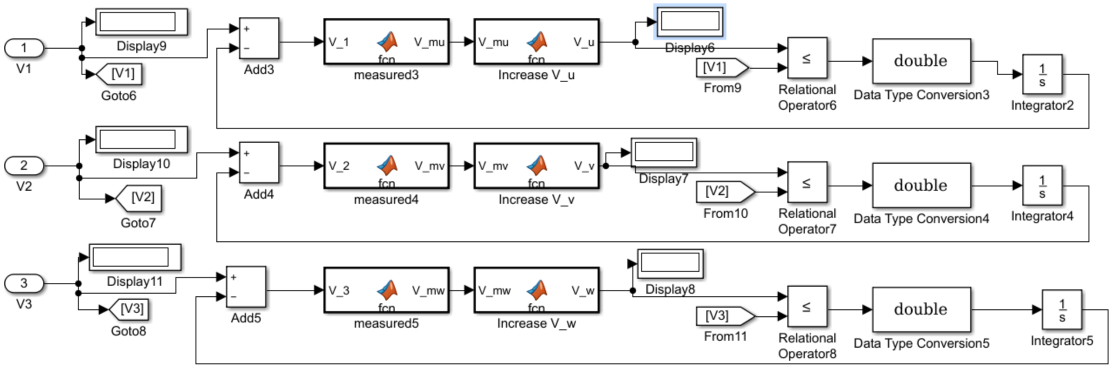

Figure 3.4: Voltage Control

In Figure 3.5, it is possible to see how starting the simulation the output voltage of power amplifier (blue) increases until it stabilizes at the reference value (yellow).

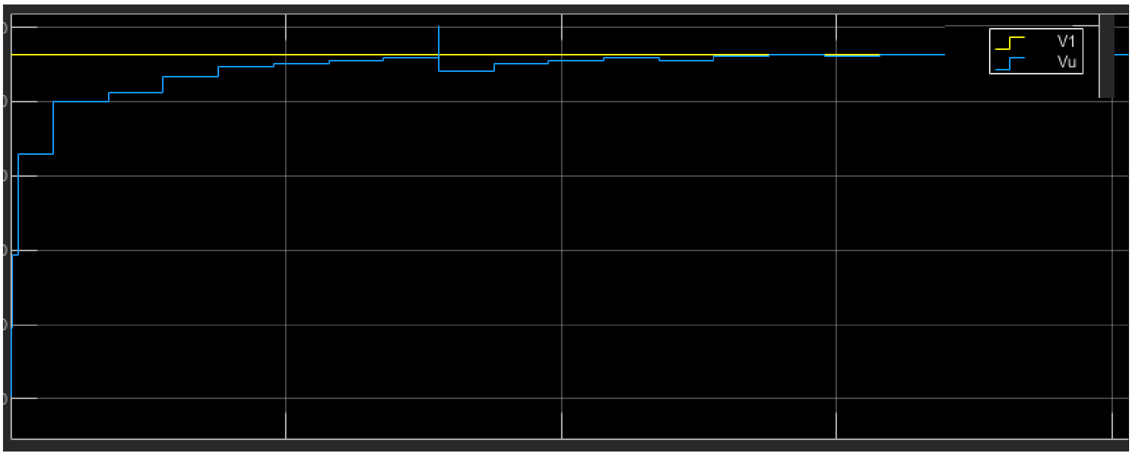

Figure 3.5: Voltage Scope of the Phase U

3.2.3 Frequency Control

The Simulink model to control the frequency follows the same logic of that Voltage Control, only for convenience, the control is done on the angular frequency, because there is a multiplicative factor, compared to the simple frequency, which makes it easier and more stable control.
Also in this case we will have two Matlab functions, the first to read the output frequency of the amplifier, the second to increase it by one unit at each cycle. The simulation ends when the frequency of each phase reaches the reference value, allowing perfect synchronism with the main network. The control and the result of the simulation are shown in Figures 3.6 and 3.7:

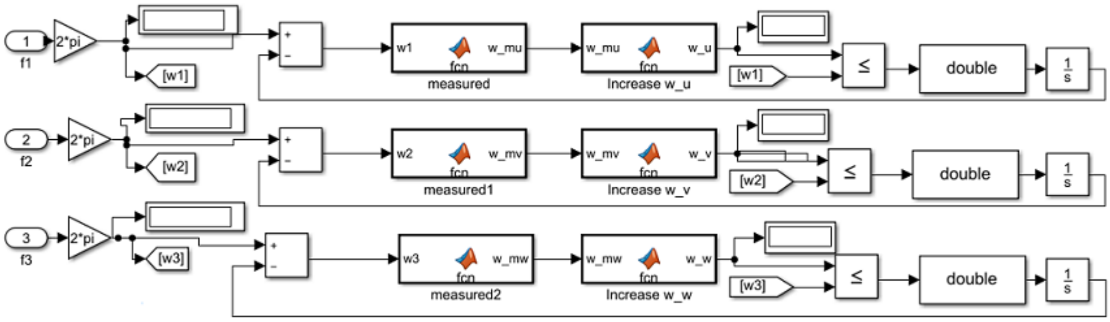

Figure 3.6: Frequency Control

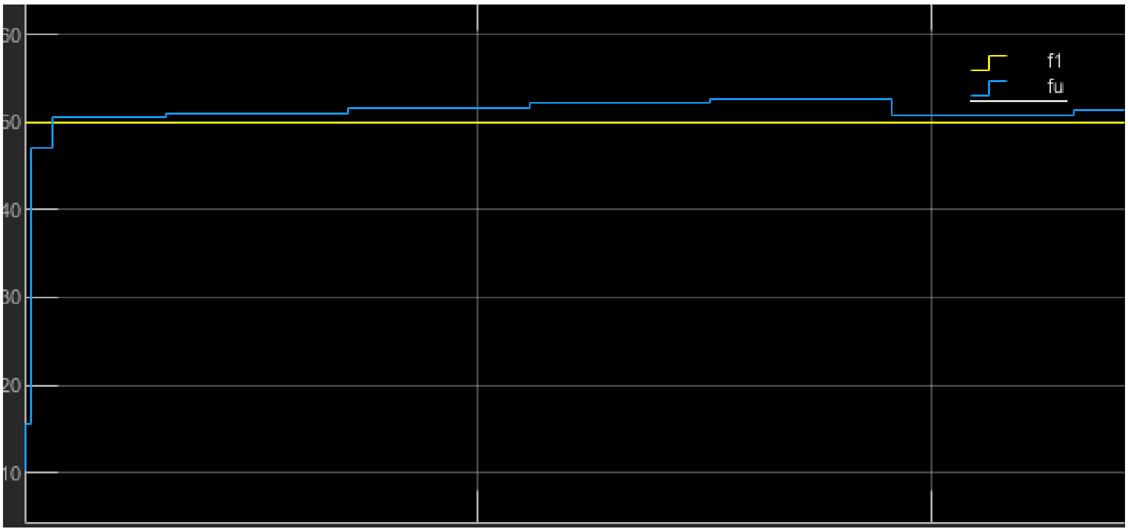

Figure 3.7: Frequency Scope of the Phase U

3.3 Network Connection

For the purpose of realizing the mentioned multi-site laboratory, the two physically separated laboratory LANs – one placed at Hanze University and the other one at Politecnico di Torino, are merged into a single Ethernet segment via a bridge connection. This communication link is based on the open-source software OpenVPN, which enables to create a VPN tunnel between the two sites. This means that a completely decentralized virtual network is built over the Internet for a secure point-to-point data exchange, allowing to protect all forwarded data and installed equipment against undesired use.

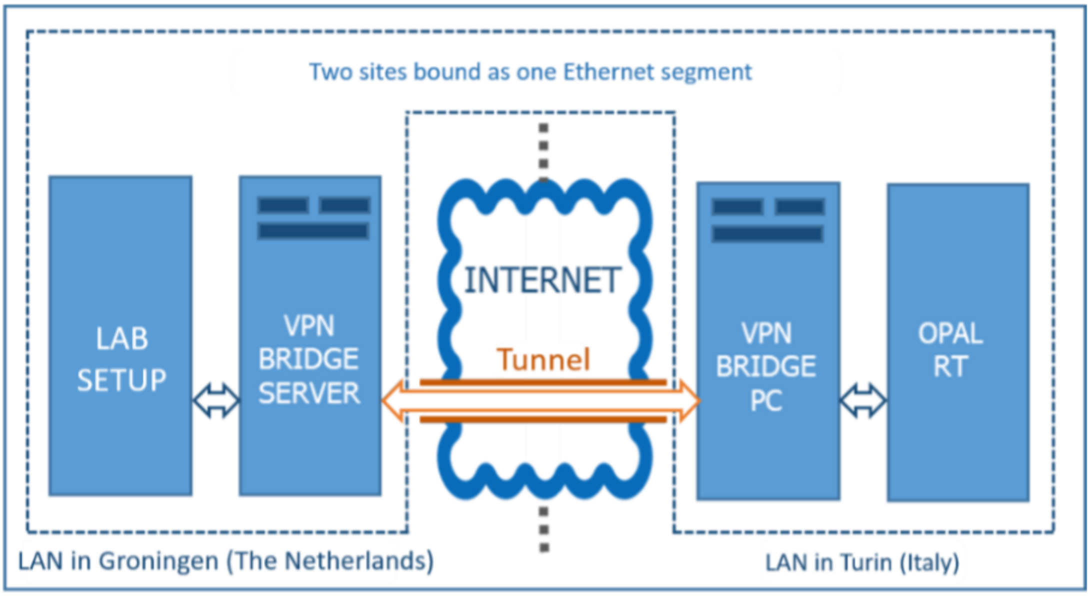

Figure 3.8: Communication between laboratory of Hanze University and G-RTSLab of Politecnico di Torino [8]

In the test configuration, Hanze's lab is the main LAN while, Politecnico di Torino's one represents the sub-LAN. Therefore, the OpenVPN software is run on the VPN server that is part of the lab setup at Hanze University and a virtual hub is created. At Politecnico di Torino, the computer connected to the same LAN of Opal-RT is equipped with a virtual VPN server and hub which is bridged to the server at Hanze University. When a connection is initiated from Politecnico di Torino, a cascade connection is established between the two laboratory LANs.

This experience is divided into two test cases:

- Enabling the remote access from Politecnico di Torino the hardware and software resources located at Hanze University, achieving the objective of the share of research infrastructures; and verify that the power amplifier voltage control works;
- Offering the possibility to remotely monitoring and controlling the devices, this constitutes the first step towards a co-simulation involving RPHIL tests on the electrolyser, performing the simulation with the electrolyser connected to the power amplifier;

3.3.1 First Test Set

The first experimental set was intended to demonstrate the functioning of the VPN communication for retrieving measurements from and sending control signals to the instruments, with special attention paid to the data transmission delay. This purpose is to compare the power amplifier control simulation done at Hanze University (local) and at Politecnico di Torino (remote). The first step is connecting, through Team Viewer, the two-laptop located in the two labs. Then once established a VPN connection, it's possible to exchange data between the two places, considering the delay of transmission signal. The last step is to load the model of the power amplifier control on the computer of G-RTSLab of Politecnico di Torino and perform a remote control from there. Figures 3.9 and 3.10 show the results of the two simulations.

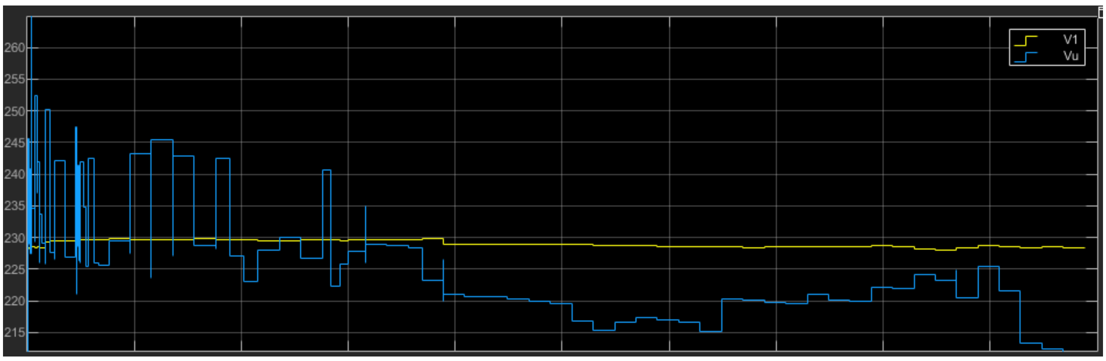

Figure 3.9: Voltage Control of Phase U - Local Measurement

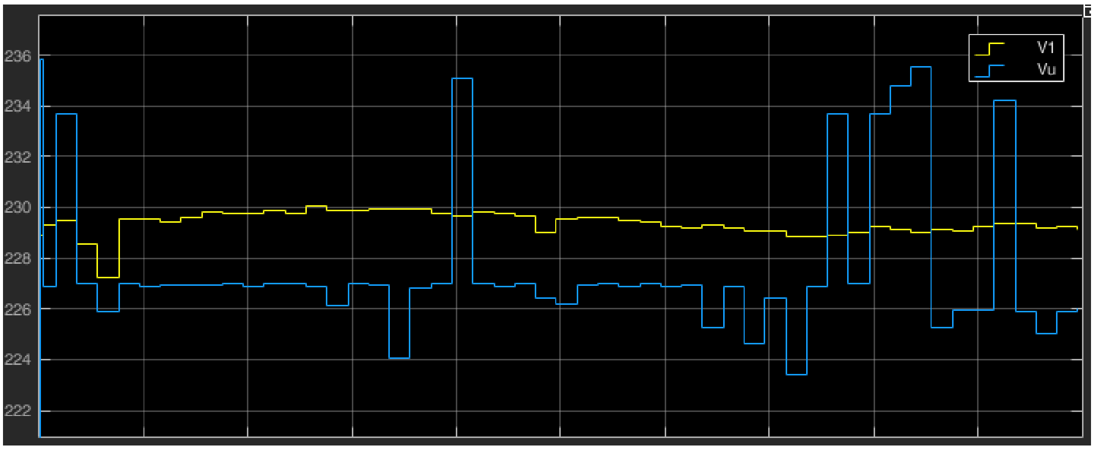

Figure 3.10: Voltage Control of Phase U - Remote Measurement

The results of the simulations are slightly different, in particular in the one carried out remotely there are greater fluctuations, all this because, in addition to the normal delay due to the VPN connection, in those days the connection between the two laboratories had problems, which caused such disturbances. Because of the Covid-19 emergency, it was not possible to try this experiment again. However, in principle, in both cases, the output voltage (blue line) from the network amplifier tends to the reference value (yellow line). In conclusion, the results achieved demonstrate the possibility to control the grid emulator directly from the G-RTSLab of Politecnico di Torino.

3.3.2 Second Test Set

The second set of experiments was aimed at carrying out the measurement of electrolyser connected to the power amplifier, using a Simulink model, both locally and remotely. The objective was to demonstrate the possibility of integrating the H_2 production unit into co-simulations on the basis of RHIL and "Internet-Distributed Hardware-In-the-Loop" concepts. For this experiment, it is necessary to make a change to the model of voltage control, because in this case, the reference is the voltage of the main grid, which supplies the grid emulator (phase R-S-T). The new model is shown in Figure 3.11.

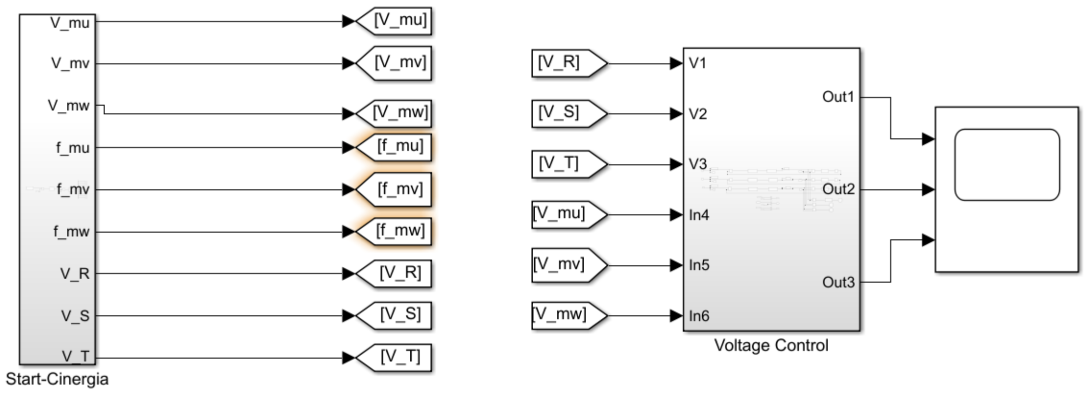

Figure 3.11: Voltage Control for The Second Test

The "Voltage Control" block is the same as before; the only thing that changes is that the reference voltages are phase voltages R, S, T. The simulation is done by changing the percentage load of the electrolyser using the flow control. The latter can be controlled in a Matlab environment through a serial connection of the TCP/IP type, where knowing its IP address it is possible to communicate with the instrument through appropriate read or write functions.

Figure 3.12 shows the Simulink model of the flow control, where it is possible to change the percentage of the load from 15% to 110% of full load.
The model is composed of two conceptual parts:

- Flow controller Modbus writing, used to write the setpoint of H_2 flow to the flow controller;
- Flow controller Modbus reading, used to read the measured data of H_2 flow from the flow controller;

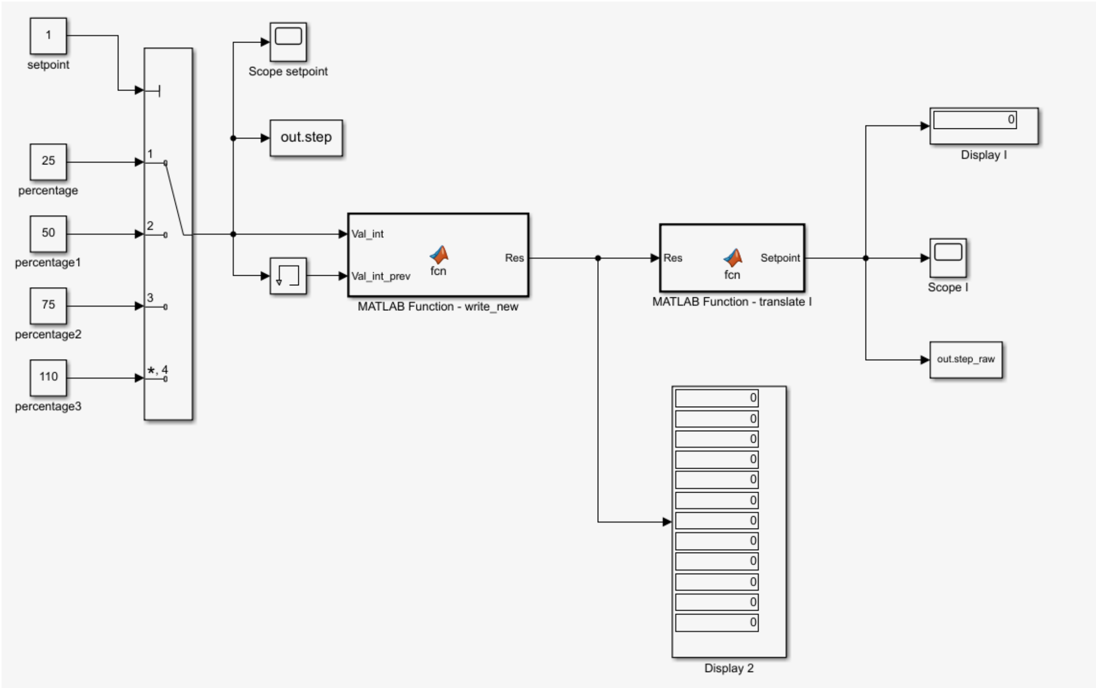

Figure 3.12: Flow Control Simulink Model

All the measurements are collected by using the power analyzer. It also communicates with PCs via a TCP/IP connection. Since it is a reading instrument, it is possible to measure the variables concerned by means of a Matlab reading function, using its Simulink model shown in Figure 3.13. It is used to read the three-phase voltage, active power and current.

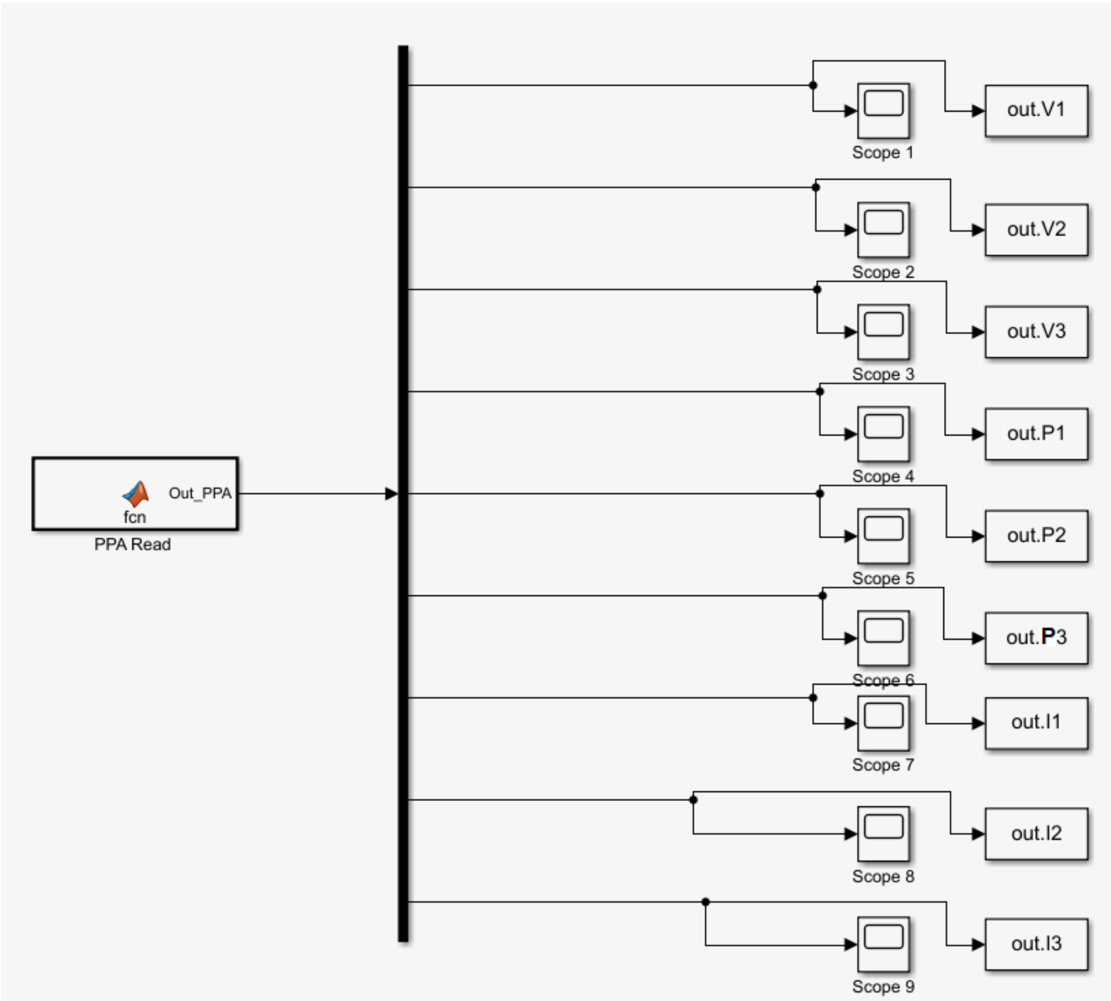

Figure 3.13: Power Analyzer Simulink Model

Figures 3.14 and 3.15 shown the results of the local and remote voltage control simulation with the power amplifier feeding the electrolyser and measurements made with power analyzer.

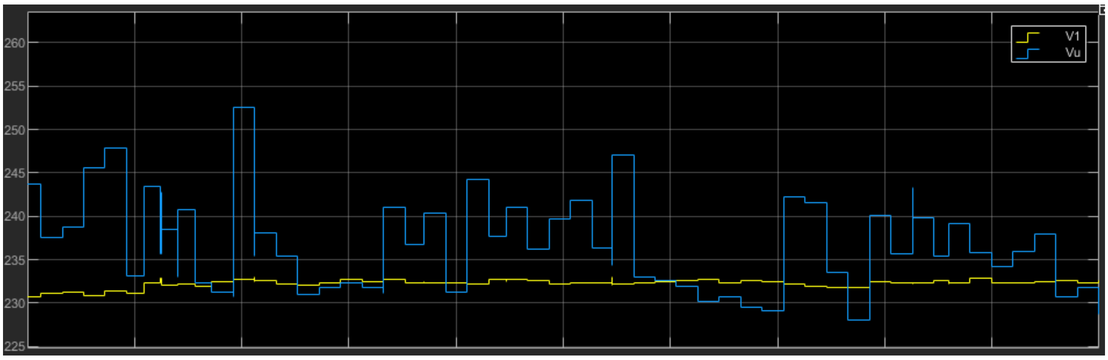

Figure 3.14: Voltage Control of Phase U - Local Measurement

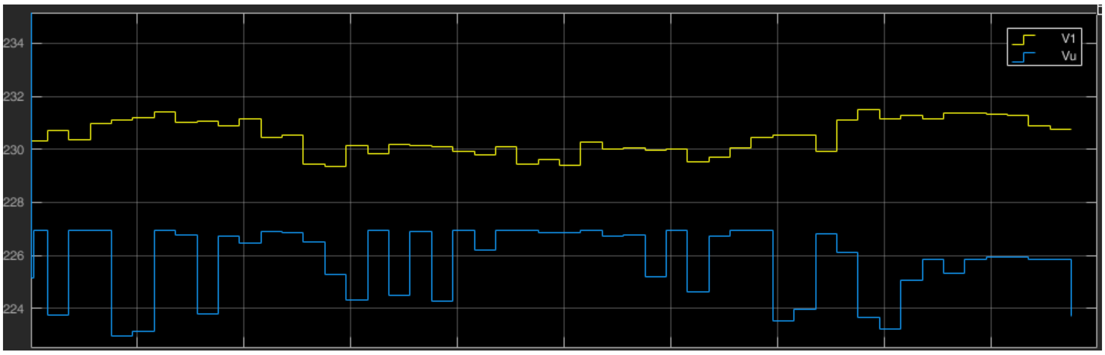

Figure 3.15: Voltage Control of Phase U - Remote Measurement

As far as the output power results of phase one of electrolyser are concerned, remote and local simulations lasting 34 minutes were carried out.
Where the load rates were programmed in this way:

- 25% of full load from 0 – 14 min;
- 50% of full load from 14 – 24 min;
- 75% of full load from 24 – 32 min;
- 25% of full load from 32 – 34 min:

Figures 3.16 and 3.17 represent the results of the simulations.

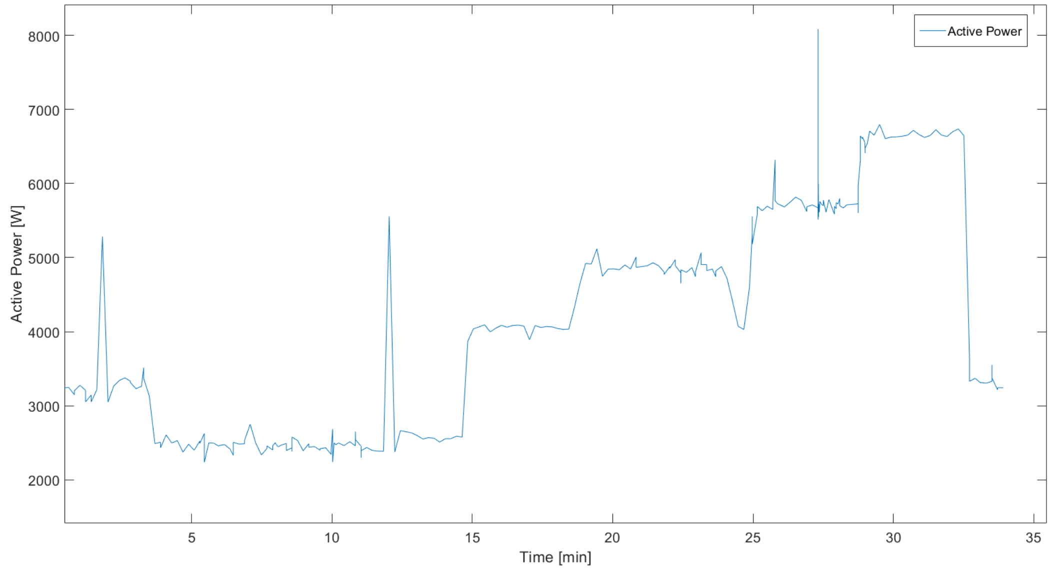

Figure 3.16: Active Power of Phase One - Local Simulation

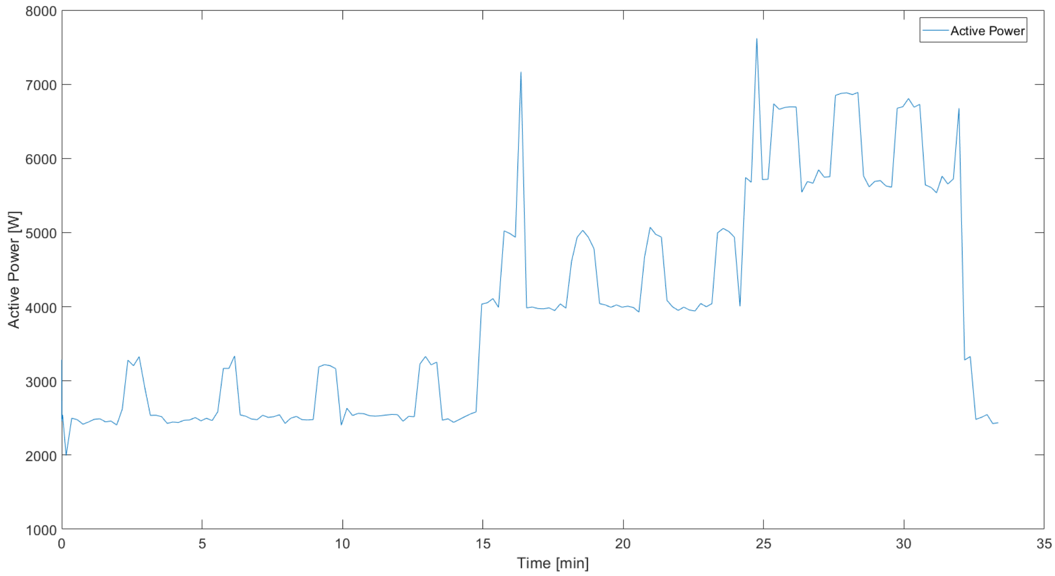

Figure 3.17: Active Power of Phase One - Remote Simulation

It is worth to note that the Simulink lock function interacts with Matlab during the simulation. At each step of the simulation the model is momentarily paused, the Matlab function interfaces with the respective Matlab file and this executes the code to read/write data to and from the tools. Finally, when the data replies are received, they are transferred from Matlab to Simulink and the simulation starts to move to the next time step. Therefore the simulation involves a certain latency, which, in the case of remote simulation, must be added to that due to the VPN connection. But during the days of the simulations the connection between the laboratories has shown an increase in the delay for this reason, the two remote and local results of the same experiment are different, for this reason they will have to be redone, but so far it has not been possible to carry them out because of the Covid-19. In any case, experience has shown the possibility to control the devices from the laboratory of the Politecnico di Torino.

Chapter 4

Modelling a Distribution Network

4.1 Introduction

This network is part of the STORE&GO project [5]. This project involves several networks of different nature: rural and urban, and is representative of the situation of the Italian distribution system. In this case the rural network has been chosen. This grid is fed at 150 kV, a voltage value typical of southern Italy. For this reason the model can be considered meaningful for a certain geographical area of southern Europe. Thus, it was decided to use the PV profiles for the city of Troia (Puglia). The network is composed of seven feeders, supplied by the HV/MV substation, 102 nodes and 101 closed branches, being the network radial. The network contains three different types of load (i.e., residential, industrial, and agricultural), divided among the nodes as follows:

- 40 nodes with residential loads;
- 14 nodes with industrial loads;
- 67 nodes with agricultural loads;
- 24 nodes with PV generation;

Figure 4.1: Schema of the Representative Rural Network [5]

The description of the network in terms of feeder, nodes and types of load is shown in Table 4.1. As shown in Figure 4.2, different types of load are considered. The time step is 15 minutes, which represents one among the typical time steps used for properly describing the behaviour of the electrical loads.

Table 4.1: Main Features of the Network [5]

Feeder	Nodes	Residential	Industrial	Agricultural	PV	Lines
F1	2-26	7	2	16	5	1-23
F2	27-32	0	2	6	3	24-29
F3	33-54	13	3	9	0	30-50
F4	55	1	0	0	1	51
F5	56-68	5	3	12	3	52-62
F6	69-75	1	1	7	2	63-68
F7	78-102	13	3	17	10	69-101

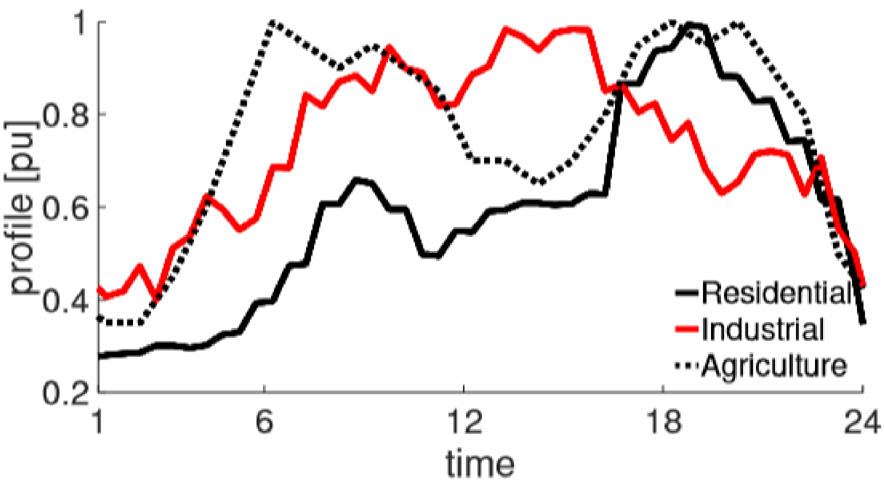

Figure 4.2: Load Profiles [5]

From Figure 4.2, it is possible to recognize the distinctive features of the three profiles:

- For the residential one can notice two peaks, one in the evening when the domestic consumption is higher;
- For the industrial there is a peak in the middle of the day and lower load during the night, where usually industries reduce their activities;
- For agriculture, there are peaks in the early hours of the day and in the evening respectively, where the breeding activity is most concentrated;

The PV generation profiles derive from the PV simulator [10] which, by entering the geographical coordinates (latitude, longitude and height above sea level) related to a location, returns in output irradiance profiles in W/m^2. Obtained the irradiance values, these values are converted into a power in p.u., through the following equations [11]:

$$T_c = T_a + \frac{NOCT - 20}{800} \cdot G \tag{4.1}$$

$$\eta_{th} = 1 - \alpha_{th}(T_c - 25) \tag{4.2}$$

$$\frac{P_{AC}}{P_{nom}} = \eta_{AC-DC} \cdot \frac{G}{1000} \cdot \eta_{th} \tag{4.3}$$

Where T_{c} is the estimated temperature of the PV panel (expressed on [°C]), T_{a} is the temperature of the air (estimated thanks to PVGIS for sites under network examinations), $NOCT$ is the temperature nominal working temperature of the PV cell (tax equal to 45°C), η_{th} is the reduction of production due to the temperature of the panel (thermal efficiency), G irradiance investing the panel [W/m^2], α_{th} is the coefficient of loss due to temperature (place equal to 0.45) and finally η_{AC-DC} is the reduction of power produced due to the connections and efficiencies of the inverters. The result is no longer a profile on the irradiance of the period under consideration, but rather a profile in p.u., directly applicable to all PV systems installed in the grid (the size of a distribution network are relatively small, and one can make the assumption of homogeneous irradiance on all panels installed in the network).

The principal goal of the study is to simulate by Simulink the grid with a PtG and compare the results with and without this technology.
Initially the aim was to connect the electrolyser present at the Hanze University in a node of the network, using the power amplifier as an interface. But due to the closure of the laboratory for the Covid-19, it was not possible to use these devices. For this reason a Simulink model of a PtG has been reproduced and the effects of its integration on the network studied. Especially focusing on network problems such as:

- Reverse Power Flow: reversal of the power flow in the HV/MV transformer which is initially directed from the transmission grid to the loads. With high penetrations, the power flow may be reversed because the generation of the RES could be greater than the load of the grid at that instant. Reverse power flow is a problem for both the transmission system operator and the distribution system operator. The presence of an energy flowing from the distribution system to the transmission system makes the interconnection between the two systems equivalent to an active node that cannot be controlled, which may create some difficulties for the proper operation of the electricity system. On the other hand, the presence of reverse energy flow can also create problems for the distribution system, for example in terms of inadequate protection schemes. Usually, this type of problem is now solved by cutting off excess production or using batteries or by network reconfiguration (connection of the feeders with high reversible power flow to parts of the network or even to other networks with higher absorption demand). The reverse power flow condition does not bring the network into an emergency condition, provided that the voltage and current constraints are respected.

- Overcurrent: it occurs when the currents flowing in the branches are higher of the branch thermal limits. In the case of RES, this issue can only affect a part of the network (e.g. the last part) or the whole network, depending on the level and of the load distributed generation, and the geographical location of the PV systems. The conductors can withstand overcurrent values for a few moments, but this condition should be avoided as much as possible, due to the deterioration of the conductor insulation.

- Overvoltage: this is a condition where the voltage is higher than the design voltage. In a typical electrical system, the STANDARD ISO IEC 60038 [12] imposes as operating voltage, a voltage between 90% and 110% of the nominal voltage of the system.

4.2 Description Simulink Model

This chapter describes in detail the implementation of the models in Simulink, using in particular the library Simscape. First of all, it is important to focus on the task of the model in general. The script must simulate the behavior of a distribution network during the span of a day, with time step of 15 minutes, considering PV generation profiles and profiles of load typical of residential, agricultural and industrial activities.
The work is composed by two file:

- Initialization_distribution_system: it is a Matlab script and its function is to set all the parameters of the system required by the Simulink model;
- Distribution system: it is a Simulink model, which represents the grid to be simulated;

4.2.1 Initialization_distribution_system

This Matlab script has the function to set the parameters in the Simulink workspace, assigning them to specific blocks. The parameters are:

- Frequency, base voltage and base power;
- Transformer data;
- Data related to the Thevenin's equivalent generator, representing the HV system;
- Branch data (resistance, reactance, length, thermal limit);
- The evolution in time of load and PV for each node, with the proper time step;
- The time steps of the time horizon;

4.2.2 Simulink Model of the Distribution Network

The Simulink model of the grid is divided into HV and MV side. Figure 4.3 represents the HV side.

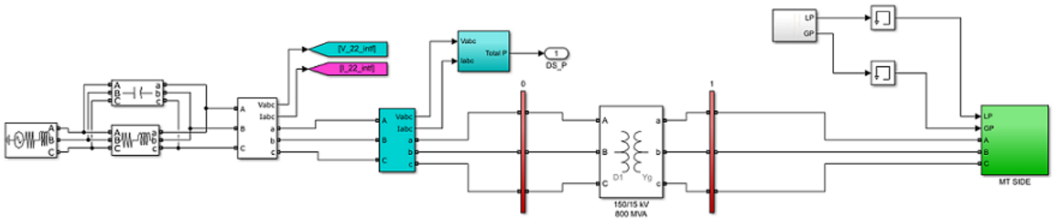

Figure 4.3: High Voltage Side of the Grid

A generator is set with its serial inductance and resistance and parallel capacity. To pass to MV side, it is required a Transformer 150 kV/15 kV, with size 800 MVA. Two measurement blocks are installed upstream the transformer to measure the active power from the phases voltage and current; these measurements are saved in a matrix that is sent to the Matlab Workspace. This matrix consists of the seven column: in the first three there are the voltages of each phase, in the other two the magnitude of the voltage and the current, in the sixth the nodal voltage in p.u and finally in the last column the active power in p.u.. The number of rows depends on the time step set for the simulation.
A similar structure is present in every node and in every line to measure electrical quantities.

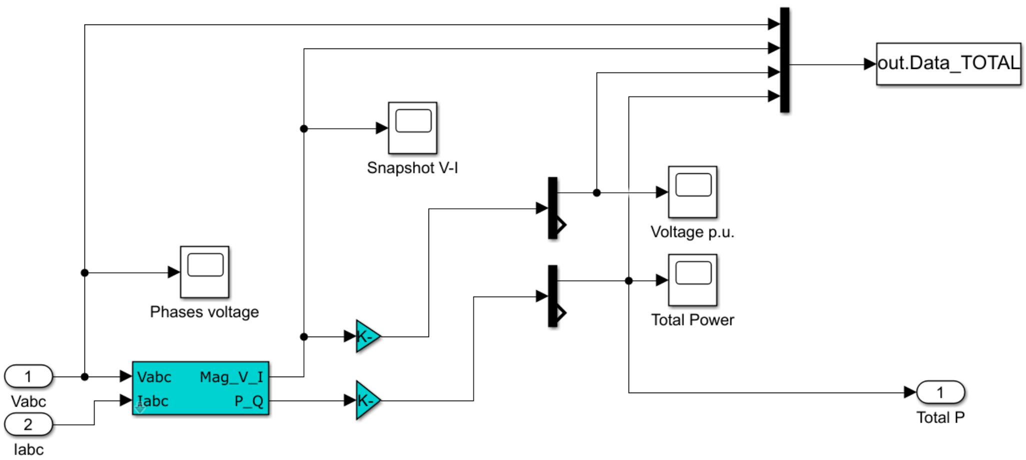

Figure 4.4: Measurement System

The secondary of the transformer is connected to another system called “MV SIDE", where there is the distribution network consisting of seven feeder, shown in Figure 4.5.
The input of this system is composed of the three phase voltages and the data collected in two matrices called **LP** and **GP**. The first matrix represents the evolution in time of the load profile, whereas the second one contains the data of the PV generation, that through the blocks Load and Gen info, are sent to the corresponding nodes.

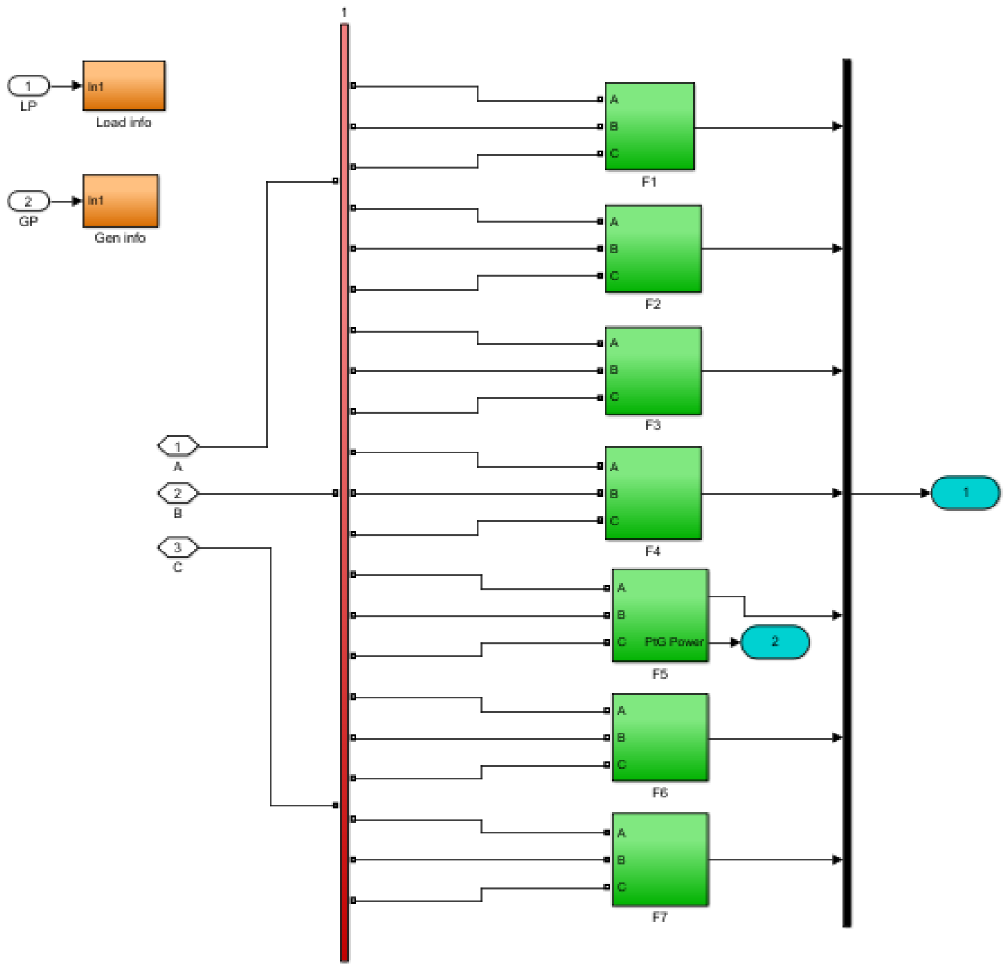

Figure 4.5: Medium Voltage Side

All feeders are composed of many nodes, with loads or PV generators connected. Figure 4.6 represents the feeder 6, which is composed by:

- Eight nodes supplied at a V = 15 kV;
- Seven lines each with its own parameters;
- Seven loads, each of them characterized by nominal active and reactive power and the load profile. At each time step, the load profile values arrive from the **LP** info through the input called PQ;
- PV generator, whose data comes from the **GP** info, but this signal is multiplied by a negative unit gain, since this power is fed into the node;
- A block to measure and save the electrical quantities refferred to each node and each line;

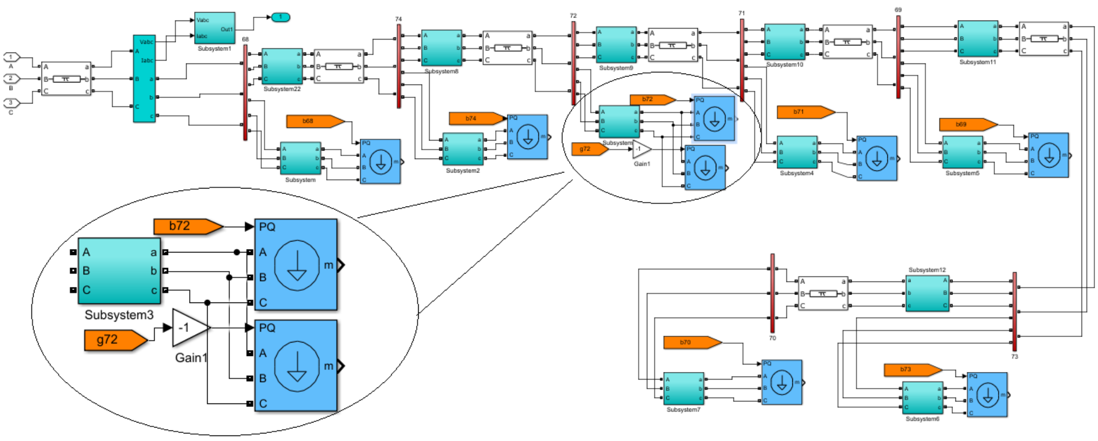

Figure 4.6: Simulink Model of Feeder 6

4.2.3 Simulink Model of the PtG

The function of PtG is to absorb power from the network at times when production is greater than demand. In other words, the PtG objective is to allow a reduction in reverse power flow and a reduction in RES curtailment.

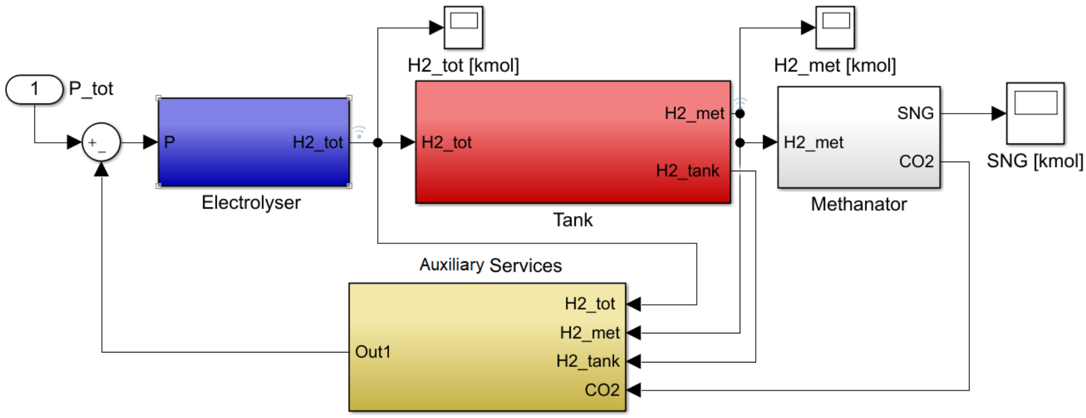

Figure 4.7: Simulink Model of PtG

Figure 4.7 represents the PtG block. It consists of four subsystems, which represent respectively an alkaline electrolyser, tank, methanator and the auxiliary services. It allows to calculate the amount of SNG produced, starting from the electrical power absorbed by the PtG.

Electrolyser Model

The first subsystem represents the alkaline electrolyzer, which has electricity and water as input, and must be first brought to a suitable temperature to produce H_2. Equation 4.4 shows the production of H_2:

$$N_{H_2} = \frac{P \cdot \eta_{elect}}{LHV_{H_2} \cdot m_{H_2}} \cdot t \tag{4.4}$$

Where N_{H_2} is the amount [kmol] of H_2 which is produced by the electrolyser, P is the active power [MW] absorbed by the electrolyser, η_{elect} is the efficiency of the elecrolyser equal to 55%, LHV_{H_2} is the lower heating value of H_2 [MJ/kg], m_{H_2} is the molar weight of H_2 [kg/kmol] and t is the time [s]
Figure 4.8 represents the Simulink model of the H_2 production.

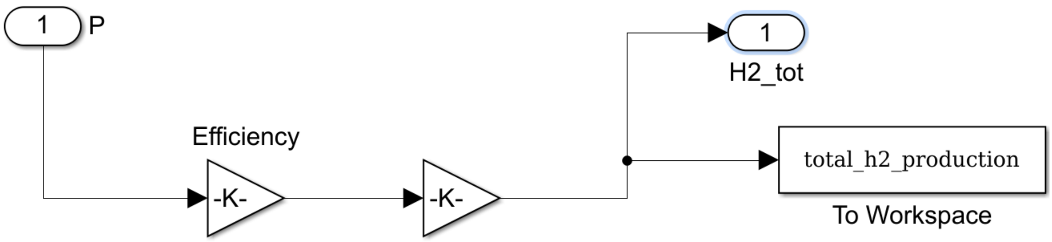

Figure 4.8: Simulink Model of H_2 Production

The two gains in Figure 4.8 represent the parameters described in the equation, to pass from electrical power [MW] to the quantity of H_2 produced [kmol], which can go directly to the methanator, where it combines with CO_2 to produce SNG, or accumulated in the tank, to be used later.
In reality, the electrolyser response has a delay in the order of seconds, but since the day is marked in quarters of an hour, this delay can be omitted.

Tank Model

The second subsystem is the H_2 tank, which has been designed so that the methanation unit always receives H_2 with a minimum flow, if the electrolyzer is not in operation. Therefore, excess H_2 can be stored in a tank until it is full (the priority is to fill the tank). This operation allows to decouple the methane unit from the electrolyser. The H_2 produced by the electrolyser is completely sent to the methanation unit, if the tank is full. Conversely, if the electrolyser does not produce enough H_2 to supply the methanator, the H_2 stored in the tank is sent to the methanation unit to ensure continuous SNG production.
Figure 4.9 represents the Simulink model of H_2 tank.

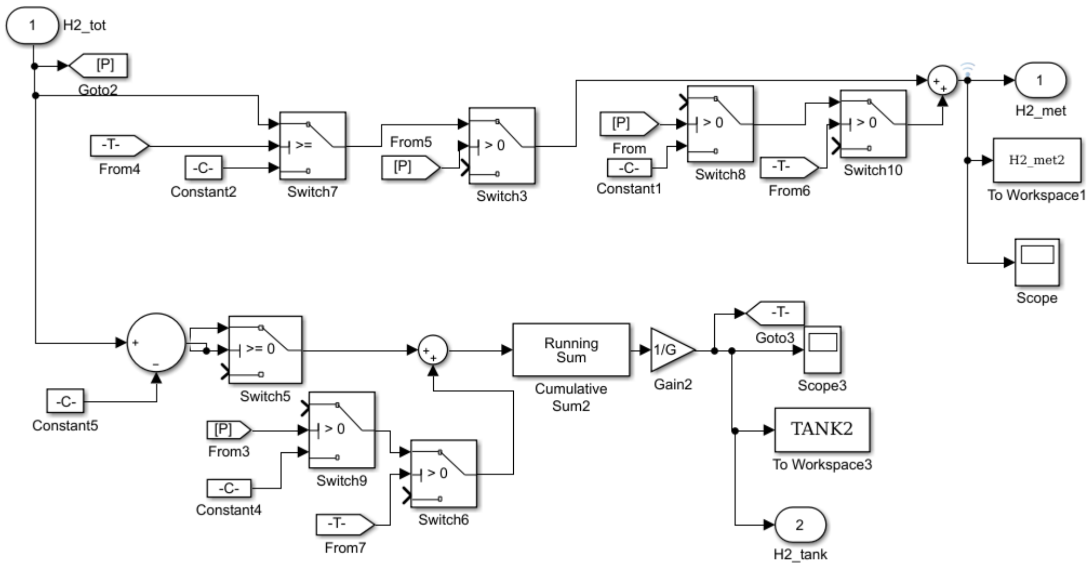

Figure 4.9: Simulink Model of H_2 Tank

Methanator Model

The last subsystem represents the methane generator, the technology that produces SNG from H_2 and CO_2. The amount of methane can be calculated using CO_2 conversion or, alternatively, hydrogen-SNG efficiency; therefore, SNG productivity can be estimated. This block is a representation of Equations 4.5, 4.6, 4.7 and 4.8.

$$N_{CO_2} = \frac{N_{H_{2,met}}}{4} \tag{4.5}$$

$$N_{CH_4} = N_{CO_2} \cdot \beta_{CO_2} \tag{4.6}$$

$$N_{SNG} = N_{CH_4} + (1 - \beta_{CO_2}) \cdot N_{CO_2} \tag{4.7}$$

$$P_{SNG} = (n_{CH_4} * m_{CH_4} + n_{H_{2,MET}} * m_{H_2}) \cdot LHV_{SNG} \tag{4.8}$$

Where N_{CO_2} is is the amount of CO_2 [kmol], $N_{H_{2,met}}$ is the amount of H_2 [kmol] which arrived to the methanator, N_{CH_4} is the amount of CH_4 [kmol], N_{SNG} is the amount of SNG [kmol] produced by methanator, β_{CO_2} is a conversion factor of the CO_2 inside the methanator equal to 99%, P_{SNG} is SNG power [MW], n_{CH_4} is the molar flow of CH_4 [kmol/s], m_{CH_4} is the molar weight of CH_4 [kg/kmol], $n_{H_{2,MET}}$ is the molar flow of H_2 [kmol/s] and LHV_{SNG} is the lower heating value of SNG [MJ/kg]

Figure 4.10 represents the Simulink model of the SNG production.

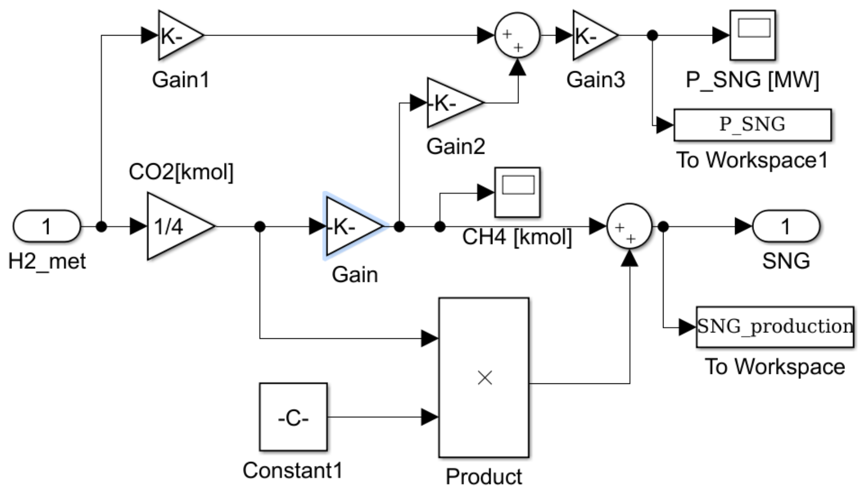

Figure 4.10: Simulink Model of Methanator

Model of Auxiliary Services

All the consumption of the Auxiliary elements of the equipment is related to the quantity of H_2 produced. The H_2 produced inside the electrolyser can be compressed in a storage tank or mixed with CO_2. Also, CO_2 can be compressed up to the pressure of the methanation. Finally, the H_2O must be heated and pumped into the electrolyser. For all these processes, electricity from the main grid is required. Figure 4.11 shows the Simulink model of the auxiliary services composed of:

- The pumping system to send H_2O to the electrolyser;
- The H_2O heating system for thermal management of the electrolyser, because it is alkaline and requires higher H_2O temperatures than PEM technology;
- Three compressors, two for H_2 and one for CO_2;

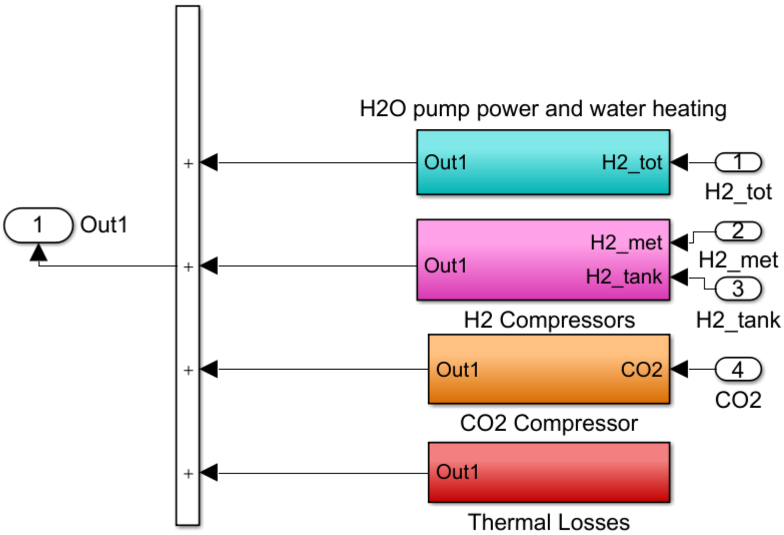

Figure 4.11: Simulink Model of Ancillary Service

In this block Simulink, the heat losses of the electrolyser and methanator have been included, to be added to the consumption of the other blocks. This sum is then subtracted from the total power absorbed by the PtG to determine the net power absorbed by the electrolyser.

Chapter 5

Simulation's Results

5.1 Introduction

The objective of the study is to compare the results of the network simulation, first without the PtG and then connecting it to the chosen node. All this to verify if the use of this technology leads to improvements in terms of overvoltages, overcurrents and reverse power flow. For this reason, the PtG is programmed to absorb electrical power at times when production exceeds demand.

Two network conditions have been considered:

- Case One: Network with PV penetration equal to 40%
- Case Two: Network with PV penetration equal to 80%

For the Case One, from the results of the STORE&GO project [5], it can be seen that to optimize the system the node where to connect the PtG is 85. Four tests were carried out in this study:

- Test A: The PtG is not connected to the network.
- Test B: The PtG is connected to the grid and works at 50% of its nominal power during the programmed time.
- Test C: The PtG is connected to the grid and works at 100% of its nominal power during the programmed time.
- Test D: The PtG is connected to the grid and in the programmed time absorbs the power needed to cancel the reverse power flow in feeder 7, In this case the PtG, in some time steps, absorbs more power than the nominal one, for this reason, a PtG with a size of 4 MW is considered, but the tank capacity and minimum flow to the methanator remain unchanged.

For the Case Two, two tests were carried out:

- Test A: The PtGs are not connected to the network,
- Test B: To cancel the reverse power flow, from the results of the STORE&GO project [5] , four 2MW PtGs were connected at the nodes 80, 85, 93, 100.

Also, for each simulation with the PtG connected to the network, an analysis was made on the production of SNG and the level of H_2 stored in the tank.
For the main equipment (electrolyser and methanation unit) a hot standby condition has been assumed (this means that the equipment is maintained at operating temperature conditions with energy absorbed by the network in order to ensure a quick start).

5.2 Case One: 40% of PV Penetration

5.2.1 Reverse Power Flow Analysis

One of the main reasons for integrating PtG into the power grid is to reduce the reverse power flow in the grid. The PtG has been programmed in such a way that it is switched on when a reverse power flow occurs, to absorb that amount of power and convert it into chemical power.
Figure 5.1 shows the results of the grid simulation in terms of active power for each feeder with the PtG not connected.

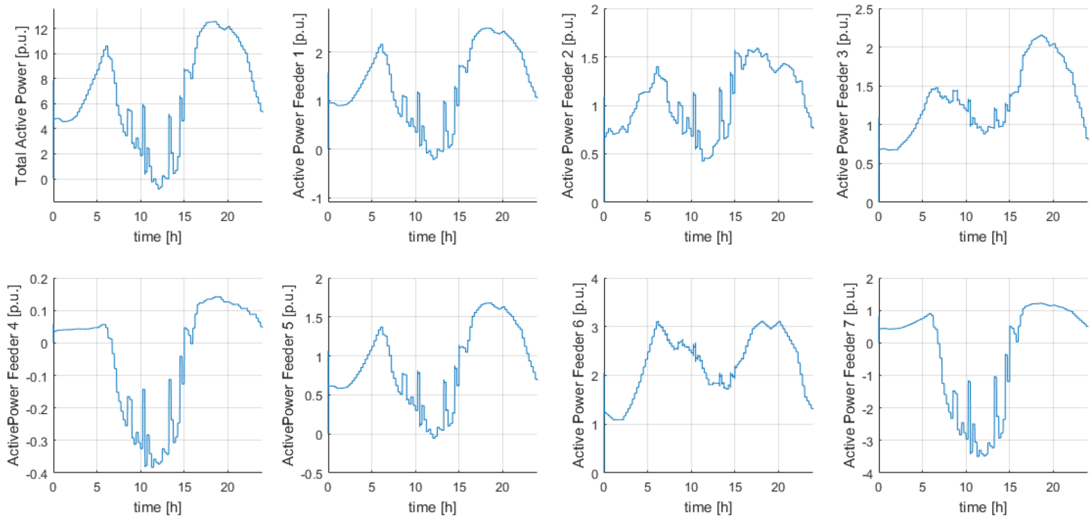

Figure 5.1: Active Power - Case One: Test A

Figure 5.1 shows that globally the grid is subject to reverse power flow with a maximum value of 0.8 MW, while among the feeder the most subject to this phenomenon is certainly the 7, with a maximum value of about 3.5 MW. For this reason, in other simulations, the PtG has the function of reducing or canceling the reverse power flow of feeder 7.

For this purpose, the PtG starts operating between 7 a.m. and 3 p.m., which is also the time interval with the highest level of production from RES. Figure 5.2 shows the evolution time of the power absorbed by the PtG in the three tests in which it is connected to the grid.

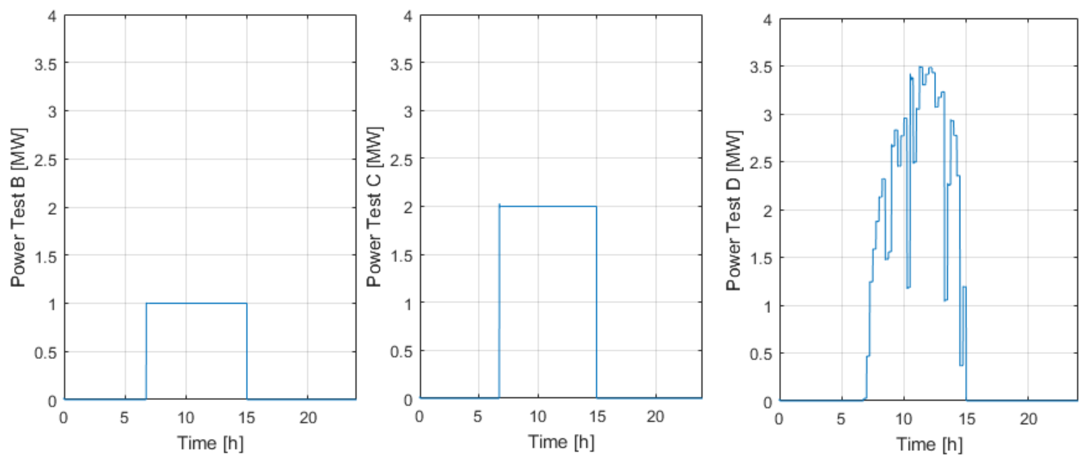

Figure 5.2: Active Power Absorbed by PtG - Case One

Figure 5.3 represents the active power of feeder 7 in all four tests.

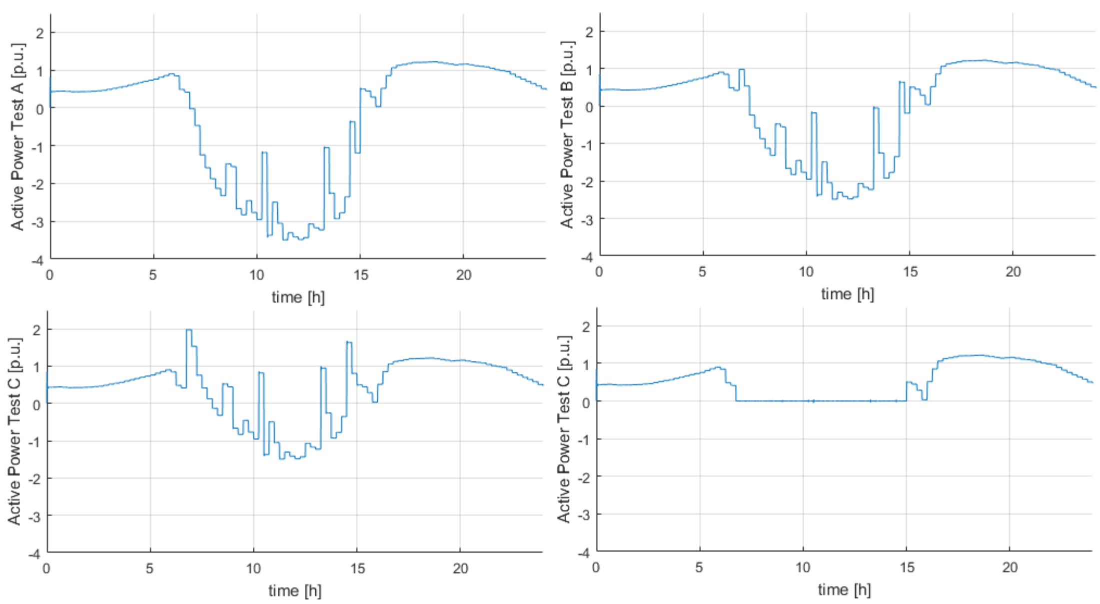

Figure 5.3: Active Power of Feeder 7 - Case One

From this figure, it is possible to notice that the reverse power flow is reduced in Tests B and C, while it is completely canceled in Test D. In detail, the results show that:

- A 40.64% reduction in reverse power flow in Test B;
- A 73.81% reduction in reverse power flow in Test C;
- A 100% reduction in reverse power flow in Test D;

Figure 5.3 also shows positive power values in the range where the PtG is on, especially in Test C. This is because in that time interval the reverse power flow is less than the power required by the PtG. This means that the feeder has to absorb a share of power from the main grid.
But in reality, even in the other two tests (as shown in Figure 5.4), the power required by the whole system is greater than without the PtG.

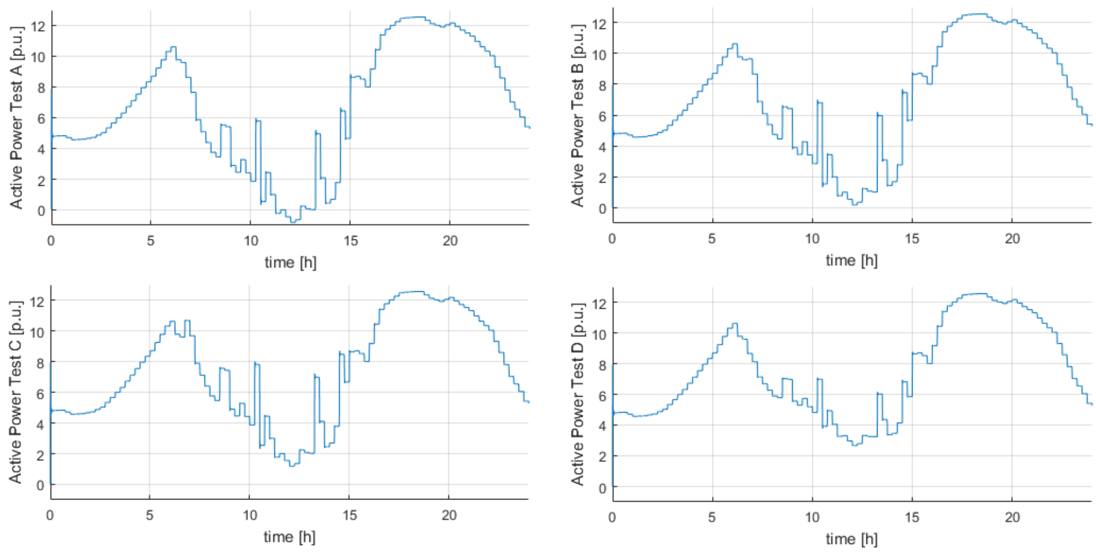

Figure 5.4: Active Power of the Global Electrical Systems - Case One

As explained in [13], to keep the demand unchanged, the PtG must absorb the reverse flow of power measured upstream of the transformer. In this case, the PtG used is a much smaller size of 1 MW and must necessarily absorb the reverse power flow of the global grid.

From Figure 5.5, it can be seen that in this case only the reverse power flow of the grid is canceled and unlike the previous cases no power surplus is required from the main grid.

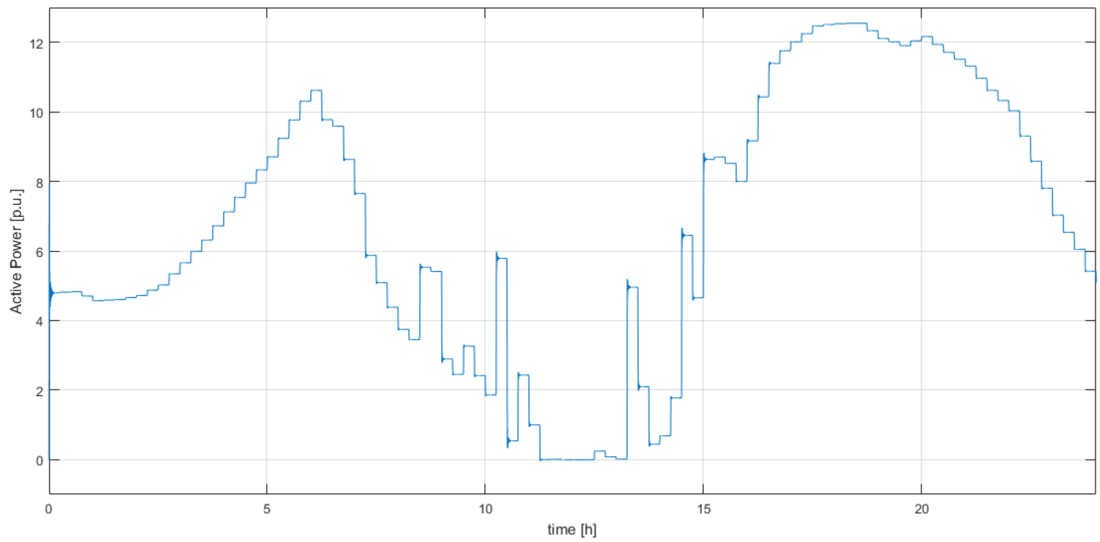

Figure 5.5: Active Power of the Grid with PtG of 1 MW

The load factor [%] is defined as the average load [MWh] divided by the peak load [MW] in a specified period [h]. Among the tests carried out is interesting to calculate the PtG load factor, in cases with a size 1 MW and Test D, as they are the only cases with a non-constant power consumption. The results obtained are:

- A load factor of 56% in Test D.
- A load factor of 66% for PtG of 1 MW.

5.2.2 Analysis of Nodal Voltages and Line Load

Figures 5.6 and 5.7 show respectively the maximum and minimum voltage per unit in each node and the ratio between the maximum currents running through the electric lines and the thermal limits of the same.

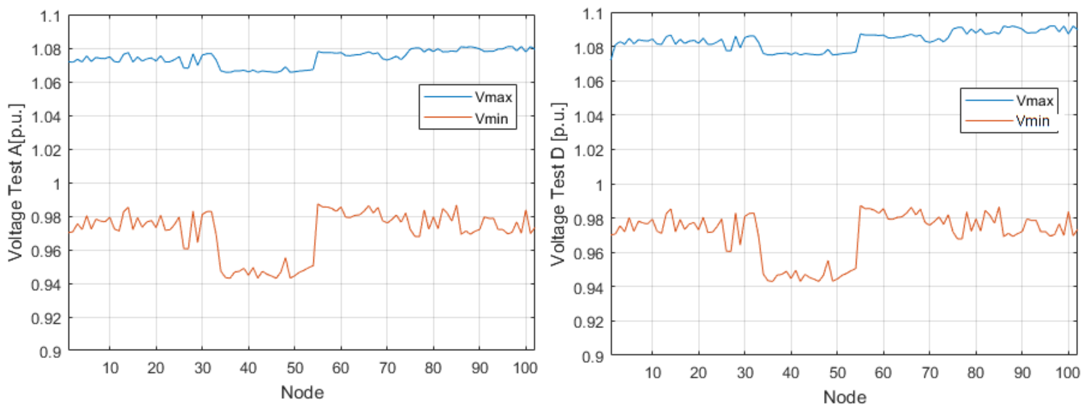

Figure 5.6: Nodal Voltage - Case One

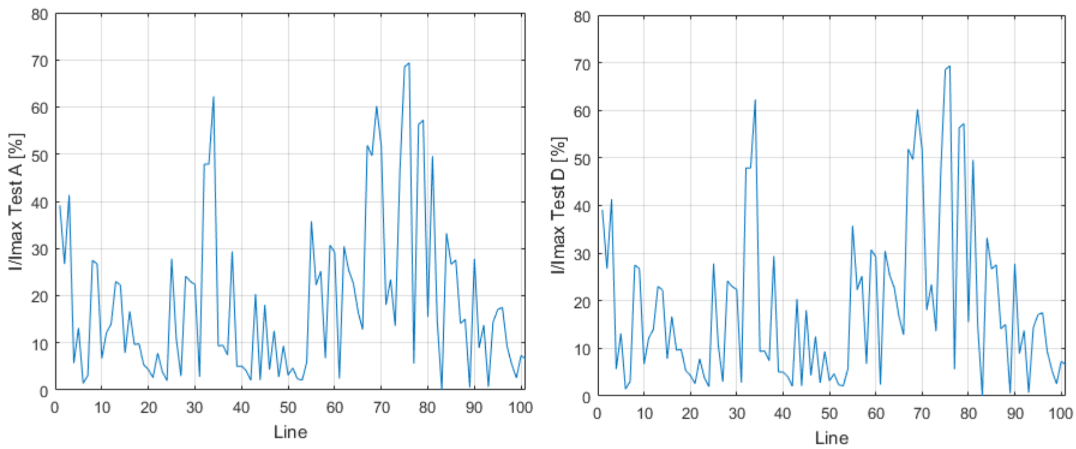

Figure 5.7: Line Loads - Case One

The analysis of the nodal voltages and line loads is fundamental to note whether the introduction of a new device could lead to malfunction of the electrical system. From the results obtained from tests with PtG, the nodal voltages are within the limits set by the STANDARD ISO IEC 60038 [12]. Moreover, there is no overloading of the lines: this is because the study was carried out with low RES penetrations. Therefore, the integration of the PtG does not compromise the proper functioning of the electrical system. The same results were obtained in Tests B and C.

5.2.3 Evaluation of the Level of H_2 Stored in the Tank

Given a certain power absorbed by the electrolyzer, a certain amount of H_2 is produced, stored in a tank waiting to react with CO_2 to produce SNG through methanation as described in Chapter 1.
The production of H_2 and the filling or emptying of the tank during the day are shown in Figures 5.9 and 5.8, for simulations with the PtG connected to the power grid.

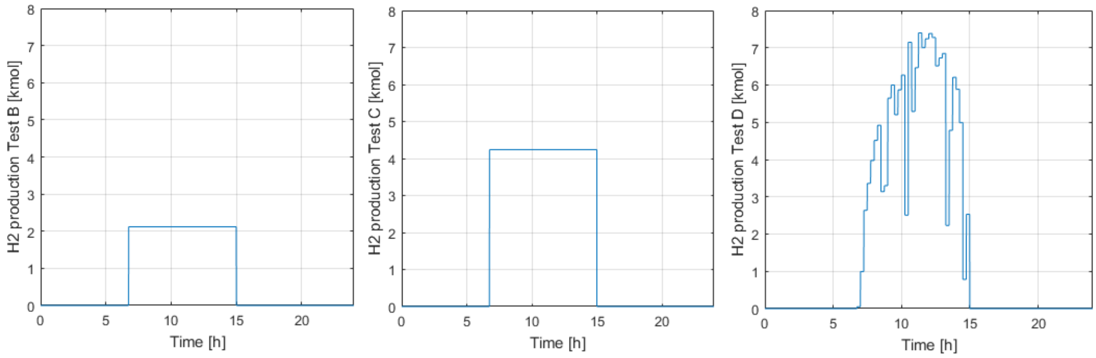

Figure 5.8: H_2 Production - Case One

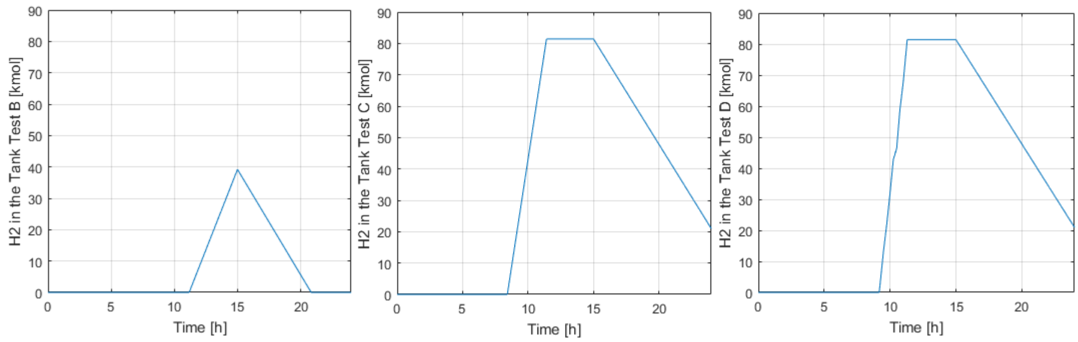

Figure 5.9: Tank Filling on PtG Day - Case One

Figures 5.8 and 5.9 show that when the eletrolyser starts to produce H_2, the tank starts to fill with a flow equal to the difference between the total flow produced by the eletrolyser and the minimum flow, that must be guaranteed to the methanator. Once the tank is filled, H_2 produced goes directly to the methanator.

When the eletrolyser stops producing, the tank starts to empty, sending H_2 to the methanator with minimum flow.

In addition, it is important to note that in Test B, the tank does not fill and is empty at the end of the day, while in the other two simulations the tank fills up and 21.3 kmol remain inside at the end of the simulation. This guarantees a continuous production of SNG for the rest of the day.

5.2.4 SNG Production

Figures 5.10 and 5.11 show the production of SNG [kmol] and the energy ratio (μ) between the chemical energy [MWh] output from the SNG generator and the electrical energy [MWh] absorbed by the PtG from the power grid.

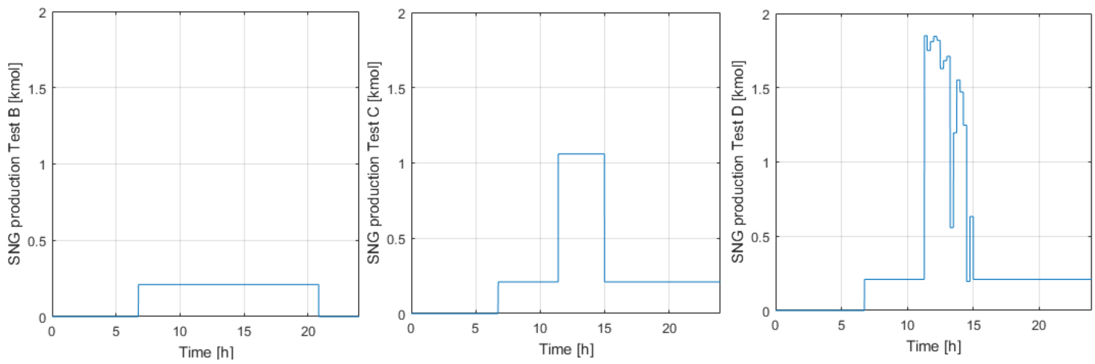

Figure 5.10: SNG Production - Case One

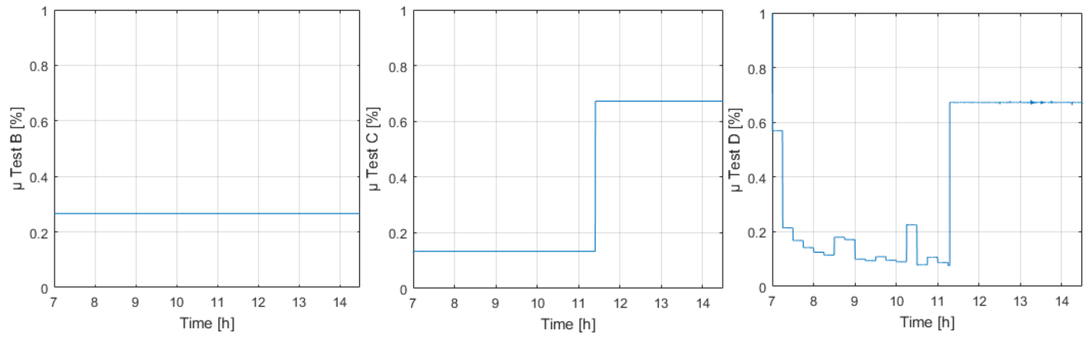

Figure 5.11: Energy Ratio - Case One

As said in Section 5.2.3, in Test B, the tank does not fill and therefore always the same amount of H_2 arrives at the methanator, for this reason, both the production of SNG and μ remain constant.
The other two cases, when the tank is full, all the H_2 produced by the eletrolyser arrives at the methanator and this leads to an increase in the production of SNG and the μ which reaches a value of 0.67. Once the production of H_2 is finished, the tank is emptied guaranteeing the continuous production of SNG.
Table 5.1 represents the daily production of H_2 and SNG. it is possible to notice that the Test D has the highest production of SNG. Defining φ [%] as the ratio between the amount of SNG [kmol] produced and that of H_2 [kmol], Test D has the higher value of φ.

Table 5.1: Overview of PtG Production Case One

	H_2 [kmol]	**SNG [kmol]**	φ [%]
Test B	69.97	11.82	16.89
Test C	139.97	27.54	19.67
Test D	161.08	32.83	20.38

5.3 Case Two: 80% of RES Penetration

The results with 40% RES penetration do not show the advantages of PtG integration in terms of overvoltage and overload of power lines. For this reason, another case study of the same network with 80% RES penetration was analyzed. Figure 5.12 shows the total active power of the distribution network (Test A).

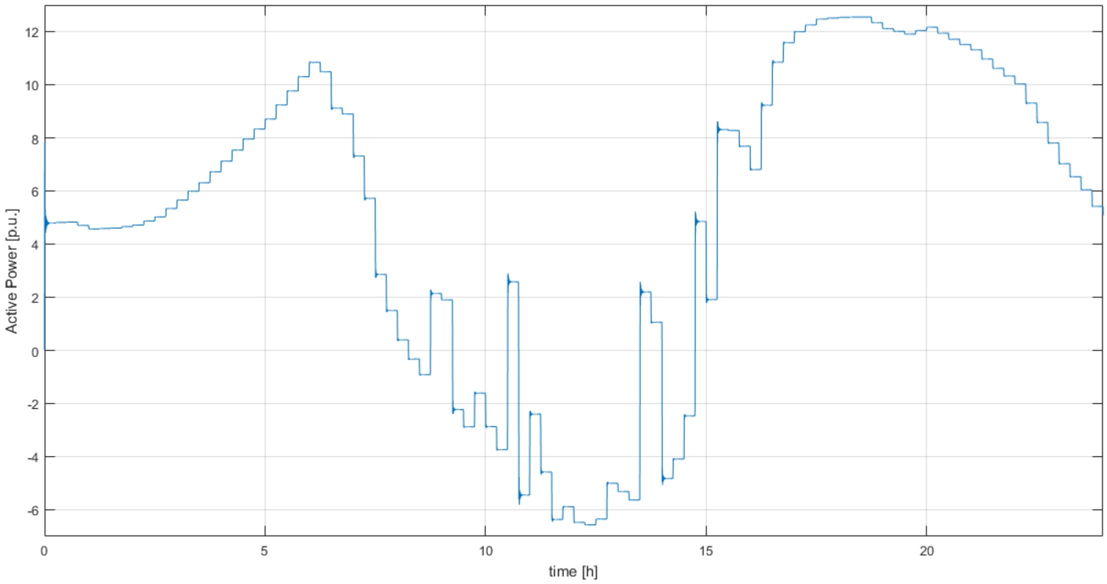

Figure 5.12: Active Power - Case Two: Test A

It is possible to note that in this case, the reverse power flow is considerably higher than in the previous case. For this reason, four 2MW PtGs have been connected to the network at nodes 80, 85, 93, 100, to absorb the reverse power flow, so they will operate between 8 a.m. and 2:30 p.m.. All four plants have the same load profile, shown in Figure 5.13, with a load factor of 41%.
The results obtained (Figure 5.14) show that the integration of PtGs, in Test B, greatly reduces the reverse power flow, almost canceling it out, making a major contribution to improve network conditions.

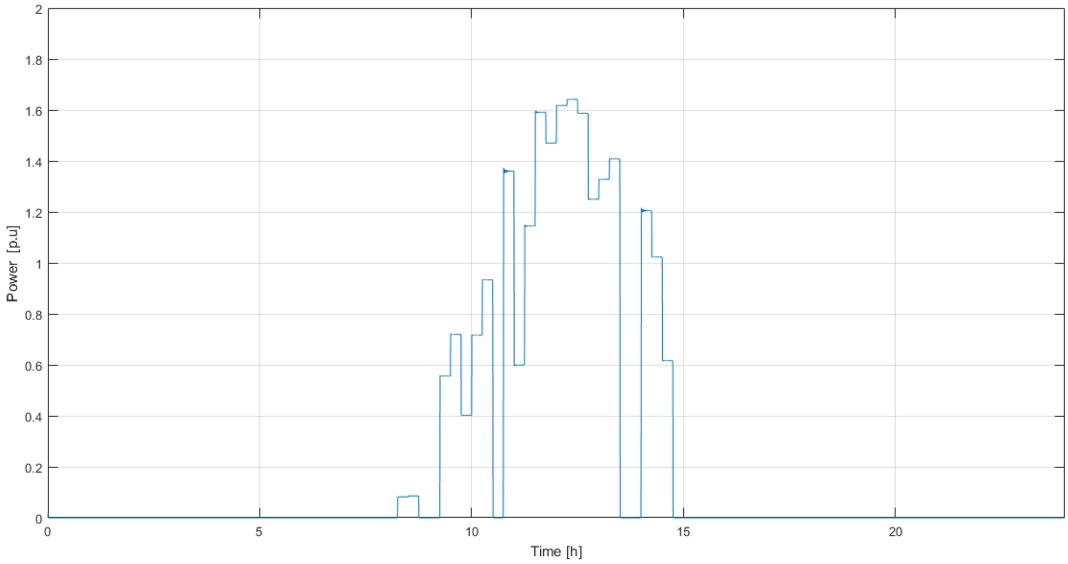

Figure 5.13: Load Profile of a PtG - Case Two

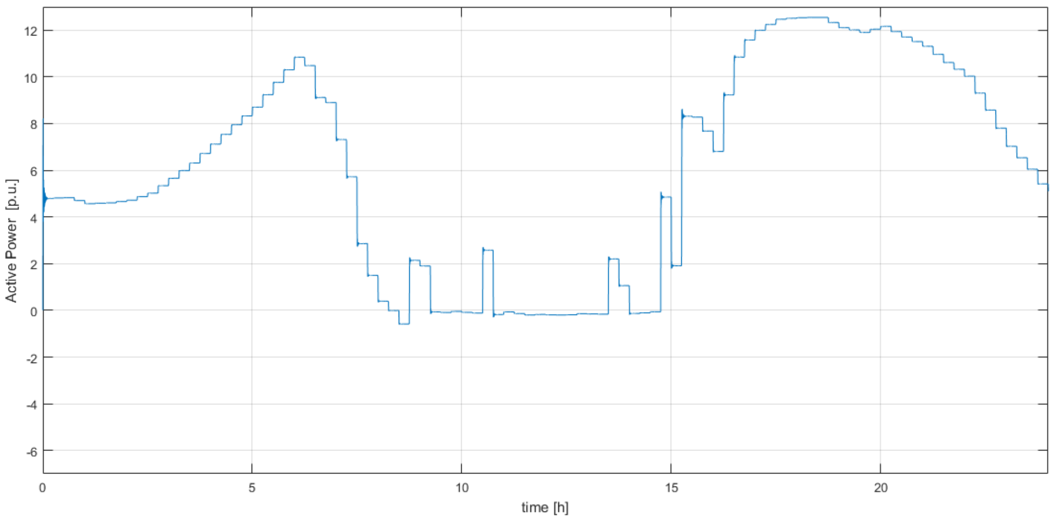

Figure 5.14: Active Power - Case Two: Test B

The improvement of the network conditions can also be seen by analyzing the features of the electrical systems, such as nodal voltage and currents in the lines. Figures 5.15 and 5.16 compare the nodal voltages and line loads, before and after installing the PtGs.

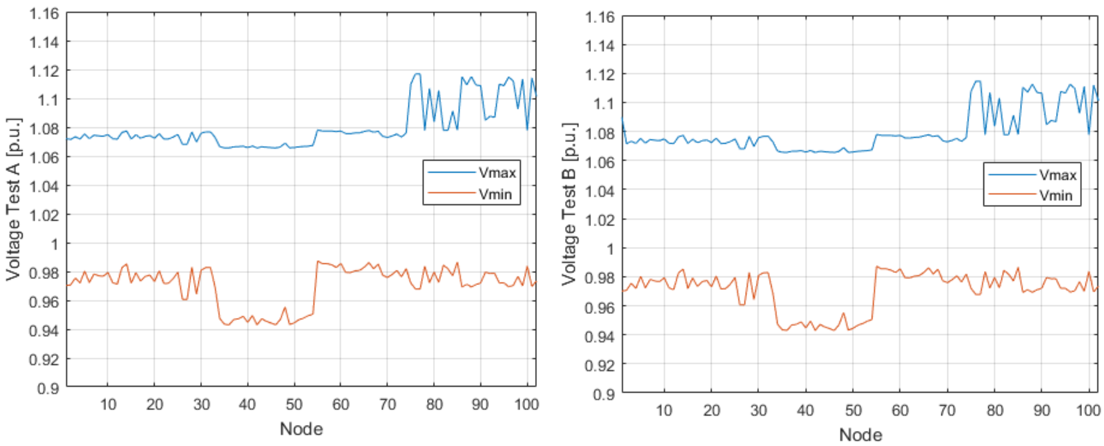

Figure 5.15: Nodal Voltage - Case Two

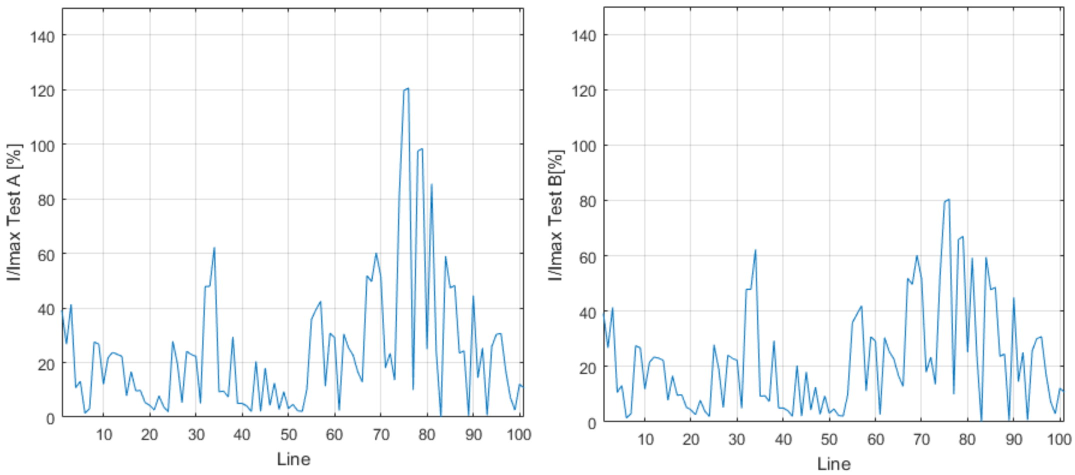

Figure 5.16: Line Loads - Case Two

It is possible to see from the results obtained, the problem of overcurrents is completely solved with the integration of PtGs, while there is a residual overvoltage, whose amplitude is however very limited, persists for a short period and this does not affect the proper functioning of the network (Table 5.2).

Table 5.2: Overvoltage Value in Test B

Node	Amplitude [%]	Duration [min]
75	10.74	4
76	11.34	4
77	11.34	4
86	11.03	4
88	11.26	4
94	10.74	1
96	11.24	1
97	10.97	1
99	11.10	1
101	11.19	1

As far as the production of SNG of only one PtG is concerned, the results obtained (Figure 5.17) show that the methanator always gets H_2 at minimum flow between 8 a.m. and 11 p.m., this is because the tank never fills up. Moreover, between 10 a.m. and 3 p.m. the tank begins to empty for a short time, because in those same moments the production of H_2 is zero and that of SNG must be guaranteed. At 9 a.m. the production of SNG is zero because the electrolyser does not produce H_2 and at the same time, the tank is not full enough to guarantee the minimum flow of H_2 to the methanator. The total production of H_2 and SNG the four PtGs is summarised in Table 5.3.

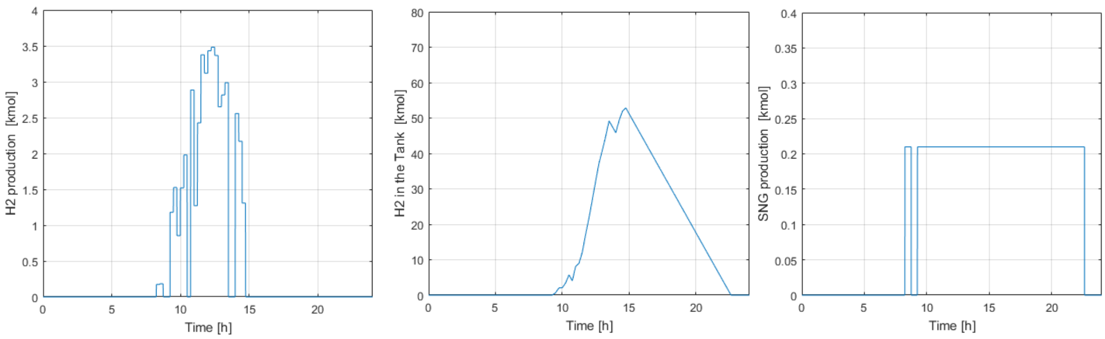

Figure 5.17: Steps of SNG Production - Case Two

Table 5.3: Overview of PtGs Production Case Two

	H_2 [kmol]	SNG [kmol]	φ [%]
PtGs	181	46.58	25.73

Chapter 6

Conclusion and Future Work

This thesis work aims to contribute to the study on the integration of PtG in the electrical system. In detail, the study can be divided into two parts.

The first part, held at the Hanze University of Applied Sciences, describes in detail the technical aspects related to the implementation of a multi-site laboratory setup for the measurement and control of the power supply of electrolyser , both from local and remote locations. In particular, this phase is aimed at the realization of a Simulink model, which allows the control of the electrical output variables of a power amplifier, used to feed the electrolyser in the laboratory. Moreover, again through Simulink, a connection between the Power Amplifier and the other devices present in the laboratory, such as the measuring instrument, has been created to form the so-called PHIL. The next step was the one known as RPHIL, which aimed to verify the functionality of the control from the Global Real-Time Simulations laboratory of the Politecnico di Torino, which is connected to that of Hanze University through a VPN connection. Despite the connection problems between the two laboratories, the results obtained demonstrate the possibility of controlling the entire system both locally and remotely and the exchange of data between the two laboratories.

The second part of the thesis describes step by step the realization of a Simulink model, which simulates a day in October of a real distribution network, with the presence of PV generation. In addition, another model was created that emulates the behavior of the PtG (consisting of electrolyser, tank, methane generator, and auxiliary service), to connect it in a node of the electricity grid and study the impact it has on it. Two case studies were carried out with different RES penetration, the

first at 40% and the second at 80%. In both cases with the right PtG setting it is possible to completely eliminate reverse power flow. In the first case study, having a low RES penetration, there were no problems of overvoltage or overcurrent, so in these terms, the integration of PtG did not bring significant results. While, in the second case study, due to the high RES penetration, overvoltage and overcurrent problems occurred without PtGs. The test carried out with the four PtGs shows that they make a major contribution to improving network operation, since there is no longer any line overload. On the other hand, there are some overvoltages of short duration, which do not compromise the correct operation of the network.
In terms of SNG production, it can be seen that it is directly proportional to the total electrical power absorbed by the PtG. From the simulations carried out, it can be seen that only in Tests C and D of the Case One the production of SNG is guaranteed until the end of the day.

Starting from the work developed in this thesis, the possible future development will be based on the connection, through the power amplifier, of the 8 kW electrolyser of Hanze University to the simulated network at the Politecnico di Torino. This connection will make it possible to study the behaviour of a real electrolyzer within a simulated environment. Scalability will be ensured by the possibility to consider such an electrolyser as a single stack, in order to make the study compatible also with different penetrations of renewable resources.

Bibliography

[1] G. Chicco A. Mazza E. Bompard. «Applications of power to gas technologies in emerging electrical systems». In: *Renewable and Sustainable Energy Reviews* 92 (May 2018), pp. 794–806 (cit. on p. 2).

[2] Andrea Ballocchi. «L'idrogeno potrebbe essere prodotto dall'acqua». In: (2017) (cit. on p. 3).

[3] V. Himabindu G. Shiva Kumar. «Hydrogen production by PEM water electrolysis». In: (2019) (cit. on pp. 5, 6, 8).

[4] G. Morandi. «Modelling and lab-setting for hydrogen-electricity integration in the energy transition context». MA thesis. Torino: Politecnico di Torino, 2019 (cit. on pp. 7, 23).

[5] G. Chicco A. Mazza E. Bompard. *Report on the model of the power system with PtG*. 2018. URL: `https://www.storeandgo.info/fileadmin/downloads/deliverables_2019/20190801-STOREandGO-D6.4-POLITO-Report_on_the_model_of_the_power_system_with_PtG.pdf` (cit. on pp. 16, 45–47, 59, 60).

[6] H. Lok. *Report status P2G grid integration experiment*. Store&GO. no published. 2018 (cit. on pp. 18, 20).

[7] *Grid Emulator (GE + ACDC) Human Machine Interface*. Cinergia. 2018 (cit. on pp. 24, 26).

[8] A. Mazza H. Lok. *Report: Real time implementation of grid models*. 2019. URL: `https://www.storeandgo.info/fileadmin/downloads/deliverables_2019/20190801-STOREandGO-D6.5-HANZE-Real_time_implementation_of_grid_models.pdf` (cit. on pp. 29, 36).

[9] *Grid Emulator (GE) Modbus data table D0270*. Cinergia. 2018 (cit. on p. 31).

[10] *Bright Solar Resource Model,* 2018. URL: `http://jamiembright.github.io/BrightSolarModel/,` (cit. on p. 47).

[11] P. Di Leo F.Spertino F.Corona. «Limts of Advisability for Master-Slave Configuration of DC-AC Converters in Photovoltaic Systems». In: *IEEE Journal of Photovoltaics* 2 (2012), pp. 547–554 (cit. on p. 47).

[12] *STANDARD ISO IEC 60038*. IEC, 2009. URL: `https://webstore.iec.ch/preview/info_iec60038%5C%7Bed7.0%5C%7Db.pdf` (cit. on pp. 49, 65).

[13] L. Serra. «Analisi dell'impatto della tecnologia Power-to-Gas sull'esercizio di reti di distribuzione con elevata penetrazione di risorse rinnovabili». MA thesis. Torino: Politecnico di Torino, 2018 (cit. on p. 63).