The main objective of this work is to complete a functional simulation of a Microgrid System using the professional software PSCAD/EMTDC. In order to accomplish this objective first it is necessary to model correctly the different elements of this type of systems. Keeping this objective in mind, a real microgrid is selected as reference, and the modelled and simulated microgrid stands upon it.

Then, when all the different parts of the microgrid are correctly modelled, several cases of study are done, from islanded mode conditions to fault conditions going through grid connected and emergency conditions. It has been carried out several simplifications of the microgrid due to lack of information and electrical schemes of the real microgrid.

Then, once the microgrid is modelled and simulated, results are analyzed and conclusions are setted. As appendix, a budget and a user guide is also done, with the aim of helping to understand what it is the procedure in power system simulation.

FINAL BACHELOR'S THESIS

ÁNGEL PAREDES PARRILLA

ELECTRICAL ENGINEERING

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Is an Electrical and Mechanical Engineer of Castellar (Jaén). He finished its second Bachelor degree at Engineering with this thesis at the Escuela de Ingenierías Industriales in the University of Málaga. This thesis complete the knowledge adquired about electrical modelling and simulation during its bachelor.
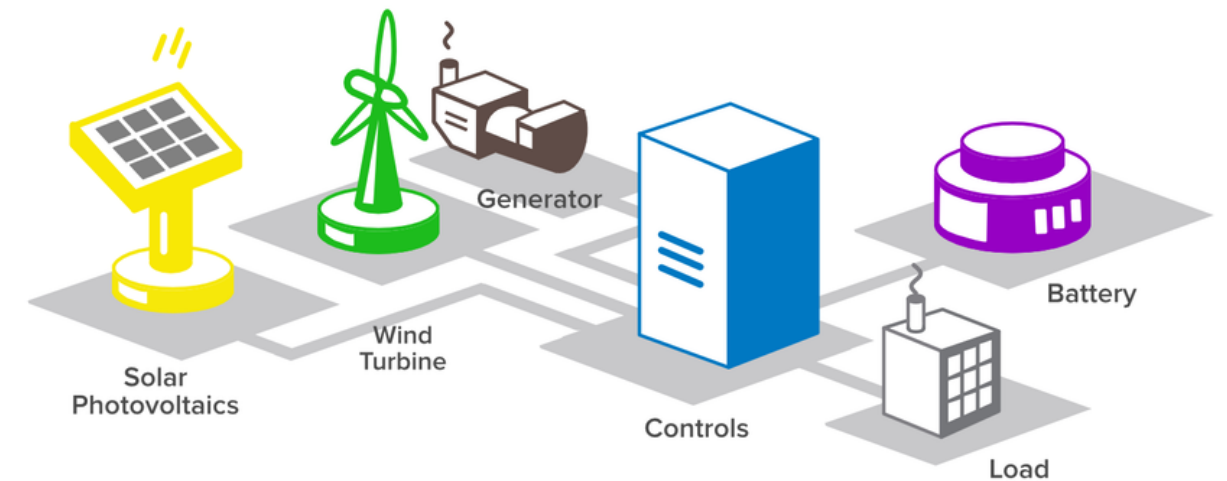
UNIVERSITY OF MÁLAGA
ELECTRICAL ENGINEERING

Solar Photovoltaics — Wind Turbine — Generator — Controls — Battery — Load

FINAL BACHELOR'S THESIS

MODELLING AND ANALYSIS OF HYBRID MICROGRIDS USING PSCAD/EMTDC

ÁNGEL PAREDES PARRILLA
2018/2019

MENTOR: Alejandro Rodríguez Gómez
CO-MENTOR: Rafael Arranz Padilla

ESCUELA DE INGENIERÍAS INDUSTRIALES

ELECTRICAL ENGINEERING DEPARTMENT

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Bachelor's Degree:

Electrical Engineering

Author: Ángel Paredes Parrilla

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MÁLAGA, July of 2.019

ESCUELA DE INGENIERÍAS INDUSTRIALES

DEPARTAMENTO DE INGENIERÍA ELÉCTRICA

TRABAJO FIN DE GRADO

Modelado y Análisis de microrredes híbridas mediante PSCAD/EMTDC

Grado en:

Ingeniería Eléctrica

Autor: Ángel Paredes Parrilla

Tutor: Alejandro Rodríguez Gómez
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MÁLAGA, julio de 2.019

Statement of Originality

Mr. Ángel Paredes Parrilla with DNI: 15521558-P, student of the Bachelor's Degree of Electrical Engineering of the University of Málaga, at 2018-2019 academic year, author of this work, titled: "Modelling and Analysis of hybrid microgrids using PSCAD/EMTDC", hereby declare:

The submitted Bachelor's thesis is the result of my own work, and that, to the best of my knowledge, it contains no sources or resources other that the ones mentioned and acknowledged. The sources used have been stated in accordance with the rules and regulations applied at the Bachelor's Degree of Electrical Engineering.

I have indicated all quotes, citations and references that were literally taken -in full, or parts of them- from publications, i.e. books, journals, academic articles, whether published or unpublished, as well as web sources, newspapers, reports, etc. I also hereby declared that the intellectual content of this thesis is the product of my own work, even though I may have received

This statement of originality is done according to the Article 10 of the Rules of Final Bachelor's Degree Thesis at the Industrial Engineering School of the University of Málaga, approved the 12th of March of 2018.

<div align="center">

Málaga, 10th of July of 2019.

Sdg. Ángel Paredes Parrilla.

</div>

Abstract

The main objective of this work is to complete a functional simulation of a Microgrid System using the professional software PSCAD/EMTDC. In order to accomplish this objective first it is necessary to model correctly the different elements of this type of systems. Keeping this objective in mind, a real microgrid is selected as reference, and the modelled and simulated microgrid stands upon it.

Then, when all the different parts of the microgrid are properly modelled, several cases of study are done, from islanded mode conditions to fault conditions going through grid connected and emergency conditions. It has been carried out several simplifications of the microgrid due to lack of information and electrical schemes of the real microgrid.

Then, once the microgrid is modelled and simulated, results are analyzed and conclusions are setted. As appendix, a budget and a user guide is also done, with the aim of helping to understand what it is the procedure in power system simulation with the software used.

Keywords

PSCAD, EMTDC, Microgrid, Photovoltaics, Diesel Engine, Gas Turbine, Power electronics.

Resumen

El principal objetivo del presente trabajo es la realización de una simulación completa de una microrred utilizando el programa profesional PSCAD/EMTDC. Para poder completar esta tarea, primeramente es necesario modelar correctamente las distintas partes de la microrred. Teniendo esto en cuenta, una microrred real es selecionada como referencia para el modelado y la simulación de la microrred de la que trata el presente trabajo.

Tras esto, una vez que las diferentes partes de la microrred están operativas, se procede a la simulación de diferentes casos de estudio, los cuales van desde simulación bajo condiciones de funcionamiento aislado, hasta condiciones de falta, pasando por el funcionamiento conectado a la red y bajo condiciones de emergencia. Se han llevado a cabo algunas simplificaciones del sistema debido a la falta de información y a la ausencia de esquemas eléctricos.

Por lo tanto, una vez que la red ha sido modelada y simulada, los resultados son analizados y las conclusiones realizadas. Como apéndices se presentan, un presupuesto y una guía de usuario con el fin de ayudar a la comprensión de cuál es el procedimiento en las simulaciones de sistemas de potencia con el software empleado.

Palabras clave

PSCAD, EMTDC, Microrredes, Fotovoltaica, Motor Diesel, Turbina de gas, Electrónica de potencia.

Acknowledgements

During the present thesis, without a doubt, has been necessary the help of much more people than referenced in the bibliography. Owing to this fact, this few lines are included as acknowledgement to these people who had been trusting in me from the very beginning of my university studies.

First of all, I want to appreciate all the hard work made by my parents Ángel and Consolación; my grandparents Antonio and Vicenta, and the rest of my family. They are the engine that propels my anxiety of knowledge and push me beyond the limits that I have ever imaged.

Special mention to my classmates, they has been by my side during all of this years of hard study, during those long nights in front of a PC, a calculator and a piece of paper. Thank you all, you made this trip much more comfortable and happier!

I strongly believe that I have found gold with my mentor and co-mentor, I have so many things to thanks to both of you that I can even start for one. Thank you for all your implication, and for your work. Without it, I have never been interested in power systems as far as I am now.

And, in last stage, but no less important, thanks to you, Fátima, you have been and are the light that make my days brighter and provides me energy to overtake adversity and anxiety. Thanks to you for being just you, and for always offers me an honest advice when I needed. You deserve heaven for trusting in me even when I was not able to. Thanks for so much, honey.

«The belief in a certain idea gives to the researcher the support for his work. Without this belief he would be lost in a sea of doubts and insufficiently verified proofs».
- Konrad Zuse [1].

Contents

Abbreviations

CIGRÉ Conseil International des Grands Réseaux Électriques

DER Distributed Energy Resources

ECTS European Credit Transfer System

EMTDC Electromagnetic Transients including Direct Current

PCC Point of Common Coupling

PSCAD Power System Computer Aided Design

PV Photovoltaic

SoC State of Charge

List of Symbols

A Area

β Blade pitch angle

C Capacity

C_p Power Coefficient

η Efficiency

γ Tip speed ratio

H Manometric lift

I Current

L Inductance

ω Angular velocity

P Output power

Q Heat

R Resistance

ρ Density

t time

V Voltage

v Velocity

W Work

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Chapter 1

Introduction

1.1 Background, motivation and objectives

1.1.1 Background

Nowadays, motivated by the energy transition that set conventional power sources aside, and opt for an energy model more sustainable, it becomes usual the usage of little isolated power sources, whether in houses or public buildings. The inclusion of these systems in the society lead to the definition of "Microgrid". A microgrid is an electric power system where the energy sources are distributed, generally renewable and installed near to the customer. These types of grids are characterised for working islanded or connected to the main grid. There are no limits in terms of size, and the definitions of microgrids are focused mainly in two features:

- A microgrid is a system locally checked.
- A microgrid can work connected to the bus or as an electrical island.

These microgrid, due to the ability to work in islanded and grid connected mode, and the installation of distributed sources, are very resilient, flexible at emergency leaks or faults in the network. These microgrids can, also, supply energy to the emergency services fastly and effectively. A microgrid has fundamentally four parts: distributed energy resources (DER), consumption, energy storage and the point of common coupling (PCC).

- Distributed energy resources (DER): A microgrid is capable to generate, mainly, two types of energy: electricity and thermal energy. The first one, is created by using

electric generators, as photovoltaic cells, wind turbines, etc. The second one, is often generated by using conventional generators as, natural gas turbine, combined cycle power plants, etc.

- Consumption: This includes all types of loads connected to the network. They are all the passive elements of the grid, from a small luminaire, to megawatts electric motors.

- Energy storage: These elements lead an important role in the properly mode of operation the microgrid. They affect to signal quality and cost of production. There are different technologies as: electrical (batteries), thermal (boiling water), kinetical (flywheel), etc.

- Point of Common Coupling (PCC): Is the point where the microgrid is connected to the main network. When a microgrid does not have it, they are called, isolated microgrids. This is often in remote places where an connection to the main network is economically unfeasible.

On the other hand, there are quite a few applications of this technology. Focusing on two of them that are more extended:

The first one, is the obvious one, it is possible, to public buildings, private houses, etc. to install little DER along the free spaces (roofs, basements, etc.) that allow to cover a part of the consumption of the loads. For that applications renewable sources are often used (Photovoltaic cells, wind turbines, etc.). For that reason, it is claim that microgrids are good solutions for the environment, they helps to reduce the necessity of conventional and no-renewable resources that are changing the climate.

The second one, is for remote locations where it is economically unfeasible to build a power transmission line that supplies electrical energy. In some locations, the installation of some photovoltaic cells and wind turbines, allows to local people to access to the energy without using the main network. This is especially recommended for underdeveloped regions where the access to the electricity it is not guaranteed. [2].

1.1.2 Motivations and objectives

The main motivation to make this thesis is passing the subject titled: "Trabajo Fin de Grado" and finish with all the Credits ECTS of the Bachelor's Degree in Electrical Engineering, included at the Double Bachelor's Degree in Mechanical Engineering and Electrical Engineering. Keeping this motivation in mind, it has to be studied, modelled and analysed the behaviour of a functional microgrid.

The work plan followed to complete this thesis had been divided in several stages. First of all, a particular case of study has to be selected in order to accomplish a real and functional microgrid. At that moment, had been necessary to identify all the different parts that make up the system. Later, a mathematical modelling of the different elements was carried out, separately. Finally, each system was modelled using PSCAD/EMTDC, and then, an analysis has been completed for each element, at first instance, separately and later, together.

The principal objectives of this thesis are:

- Modelling of the different elements of a Microgrid.
- Modelling of the complete Microgrid system.

1.2 Outline of the document

This thesis is divided in five chapters and three appendixes:

- **Chapter 1: Introduction**. This chapter is used as introduction to the thesis and it would be here where background, motivation and objectives are explained.

- **Chapter 2: State of the art**. The second chapter introduces to the current state of the technology in terms of Microgrid Techniques. This chapter deepen on all the different types of distributed generation, consumption, energy storage and control techniques available in the present time. Several equations are drawn setting the basics in the modelling and simulation.

- **Chapter 3: Microgrid Modelling**. The third chapter is used to explain the characteristics of the reference microgrid and to explain how is modelled each part of the microgrid simulated in this thesis.

- **Chapter 4: Microgrid Simulation**. In this chapter, once when all the different parts of the microgrid are modelled, it is time to merge different parts an to start simulating different case of study, that is, islanded mode, grid connected mode, emergency mode, and fault mode.

- **Chapter 5: Results Analysis and Conclusions**. After all simulations are done, in this chapter is drawn a analysis of the main results obtained in the previous chapter. Also, there are explained the conclusion of this thesis and the future lines of work.

- **Appendix A: Budget**. In this appendix a little and indicative budget is done. This budget considers three parts: Computer equipment, Human resources and Material resources.

- **Appendix B: PSCAD User Guide**. In this appendix is done a little PSCAD User Guide. First of all, interface is explained and next is done a simple example to lay the groundwork of what is a Power System Simulation.

- **Appendix C: Drawings**. In this appendix, drawing are listed.

1.3   Gantt Diagram

Gantt Diagram of the whole thesis is represented in table 1.1:

	Feb.	Mar.	Apr.	May	Jun.	Jul.
1. Project Starting						
1.1. Proposal and feasibility analysis						
1.2. Selection of the reference MG						
2. Microgrid Modelling						
2.1. Learning PSCAD basics						
2.2. Modelling each component						
2.3. Models debugging						
3. Power system simulation						
3.1. Microgrid setup						
3.2. Simulation of the studies						
3.3. Results analysis						
4. Project Documentation						
4.1. Writing of the thesis						
4.2. Information Research						
4.3. Presentation training						

Table 1.1: Gantt Diagram of the thesis

Chapter 2

State of the art

2.1 Introduction

As it is discussed along chapter 1, Microgrids are little versions of the main electrical grid. The Microgrid concept dates back to the early 1880, more specifically, to 1882, when Thomas Alba Edison create the first electrical system. Although he created it without the guidance of any standard, that first system fits really well in the current concept of Microgrid.

That first Microgrid was self-sustained, including six jumbo generators powered by coal fired steam engines, creating 1.100 kW (DC) with some batteries. It only supply energy to a few residential blocks with the limitations of the DC grid. This description of the first grid ever opened fits very well with current idea of Microgrid. [3].

After that, about 1930, the principal grid evolves to a state regulated model, leaving aside all the technological advances done in the field of Microgrids. Until recent years, that model have not changed so much: the early years, there were great power plants, most of them used non-renewable resources, at significant points of the terrain; when renewable energy was developed, the usage of hydraulic and solar plants become more usual, but, even they were around strategic points over the terrain. The electrical system was, as is logical, unidirectional.

The main causes of the appearance of microgrid in the current society are two: grid stability against faults, and the increasing concern about climate change. In order to overcome the first problem it is necessary leave aside the current model of generation and opt for an distributed one, in this way, the electrical system are much more robust against faults and

contingencies. In the other hand, conventional power plants have been contributing greatly to the climate change, it is easy to find in Microgrids their natural substitute, because the usage of renewable resource in their DER's units.

Another advantage of Microgrids is that their control are local, and for that reason, it can fits very well to the user necessities. The current system has much larger control systems that are not so accurate in what control is referred.

In the current chapter, a formal definition of a Microgrid is done, emphasising in different types of the technology, elements they have, and what are their advantages and drawbacks. Also, a deeper description is done of all the components, describing it descriptive and mathematically.

2.2   What is a Microgrid?

2.2.1   Definitions

There are several formal definitions of what a Microgrid is. Mainly, there are no limitations in terms of size, in fact, the definitions of the microgrids are focused on two characteristics:

- A microgrid is an local controlled system.
- A microgrid can work autonomously and synchronised with the conventional grid.

Wikipedia defines them as a *"localised group of electricity sources and loads that normally operates connected to and synchronous with the traditional wide area synchronous grid (macrogrid), but can also disconnect to "island mode" and function autonomously as physical or economic conditions dictate."*. [2].

According to the Working Group 6.22 of the International Council on Large Electric Systems (CIGRÉ), Microgrids are: *"electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded."*. [4]

2.2.2 Types of Microgrids

Fundamentally, there are two classifications of microgrids, one focused on their size and another in their controllability.

Focusing on their operability:

- *Grid synchronised:* when Microgrids works as another part of the whole conventional grid. In this mode of operation, they have fixed the value of voltage and frequency.

- *Islanded mode:* when microgrids works autonomously, i.e. apart of the main system, due to an failure in the principal grid, or due to economically unfeasible connection to the main grid. In this mode, if the control allows it, frequency and voltage can be modified with the requirements of the users.

Berkeley Lab has done a classification focusing on their size [5]:

- *Customer microgrids:* This is, microgrids as its strict definition, they are downstream a PCC, self-governed and can work in grid connected mode or islanded mode. There are many different demonstrations of this type, because they fit with the current regulations and technology.

- *Utility or community microgrids or miligrids:* They do not have very differences with the customer microgrids, but their size. They are usually used by a larger amount of users, as they are more powerful than first type. Here, the regulatory take a more important role, and it can modify some characteristics of the grid.

- *Virtual microgrids:* Using DER units distributed at multiple sites, they are coordinated by only one controlled entity. There are not so much examples of this kind of grid.

2.2.3 Advantages and disadvantages of Microgrids

Due to it characteristics, Microgrids has several advantages, and disadvantages that it is necessary to notice:

First of all, this kind of microgrids, taking advantage of the distributed generation, can give energy supply to remote locations where it is economically unfeasible to carry out the conventional grid.

Also, there are some technical advances that lead to the reduction of the costs. Some examples can be: Internet of Things (it would be easier to control the microgrid if we have multiple and different measure of its state), Smart Electric Meters (allow to the company to know what the microgrid is doing at each moment), etc.

Another advantage is that the Joule losses are reduced because the consumption are near the generation, getting rid of the really long Power Transmission Lines, at its losses.

But, on the other hand, there are some drawbacks that can not be obviate. Microgrids, especially when there are great amounts of photovoltaical energy generated. There is widely know the problems that chased Germany in the past when there was more difficult to control what a PV cell could produce. Due to the oversupply of power to the system, it accelerates leading the frequency to get up to 50,2 Hz.

There is another disadvantage of the use of Microgrids. All DER's units have what it is called, an inverter. It generates harmonic signals that may produce a failure of the entire grid if some system is sensitive to the harmonic frequency generated by electronics. That is to say, that this problem can be solved by the usage of signal filters, with capacitors and coils, but it is really expensive, and, in some cases it can be economically unfeasible.

All in all, it is possible to notice that drawbacks are not so harmful as they may appear. Nowadays there are solutions to the majority of the problems that microgrids have, for that reason, new advancements are done in the line of the implementation of Microgrids in the conventional grid.

2.2.4 Present and Future of the Microgrids

There are different implementations of this kind of electrical power system in our society. One of this examples, is the SmartGrid managed by Endesa in Málaga. The aim of this project, is to update and optimise the previous grid.

The main structure of this project involves two electrical substation 66/20 kV, Polígono and San Sebastian. These electrical substations connect with 72 electrical substations of 20 kV/400 V, with 40 km of power transmission lines. This project is done in the "Carretera de Cádiz" area. [6].

The installed power of the DER's of the grid is about 13 MW:

- One Co-generation power plant, placed in Guadalhorce, 10 MW.

- One Tri-generation unit, placed in the Deputation of Málaga, 2,74 MW.

- Different solar photovoltaic resources, placed in different public organizations, as Palacio de Ferias y Congresos, public schools, etc. 300 kW.

Microgrids are supposed to be one of the main strategies in order to accomplish a functional option for the recharge of electric cars. Due to the high current necessities of a Electric Vehicle, that could cause issues and constraints in the public grid, self-consumption and DER's are in favour of reduce the stress to the public grid.

Microgrids can be integrated correctly in different strategies in order to overcome the issue of random charging, as car parking with recharge options, that integrated different PV systems to supply the required energy. [7].

2.3 Main Elements of a generic Microgrid

According to Wikipedia, there are four basic components that most of the Microgrids have in common [2]:

- *Local generation:* A microgrid is able to generate, fundamentally, two types of energy: thermal and electrical energy. The first one is obtained from conventional power supplies, such as Nature Gas, Biogas, or even little combined cycle power plants. Last one, is able to produce both electrical and thermal energy. The second type of energy is obtained from both conventional and renewable power supplies, this could be, PV cells, little wind turbines, etc.

- *Consumption:* This refers to elements that consume energy from the grid, this energy could be both electrical (illumination loads, commercial centers, etc.) and thermal (heating system, etc.). If there are controllable loads, this consumption could be modified.

- *Energy Storage:* A microgrid have some elements, such like batteries, pressure, flywheel, gravitational and heat storage systems, that allows to the system to perform smoother

responses to the requirements of the grid (both frequency and voltage). These elements play a fundamental role in the cost analysis, and in the signal quality.

- *Point of Common Coupling (PCC):* when a microgrid is connected to the main grid, the place of the grid where both grids are connected is called PCC. Those microgrids that does not have the PCC are called isolated grids.

2.4 Distributed energy supply

Microgrids, by its definition, are little power plants distributed there where are installed. Mostly, the power of this little power plants are less to 1 MW, and this power is used in little electric systems of low voltage.

All these little power plants are managed by a central controller that are upstream in the hierarchical control system. This control system is the one who fix the reference variables for the rest of components connected.

In this section, will be discussed the different technologies of distributed energy supply. Wind generators, PV systems little co-generation power plants, little hydraulic turbines, and Diesel generators will be analysed.

2.4.1 Micro wind turbines

In terms of what wind turbines is referred, there are two main types of them, in function of the power they are able to supply. The first type are wind turbines with vertical vanes and in second place are low powered conventional wind turbines.

Little vertical wind turbines

This type of micro wind turbines can be installed in public lighting. Although there are, also, an horizontal configuration, but is not so common as the vertical one. As figure 2.1 shown, vertical wind turbines can be installed properly in the streets. This generators are done with flexible vanes, that allow to reduce the aerodynamic resistance when they moves backwards the wind while rotating.

In the transmission system, they have integrated both the DC generator and the inverter, and, for that reason, they can be connected directly to the main grid without more than a
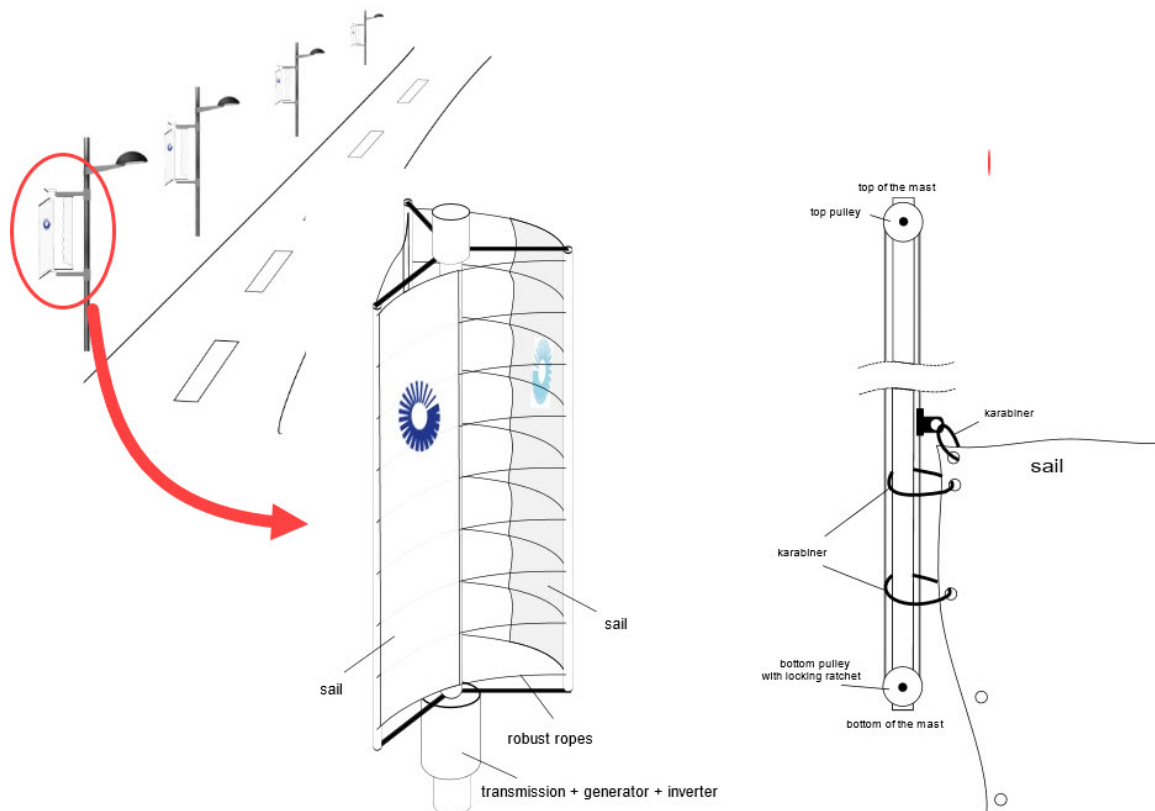
Figure 2.1: Vertical Wind Turbine installed in street light posts.

electric meter and a little controller.

Low powered conventional wind turbines

In contrast with the conventional and huge wind turbines installed in wind farms, this kind of wind turbines are characterised for not being able to supply more than 300 kW of power, according to the classification done by the Canadian Wind Energy Association.

This type of turbines has a vane length of about 1,5 and 3 m. They are widely used in household level, supplying between 1 and 10 kW with optimal wind conditions. Unlike the first type, these turbines are usually designed with an horizontal axis, but, nowadays it is becoming popular the use of vertical axis. In figure 2.2 is shown two types of wind turbines: (a) has an horizontal axis and (b) has an vertical axis.

They usually requires a minimum wind speed of 4 m/s to work properly, and they usually use what is called "Dynamic breaking" that allows to the machine to work even when the wind has huge ratios of speed. It is possible, also, to install rheostats where the energy can

Figure 2.2: (a). Horizontal axis. (b). Vertical axis.

be dumped when there are an excess of it, they could heat a house, for example.

This types of wind turbines often supplies 12 V of voltage, what is ideal to recharge batteries from the energy storage system. They are usually installed, at least, at 9 m of height without any obstacle within 150 m around. [8].

Mathematical description

For a typical wind turbine with horizontal axis and three blades, the equations that describes the output power of the wind turbine are [9]:

$$\gamma = v_W/\omega_B \tag{2.1}$$

$$C_p = \frac{1}{2}(\gamma - 0,022\beta^2 - 5,6)e^{-0,17\gamma} \tag{2.2}$$

$$P_W = \frac{1}{2}\rho A C_p v_W^3 = \frac{1}{2}\rho A \omega_B C_p \gamma v_W^2 \tag{2.3}$$

where:

- P_w: Output power of wind turbine [W].

- γ: tip speed ratio [m].

- v_W: wind velocity [m/s].

- β: blade pitch angle [deg].

- C_p: Power coefficient [].

- ω_B: blade angular velocity [rad/s].

- A: blade impact area [m^2].

- ρ: air density [kg/m^3].

It is also possible to define the tip speed ratio as shows equation 2.4, using the greek letter λ, where R is the radius of the wind turbine blade.

$$\lambda = \frac{\omega_B R}{v_W} \tag{2.4}$$

Then, it is possible to draw the two graphs shown at figure 2.3. The first one express how the power coefficient varies when λ ratio is changed. Then, is possible to draw the second figure, where Wind Power curves are shown for some wind speeds, and with discontinuous line is draw the load curve. [10].
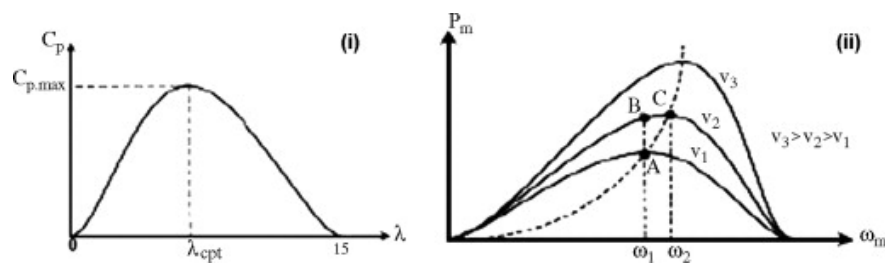
Figure 2.3: (i) Power coefficient vs tip speed ratio and (ii) Output power vs rotor speed for three different wind speed

2.4.2 PV Systems

In order to exploit solar energy in a microgrid, there are various technologies capable to supply power in terms of electricity and hot sanitary water. Last one, can be used for heating

too. Technologies available nowadays can be summarised in two: Solar Photovoltaics and Solar Heated Water. [11].

Solar Photovoltaics

They have the ability to convert solar energy to electrical energy by using semiconductor materials. In the present times, exits two ways of exploiting this technology: little PV generators distributed in the roof of the houses and buildings, and greats solar plants connected to a near bus, as it is possible to observe in figure 2.4.

Figure 2.4: (a) Little distributed solar generators. (b) Solar Plant

Solar Heated Water Systems

This systems use the solar energy in order to increase the water temperature, using what it is called "flat plate solar collector" or "evacuated tube collector", as it is possible to see in the figure 2.5.

Mathematical Modelling

A simplified mathematical model of the PV panel is shown at figure 2.6, called "one-diode model". The output current I can be expressed by a photo current I_{SC} and a diode current I_D, as is shown in equations 2.5 and 2.6. The temperature dependency is neglected. [12].

$$I = I_{SC} - I_D \tag{2.5}$$

$$I_{SC} = I_0 exp \left(\frac{V + IR_S}{V_t} - 1 \right) \tag{2.6}$$

CHAPTER 2. STATE OF THE ART
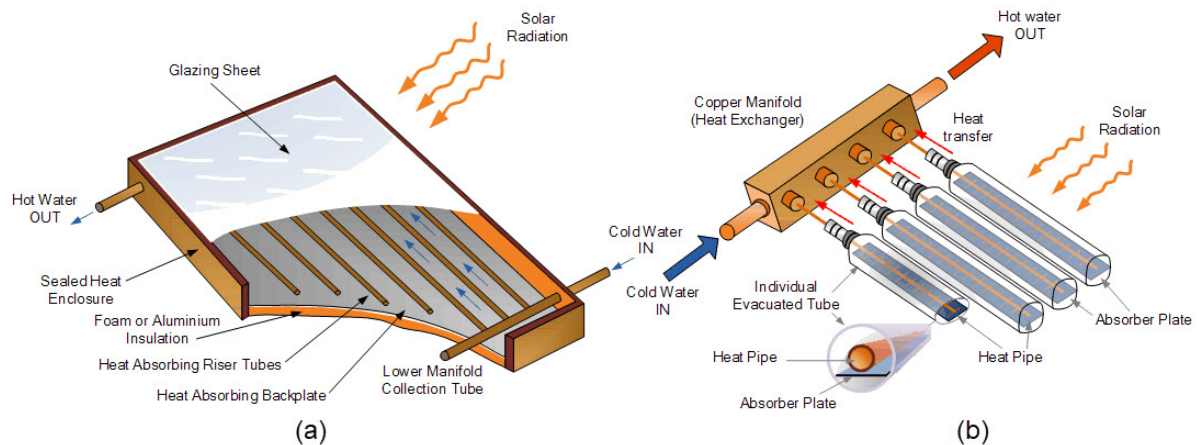
Figure 2.5: (a) Flat plate solar collector. (b) Evacuated tube collector
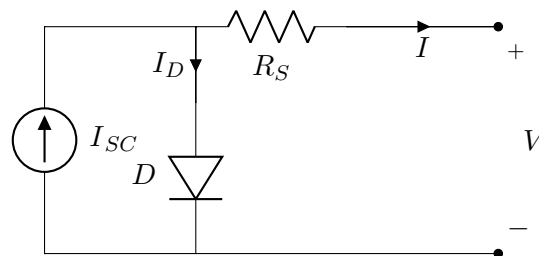
Figure 2.6: Equivalent circuit of a PV cell

where:

- I_D: Diode Current [A].

- I_0: Saturation Current [A].

- V_t: Thermal Voltage [V].

- R_S: Series Resistance [Ω]

The voltage and current characteristic curves of a PV module for different irradiations, are shown in figure 2.7. [13]. In figure 2.8, different Power/Voltages characteristics curves are shown, as it is possible to observe, the maximum of the curve changes with the value of the irradiation. For that reason it is very important, what is called, Maximum Power Point Tracking, that allows to the PV module to supply the maximum amount of electrical energy.
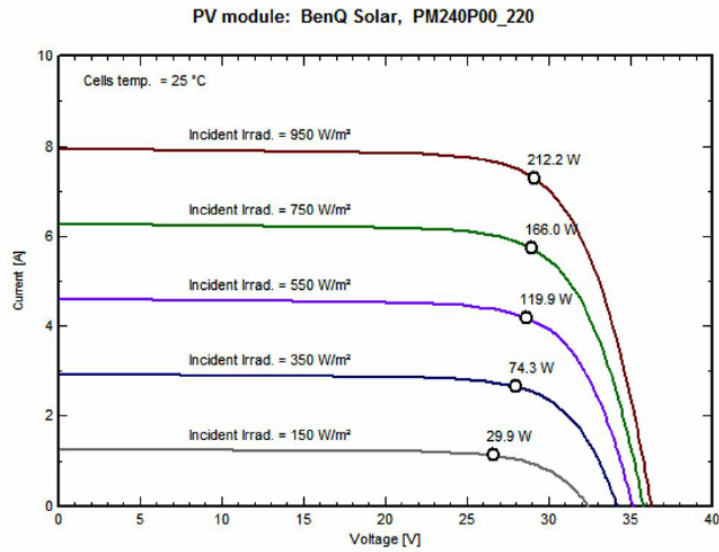
Figure 2.7: Voltage/current characteristic curves for different irradiations
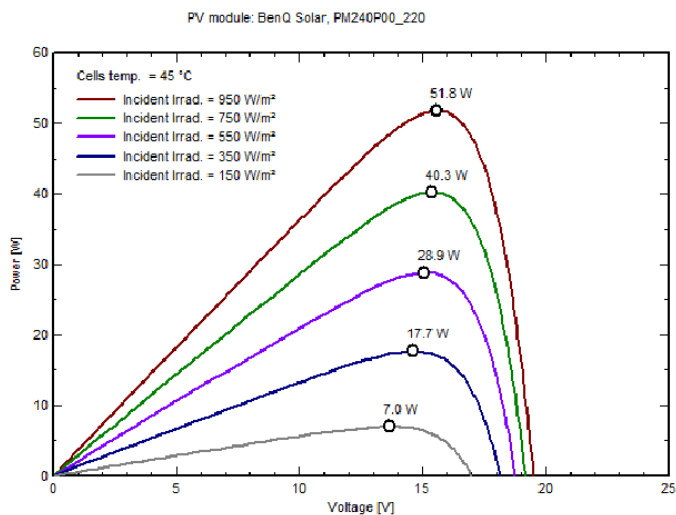
Figure 2.8: Power/voltage characteristic curves for different irradiations

2.4.3 Little Co-generation Power Plants

Fist of all, it is very important to know what the term "Cogeneration" means. Technically is the use of a thermal engine to produce both electricity and useful heat at the same time. There are another concept called "Trigeneration" that can be referred to two industrial processes:

- The generation of electricity, heat and cooling.

- The generation of electricity, heat and some industrial chemicals like hydrogen, syngas, etc.

There are quite a few configurations of this kind of cycle, depending on what element are drive by the high temperature steam. The supply of high temperature heat can drive a gas or steam turbine, or, if the power are below 1 MW, a gas turbine or a diesel engine could be used. [14].

This kind of power centrals reduce between 30 and 55% the emissions of greenhouse gases to the atmosphere, than conventional combined cycle power centrals. This is due to the usage of the exhaust gases as thermal energy, in order to increase the temperature of water. This allows an increase of, at least, 25% of the system efficiency, according to the Energy Department of the United States.

The followed process is shown in figure 2.9:
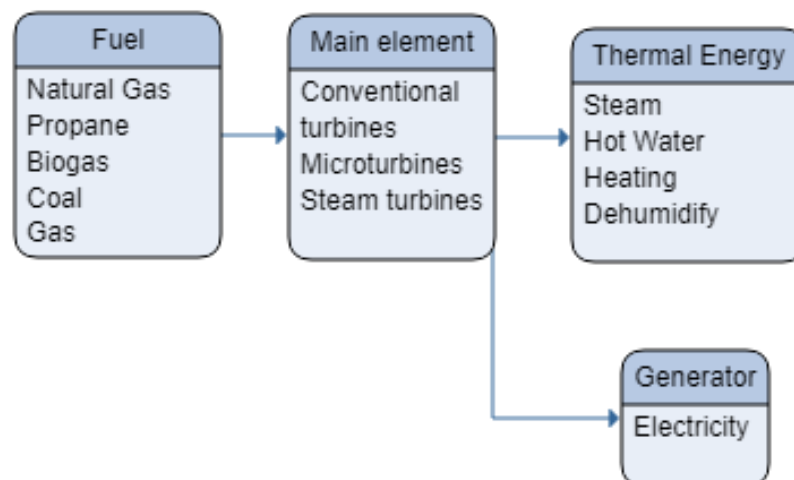
Figure 2.9: Little co-generation power plant diagram

These systems have different sizes, they go from 50 kW to the most little micro-turbines to 20 MW of power to gas turbines.

Mathematical Modelling

Fist of all, it is necessary to do the power balance in the thermal cycle, in order to obtain the amount of energy used in each element of the cycle, this is, the amount of heat introduced

to the system, the amount of electricity produced, the wasted heat, etc. The calculus of this magnitudes depend on the type of generator used.

Once thermal balance is done, it is time to calculate the efficiency of the whole system. Thermal efficiency in a cogeneration system is defined as:

$$\eta_{th} = \frac{W_{out}}{Q_{in}} \tag{2.7}$$

where:

- W_{out}: Total work output by all systems [kW].
- Q_{in}: Total heat input into the system [kW].
- η_{th}: Thermal efficiency [].

2.4.4 Little Hydraulic turbines

In the context of distributed generation, mini hydroelectric power plants have several advantages, as little generation cost per unit of generation, continuity in the generation while the flow is maintained approximately constant during the year, and the reliability of the technology used.

The most important characteristic is that the generation of energy is approximately constant along the year, and for that reason the energy storage systems are reduced. The electric systems are reduced in this kind of technology, due to, energy is ready to consumption when it comes from the electric machine.

This hydroelectric groups has the typical elements of a mini hydraulic power plant: a hydraulic turbine controlled by a electronic controller, this turbines, usually are Pelton turbines, due to the height of the waterfall (they are usually installed in high mountain), and a electric generator drives by the hydraulic turbine that convert the mechanical energy of the turbine to electrical energy.

These kind of systems are characterized by their high efficiency, (over 90%) with a low maintenance cost. In the figure 2.10 a hydraulic turbine typically used for mini hydraulic power plant is shown, as it is possible to see, there are six electric controllers.

Figure 2.10: Typical installation of a hydraulic group

Mathematical Modelling

In order to model the efficiency of the system, and the output power that can be supplied by these systems it is necessary to know with detail all the different elements of the hydraulic installation. Generally, the following analysis can be done. First it is necessary to define some concepts:

Jump power: Is the maximum amount of energy that it is possible to obtain of the power plant, for a rate of loading and a some height of the reservoir.

$$P_{Jump} = \rho g Q H \tag{2.8}$$

where:

- P_{Jump}: Total jump power [kW].

- ρ: water density [kg/m^3].

- Q: Water flow [m^3/s].

- H: Height of the water fall [m].

Gross Jump Power: Is the amount of energy that a power plant is capable to supply con-

sidering the losses in the hydraulic elements, except for the penstock.

$$P_{GrossJump} = \rho g Q \left(H - \sum_{i=1}^{n} H_{ri} \right) = \rho g Q H' \tag{2.9}$$

where:

- H': Gross jump [m].

- H_{ri}: Losses in the different hydraulic elements [m].

Net Jump Power: Is the amount of energy that a power plant is capable to supply considering the losses in the hydraulic elements, including the penstock.

$$P_{NetJump} = \rho g Q \left(H - \sum_{i=1}^{m} H_{ri} \right) = \rho g Q H'' \tag{2.10}$$

where:

- H'': Net jump [m].

Intern Power: Is the power that the machine can supply considering the losses in the runner, spiral case, injectors, etc.

$$P_{InternJump} = \rho g Q \left(H - \sum_{i=1}^{o} H_{ri} \right) = \rho g Q H_u \tag{2.11}$$

where:

- H_u: Intern jump [m].

Shaft Power: Is the power that supplies the turbine to the generator.

Then, a Sankey Diagram can be done using these different powers, as figure 2.11 shown:

2.4.5 Fuel Cells

Fuel Cells has great advantages to become considered the great candidates for microgrids: they have a great reliability and low greenhouse emissions, but, on the other hand, they also have some drawbacks, they can be really voltage-sensitives, i.e. unstables. Also, they have high prices, and the cost of the electricity with that technology are five times greater than conventional ones. For that reasons, they are hardly ever used in electricity generation.
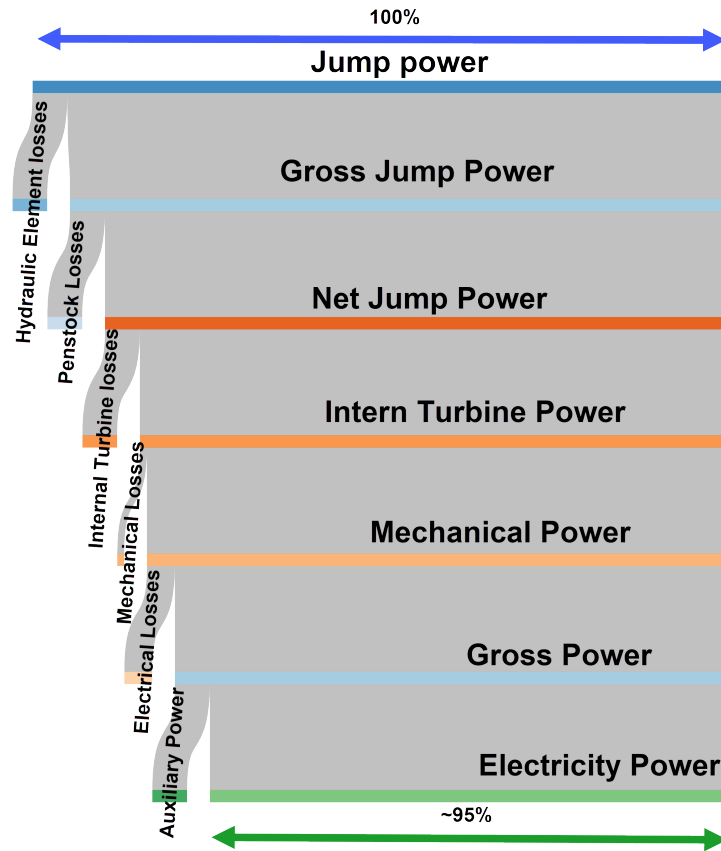
Figure 2.11: Sankey Diagram of the installation

There are only 116 MW of fuel cells deployed globally in microgrids, according to Navigant Research's Microgrid Deployment Tracker. [15].

Basically, a fuel cells is a kind of battery, that is able to supply electricity using a electrical-chemical reaction. This technology requires an fuel in order to keep the supply of energy.

There are, at least, 6 different types of fuel cells, classified, generally in terms of the nature of its electrode and its electrolyte. The three major commercial technologies are: proton exchange membrane (also known as polymer), solid oxide and molten carbonate.

Mathematical Modelling

Generally, the mathematical models of fuel cells are experimental, and all of them follows an exponential law. According to reference [16], it is possible to model the steady-state V-I curve at the nominal temperature by fitting the parameters of the equation 2.12.

$$V_{FC} = A - Bln\left(1 + \frac{i_{FC}}{C}\right) - De^{\frac{i_{FC}}{E}} \qquad (2.12)$$

where:

- V_{FC}: Fuel Cell Voltage [V].

- i_{FC}: Fuel Cell Output Current [A].

- A, B, C, D: Fitting parameters.

2.4.6 Diesel Generators

They are often used as recovery generators, they supply energy when the other resources are not capable of generate all the energy necessary to maintain the system stable. Also, they are used in case of emergency. All in all, in very few occasions because of the high levels of greenhouse emissions they produce.

Mathematical Modelling

Make a mathematical modelling of these generators it is only possible, at first sight, in terms of efficiency, the equations are the same as the co-generation model.

2.5 Consumption

Consumption points in a Microgrids and load in a conventional system are the same. There are no differences between both of them. As figure 2.12 shown, the power transmission system of a microgrid and the conventional power transmission system fit perfectly. Loads can be connected to the grid without any different.

As figure 2.12 shown, there are many different types of consumption points: Residential, Commercial and Industrial, that is, Industry,Buildings, Datacenters, etc. Also, there is possible to observe that the flow of energy and data is bidirectional. This is one of the more characteristic features of the microgrids.

On the other hand, create a mathematical model of the consumption is really difficult, because, this type of models are fundamentally, stochastic. In this thesis, it will be assumed that the rate of loading will be identical to the power generated by the generators.
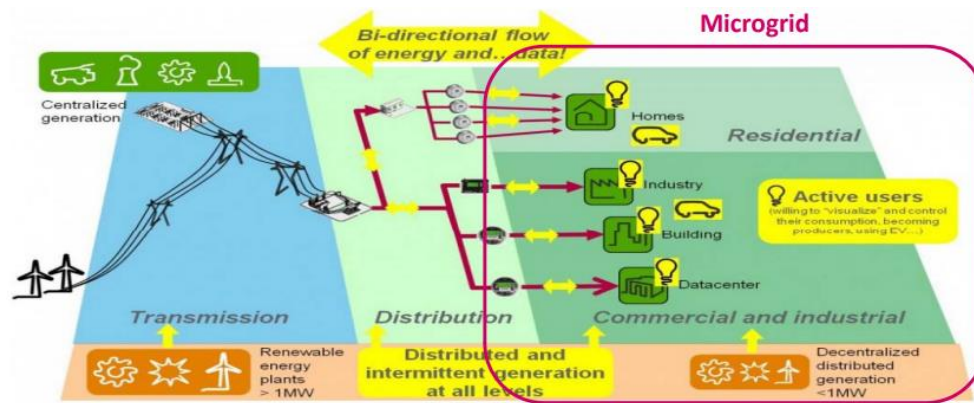
Figure 2.12: Descriptive Scheme of the different types of loads in a Microgrid

2.6 Energy Storage Technologies

In terms of energy storage, there are different technologies depending in the type of energy that excess energy is transformed : mechanical, chemical, electrochemical, electrical and thermal store systems. [17].

2.6.1 Mechanical Energy Storage Systems

Mechanical Energy Storage Systems can be classified as pressurized gas, forced spring, kinetic energy, and potential energy. This systems are very flexibly to convert and storage energy from the microgrid. However, from a technological point of view, there are three techniques: flywheel, pumped hydro storage, and compressed-air energy technologies.

Flywheel Energy Storage Systems

They consist in a cylinder that turn at high rates of speed. This technology does not use conventional bearings, but magnetic ones. Depending on the speed that turn the cylinder, there are two types of flywheels: high speed flywheel (over 10.000 rpm) and low speed flywheel (under 10.000 rpm). They have a directional converter, that allows to accelerate the cylinder when energy is introduced to the system, and decelerate it when energy is supplied to the microgrid.

The rotating cylinder action is actuated by the usage of a electrical machine, as figure 2.13, shown:
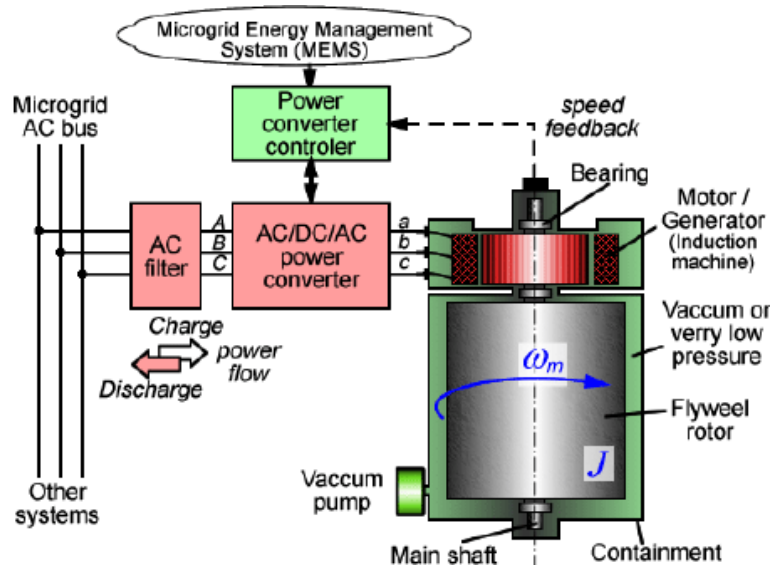
Figure 2.13: Flywheel energy storage system

The equation for the total energy stored in the flywheel can be derived as:

$$E_{fw} = \frac{1}{2}J\omega^2 \tag{2.13}$$

where:

- E_{fw}: Total energy stored in the flywheel system [J].
- J: Moment of inertia of the cylinder [m^4].
- ω: Angular velocity [rad/s].

Compressed-air storage energy technologies

This kind of systems are able to store energy inside of tanks, they can be installed in the surface or buried in the ground. The system has a compressor that introduces pressured air inside of these tanks in the moments when exits excess energy, and a generator drove by a turbine, used when there are lacks of energy. As there are thermal losses in the compression, it is very common to use a thermal exchanger to recover some energy.

A simplified model of this technology is shown in figure 2.14:

This systems can be used both little and huge capacities. But, however, they have a slow response as drawback. For that reason this kind of systems are usually used to smooth the power generation in the wind turbine systems.

CHAPTER 2. STATE OF THE ART
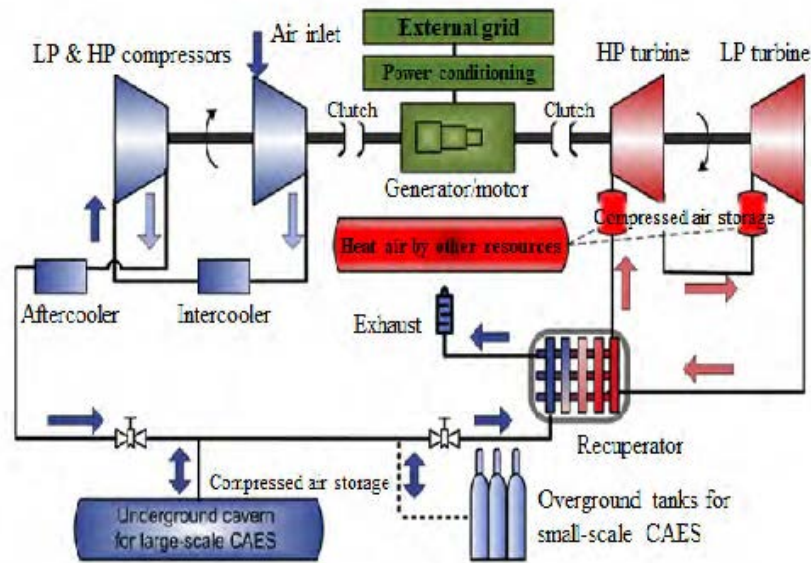
Figure 2.14: Simplified scheme of a compressed-air store energy

On the other hand, the gas used it is very important in terms of efficiency of the system. Nowadays, the gas that offers better performance it is CO_2.

Pumped hydro storage systems

This systems are widely know by its application in pumping stations, because they are used in the conventional grid as storage systems, pumping the water from a lower reservoir to another several meters higher. This technology is used in microgrids with an reversible pump-turbine system that drives a electrical generator, a piston, a container and a return pipe.

When there is the necessity of supply energy, the piston pump the water to extract it from the container through the return pipe. This flow pass through the turbine, and then, electricity is generated by the electrical machine. When there are a excess of energy, the reverse process is followed, water pass through the pump that is drove by the electrical machine, and water is storage in the container, increasing its pressure.

It is only possible to do a efficiency analysis from this technology. The equations are the same that for the cogeneration case.

2.6.2 Electrochemical Energy Storage Systems

In the electrochemical storage systems, chemical energy is converted into electrical energy. This energy conversion is completed by a chemical reaction, and energy is stored as electric current for a specific voltage and time.

This systems are available in different sizes, which is the main advantage of this technology. There are quite a few examples of this technology: Lead-acid, lithium-ion, sodium-sulphur, nickel-cadmium, nickel-metal hydride, etc.

Redox Flow Battery Storage Systems

They work charging and discharging in a reversible chemical reaction between two electrolytes separated in two tanks with a membrane. The capacity of this battery is function of the volume of the electrolytes contained in the tanks and the number of cells (pair of tanks) that the battery has.

The efficiency of this battery is around the 85%, with a long life-cycle. Talking about their characteristics, they have a huge storage capacity, and it is very stable, even when the working conditions changes. The main advantage of this technology is the response time, that is very short. For that reason, they can supply energy to those applications that, for its nature, needs a short response period. However, this batteries have some drawbacks: they are very expensive and its reliability is reduced because of the complexity of the whole system, in some cases, this batteries would need a auxiliary electrical system for its correct functionality.

The chemical reaction that occurs inside of the cell is shown in the reaction 2.14 and 2.15. If V^{2+}/V^{3+} and V^{4+}/V^{5+} are two liquid electrolytes. The chemical reaction are as shown when the cell voltage is about 1,4 V.

$$V^{4+} \leftrightarrow V^{5+} + e^{-} \tag{2.14}$$

$$V^{3+} + e^{-} \leftrightarrow V^{2+} \tag{2.15}$$

Battery Energy Storage Systems

This systems is widely applicable for various purposes in all sections of the Microgrid (generation, transmission and distribution), it provides benefits to consumers. The profile of charge is really similar in all of microgrids, charging them at night hours and discharging them when there are no enough supply of the generators in the peak hours, as a pumping power central in the conventional system.

Their capacity may be defined as the total quantity of electrical energy that can be delivered in a single discharge by the battery. The state of charge (SoC) can be described as the ratio of remaining capacity to the nominal capacity. In batteries, the SoC is described as equation 2.16 shows.

$$SoC = \frac{idt}{C_i} \tag{2.16}$$

where:

- SoC: State of Charge [].
- i: Output Current of the Battery [A].
- C_i: Capacity of the battery [F].
- t: Time [s].

There are different technologies in this field, in this section Lead-Acid Batteries, Lithium-ion batteries and Sodium-Sulfur are explained.

Lead-Acid Storage Systems

This is the most widely used rechargeable storage with various sizes and designs in different applications. As the most of the electrolyte batteries, their efficiency are around 70 and 80%, and possesses the highest cell voltage. Their cathode is made of PbO_2 and their anode of Pb, and sulfuric acid is used as electrolyte.

This is the cheapest technology and they are widely used in the most of the microgrids, the principal drawback it is its life-cycle, because it is reduced to 500-2.000 cycles of charge and discharge. Also, they are very bulky, and need periodic maintenance. The different parts of the battery is shown in the figure 2.15.
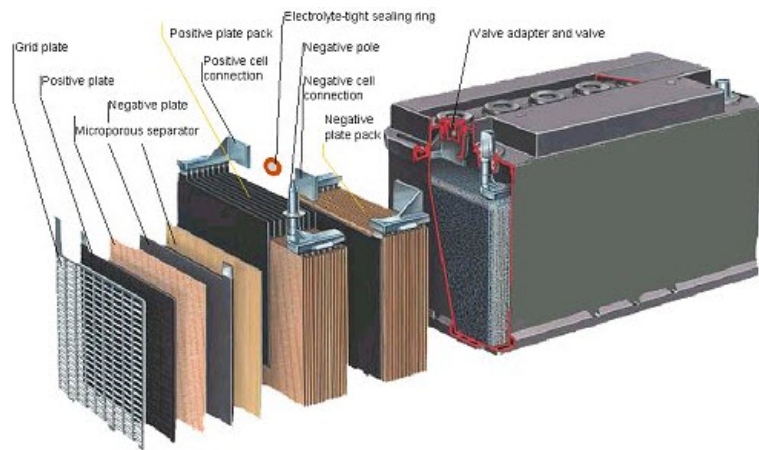
Figure 2.15: Parts of a lead-acid battery

The overall electrochemical reactions that take place during the charging and discharging in this type of batteries is shown in the charging and discharging equations:

Charging equation:

$$2PbSO_4 + 2H_2O \rightarrow PbO_2 + Pb + 2H^+ + 2HSO_4^- \tag{2.17}$$

Charging equation:

$$PbO_2 + Pb + 2H^+ + 2HSO_4^- \rightarrow 2PbSO_4 + 2H_2O \tag{2.18}$$
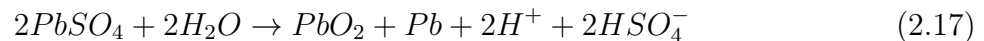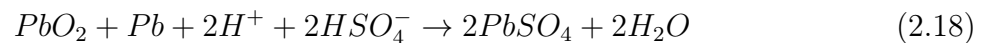
Lithium-ion battery

Even though this type of batteries began to be commercialized at the beginning of the 90's, nowadays is when there are more sales. This batteries are able to store MW powers, they could be used in high-scale machines.

Its principal characteristic is their efficiency, over 90% in most cases, their compact size, comparing with the lead-acid batteries, and for that, it high energy density. As the most of batteries, they have a quick response to demand. The cathode and the anode are made of lithium metal oxide ($LiCoO_2$), and graphite carbon cell, respectively. The electrolyte is usually made using an organic solvent with dissolved lithium salt or solid polymer. The complete electrochemical reaction that take place in this types of batteries can be written

as reaction 2.19 shown.

$$LiMeO_2 + C \Leftrightarrow Li_{1-x}MeO_2 + Li_xC \tag{2.19}$$
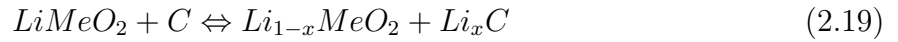
This types of batteries are charged and discharged following the curve shown in figure 2.16, in order to get a long life-cycle.
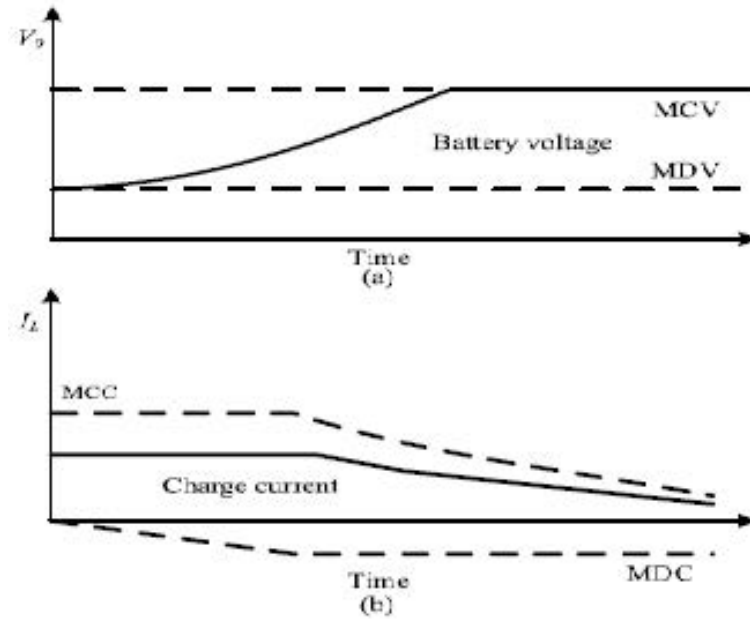
Figure 2.16: Charging and discharging curves of a Medium Power LiPo battery

This batteries are designed to support high temperatures. On the other hand, their high energy density that are capable to store are from 75 to 200 Wh/kg, makes this batteries a little dangerous in case of accident. However, their principal drawback is its price.

Sodium-Sulfur batteries

This batteries comprises of molten electrodes (both sodium and sulfur) and non-aqueous beta alumina electrolyte. Sodium is used as the negative electrode and sulfur is treated as the positive one. Generally, this technology is used to smooth the supply of energy of the aerogenerators, as well as, to level the loads with different consumptions.

The overall electrochemical reaction that take place in the battery can be written as the reaction 2.20 shown. Usually the value of the variable x are between 3 and 5.

$$Na + xS \Leftrightarrow Na_2S_x \tag{2.20}$$

 Due to its composition, this kind of batteries needs high operative temperatures in order to the maintenance of the electrochemical reaction. With the correct optimizations of this kind of batteries, nowadays it is possible to get life-cycles of 15 years, with quick battery responses and good prices, reaching four times energy density comparing with Lead-Acid batteries.

2.6.3   Chemical Storage Systems

This systems are able to store a significant amount of energy for a long duration. This technology store the energy directly inside the atoms and molecules chemical bonds, which can be released through electron transfer reactions directly to produce electricity. It is widely known this technology uses principally hydrogen as main fuel, because of its ability to store a large amount of electrical energy.

This systems are also known under the name of "Hydrogen fuel cell", and are characterized for being suitable the emission-free electricity generation and can be applicable in distributed generation to the automobile industry. And, what is more, the hydrogen is easy to obtain from the air.

Due to its size, this technology has a great energy density comparing with hydrocarbons. A simplified scheme it is shown in the figure 2.17. As can be seen, using as reagents, hydrogen (H_2) and air, water (H_2O) is obtained and a electron flow (e^-) as products, as the reaction 2.21 shown.

$$2H_2 + O_2 \leftrightarrow 2H_2O + e^- \tag{2.21}$$

The hydrogen required for the reaction can be produced in the same place of consumption, or using external sources, but the first case is cheaper. The optimal method for the hydrogen generation, nowadays, is under research, but there are several ways of production: from natural gas, coal, gasoline, diesel, or the electrolysis of water and the biomass.

This technology could be the one who supply the great part of the energy to the microgrid, because it is completely renewable, but it is important that the price of the electricity produced using this technology reduces.
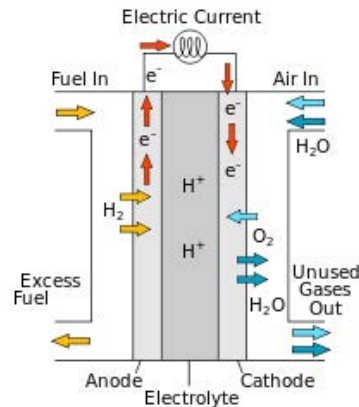
Figure 2.17: Simplified scheme of a hydrogen cell

2.6.4 Electrical Storage Systems

This types of systems does not need of a conversion of the type of energy, as far as it is only stored the electrical energy during a short period of time. The energy could be stored in terms of electrical energy with the aid of supercapacitors and supermagnets.

This technology helps with the operations that are necessary to do in the microgrid, as is, load balance, signal quality, and the necessity of reduce the importation of energy.

This two technologies are detailed in the following subsections.

Supercapacitor Storage Systems

A supercapacitor is an element able to storage energy between a double sheet of conductor material, with a dielectric between of them. This systems have a really high energy density, as well as, the output power that is possible to obtain from them. Their life-cycle is much larger than Lithium-ion or Lead-Acid batteries. It is possible to obtain millions of discharges and charges of these systems without its life-cycle being committed.

The capacitance of the supercapacitor is not constant; instead, it varies with the change of the voltage, which depend on the current demand and the supply from the supercapacitor, therefore, the charge concentration also varies, as can be shown at the equation 2.22.

$$d_c = \sqrt{\frac{\epsilon RT}{2F^2 C_e}} \tag{2.22}$$

where:

- d_c: Debye length [m].

- C_e: Level of the electrolyte [F].

- ϵ: Dielectric strength [V/m].

Also, in the figure 2.18, the equivalent model of the supercapacitor is shown. It is composed of two parallel capacitors: constant capacitance (C_0) and voltage-dependent capacitance (k, v_c).
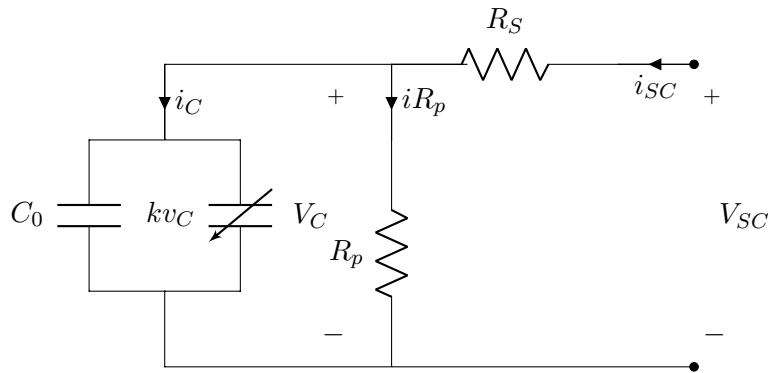
Figure 2.18: Equivalent electric model of the supercapacitor

Thus, the total capacitance, denoted by C_r of the supercapacitors is shown in the equation 2.23.

$$C_r = C_0 + kv_c \tag{2.23}$$

The main problem of this technology is the distortion generated in the microgrid by the capacitors, for that reason, supercapacitors are used, they are made of active carbon, whose quick response characteristics are able to level and balance the power, with the correct control system.

Another problem of this technology is the high discharge rate it has, making difficult store energy inside of them, this rate could reach 40%, and its high prices. Nowadays, research is focused on the development of supercapacitors economically and technically feasible.

Super Magnetic Energy Storage Systems

This system is based on the magnetic energy storage in a system made up of an electromagnet make with superconductor, where it is possible to store the energy until it is demanded by the grid. It that moment, the energy flow is reverted and the energy is dumped to the

microgrid. Energy stored in the system can expressed as shown the equation 2.24.

$$W_{LS} = \frac{1}{2}LI^2 \tag{2.24}$$

where:

- L: Self-inductance of the coil [H].
- I: Current flowing through the coil [A].
- W_{LS}: Energy stored inside the coil [J].

There are two types of this systems, the first, super conduction state is maintained around 70 K (high temperature mode) and the other, where super conduction state is maintained around 7 K (low temperature mode).

This systems are available from 100 kW to 10 MW. The main drawback is its price, about (9.000 €/kWh), due to the low temperatures necessary to maintain the super conductivity state.

2.6.5 Thermal Storage Systems

This technology has the ability to store the energy in terms of heating and cooling, for example, using water heating or cooling. This is a great alternative to the use of fossil fuels, and it is able to supply the consumption in a more sustainable way. In fact, it is expected an increase of the usage of this technology in the next years, about an 11%.

It is available both to the industrial sector and the residential, this technology can be divided into two groups, the first, works with low temperatures, and the second one, with high temperatures (over 200 ºC). Also, the last group it is possible to dividing itself intro three groups more, depending on the mode they store the energy: sensible heat, latent heat and absorption and adsorption system.

The main advantage of using this technology is the low cost of it, and a acceptable energy density, and its low rate of greenhouse emissions. On the other hand, the life-cycles of this technology is short. The most wide use of this technology is the ice generation during the nights used for refrigeration during the day.

2.7 Point of Common Coupling (PCC). Microgrids Interconnection Methods.

In previous sections is mentioned that microgrids have two ways of functionality: islanded mode and continental mode. The point or points where the microgrid and the conventional grid are connected is called, "Point of Common Coupling".

It is recommendable for the grid stability and reliability that the microgrid were connected at several points of the continental grid in a recursive way. If this is possible, when a fault occurs, there are always another path where electricity can flow in order to supply the demand. This type of connection is called "Ring Connection", and it is widely used to connect electrical substations and power plants even in the conventional grid.

A scheme of the installation could be the one shown at figure 2.19, where the point of common coupling is represented by a blue circle.
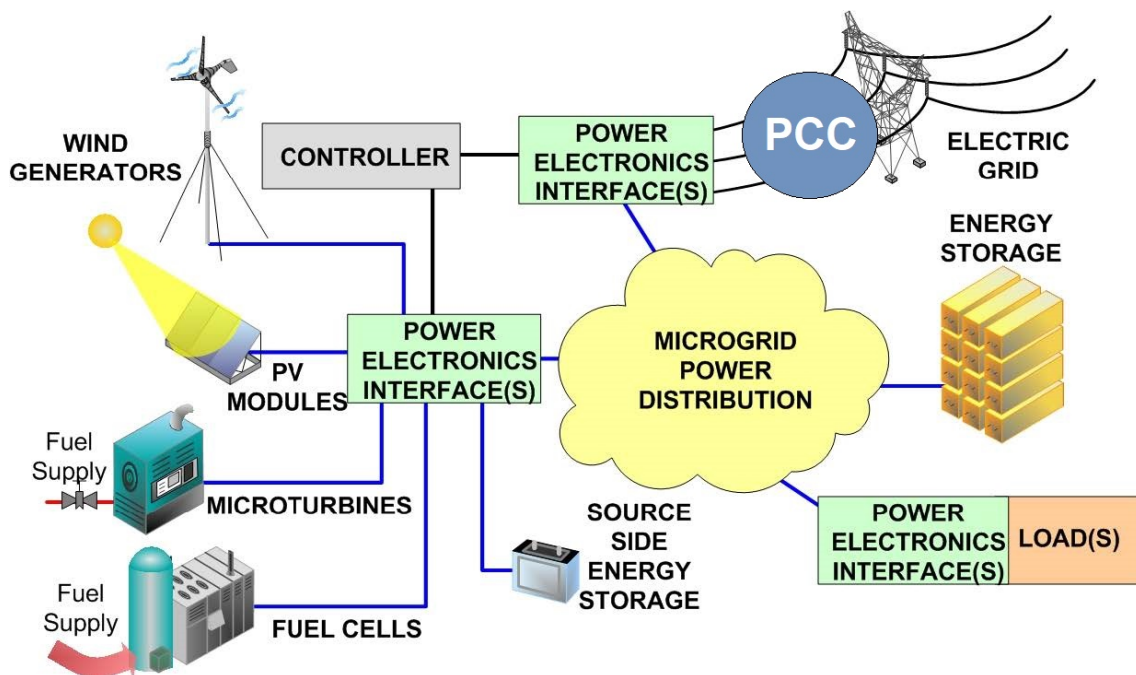
Figure 2.19: General Scheme of a Microgrid

There are several interconnection methods for microgrids, all of them described in the next subsections [18]:

- Directly through a switchgear.

- Static Switches.

- Power Electronics Interfaces.

2.7.1 Directly through a switchgear

This kind of connections has the advantage of being simple and low-cost, but it has several drawbacks:

- Its response are slow, as well as, it needs between 3 and 6 electrical cycles for the complete disconnection.

- It is completely necessary the usage of a electrical generator in order to have the same voltage levels in the main grid and the microgrid, because, if it is not accomplished, a fault occurs. Here the usage of the microgrid is committed.

- The power flow through the PCC can not be controlled.

A general scheme of this connection is shown in the figure 2.20:

Figure 2.20: Direct connection using circuit breakers

2.7.2 Static Switches

Generally, this technology is based on two SCR's (thyristors) in antiparallel connection, in order to permit the bidirectional power flow. They are much complicated than the first one, and even, they usually needs a bypass-switch for maintenance reasons.

They have as advantages that they permit a lot of open and close operations, and its quick response (much more quickly than the mechanicals). Ta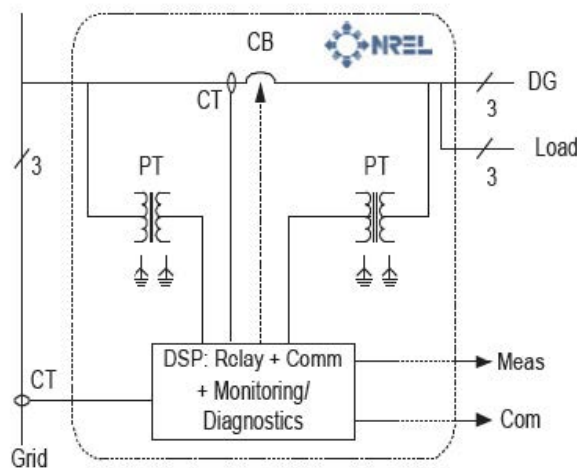king the velocity of the response in mind, it is usually to use IGBT's instead of SCR's, because the first one are quicker.

Its principal drawback is that, as every single power electronic component, they have losses, and the power flow can not be controlled. A descriptive scheme is shown in the figure 2.21:
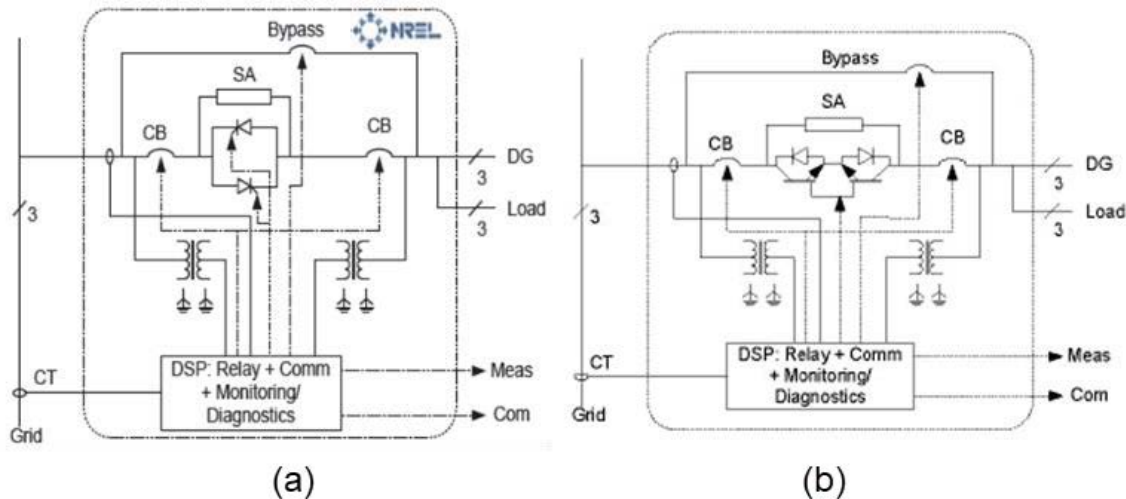
Figure 2.21: (a) Static Switch made up by SCR's. (b) Static Switch made up by IGBT's

2.7.3 Power Electronics Interfaces

Even though this is the most expensive solution, is the most flexible, due to:

- Voltage level could be different in the microgrid and the continental grid. This improves the Microgrid operatibity.

- Active and Reactive power can be controlled.

- Connection and disconnection times are similar to the obtained using thyristors.

But, on the other hand, they have some drawbacks that have to be considered:

- They have current losses, unavoidable in every power electronic system.

- It still unavoidable the usage of a mechanical switch for the total disconnection in islanded mode.

2.8   Microgrid Control Techniques

Control systems of a microgrid follow a simplifying trend, due to the nowadays complexity of the systems used. Generally, engineers in front of this microgrid part, divide control methods in two sheds, systems where communication is used and those where not.

These control system are as much or more important as storage systems are. All of this is due to the unpredictable behaviour of the distributed energy sources. Depending on the circumstances, a distributed energy system can operate in three ways: battery charging, battery discharging and voltage control mode.

One of the main problems associated to the renewable energies is the absence of a direct controllability, due to its stochastic nature. For all this, is fundamentally storing generation data from sources for future processes.

In the microgrid control is used, what is called, "Decentralized approach", that consists in divide the distributed energy resources in little grids connected, each one, to the main grid, as it is possible to see in the figure 2.22.
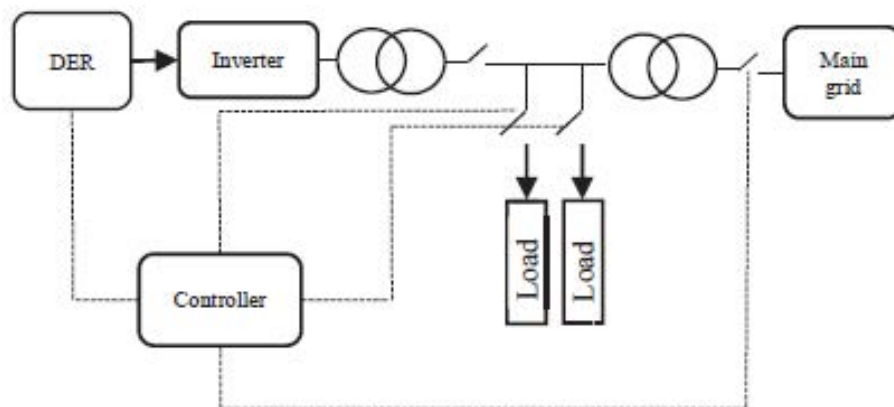

Figure 2.22: Connection Scheme of a MG

In order to be able to connect the DER's unit to the grid, it is necessary, as previously stated, an inverter, which is used to extract a certain amount of active and reactive energy. Inverters are capable to work both in continental mode and islanded mode, working at "Power Control Mode" or "Voltage Control Mode", respectively. [19].

2.8.1 Control without communications

In this kind of control, voltage and frequency is controlled. Using this variables as references, generators are able to distribute automatically the proportional load without sending any message, due to the electromagnetism phenomena. Inverters are automatically controlled by the own system.

Here, it is possible to control the frequency and the voltage when the system works in islanded mode, saving the communications costs.

On the other hand, also, it is possible to use active and reactive power to the microgrid control. In this way, it is possible to copy the working principle of a synchronous machine. Controlling the voltage with a proportional control, this is possible to accomplish, however, little oscillations in frequency and voltage should be controlled by other systems, as batteries.

2.8.2 Control with communications

In this systems, different agents are taking action in the stability of the system (different DER's). They divide the passive loads of the system, in a certain way that allow to the system gain much more stability than the previous case.

More specifically, an "agent" can be defined as a software or hardware able to receive information through sensors and able to communicate with others agents. There are a central agent which decide the global control goals, as well as, the best strategy in order to achieve it.

Multi-agents systems, as these systems are also known, can be classified in three different layers: proactive, reactive and social. In normal working conditions, the system will work in the proactive layer, if a fault occurs, then active layer will be activated and the system will look for a solution, but if this does not finish the fault, then social layer comes into action, agents will communicate between them look for the optimal solution.

This systems are usually hierarchical, as it is possible to see in the figure 2.23. The main controller is called "Distributed Management System" (DMS), which control each one of the micro-controllers of the "Distributed Generator Systems" and the "Load Controllers" (LC), as well as the Main Central Controller (MCC).
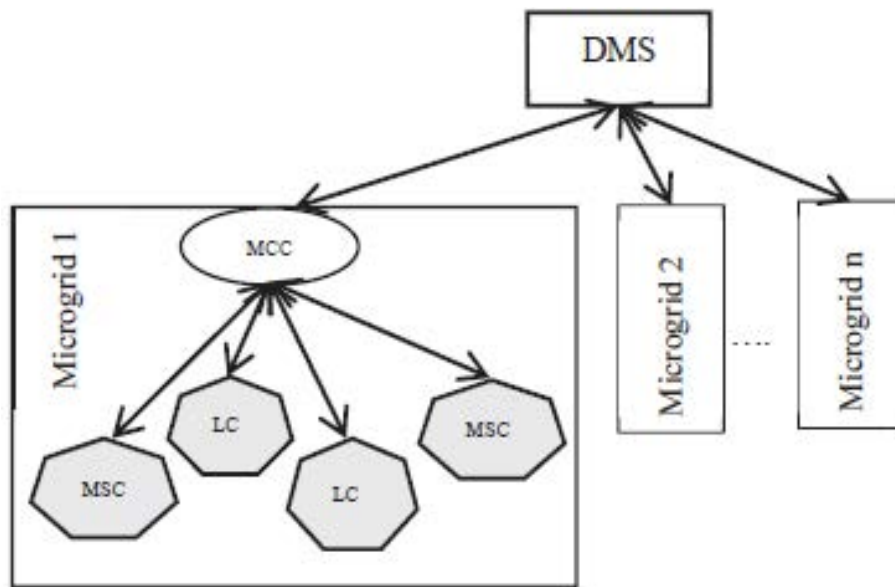
Figure 2.23: Hierarchical Structure of the control system of a microgrid.

A simply multi-agent control consists in four agents which have different functions, as: control agent, distributed generators system agent, user agent and database agent.

The Control Agent manages, in a general way, the stability of the grid and it can send signals to the main circuit breakers in order to connect or disconnect different microgrids. The Distributed Generators System Agent controls the output power of each generation system. The User Agent monitors the current and the voltage demanded by the user, the active and reactive power consumed by the controlled loads and choose when they have to be used. Finally, the Database Agent is the one in charge of the storage of the information shared between agents and information systems.

Chapter 3

Microgrid Modelling

3.1 Introduction

In this chapter, the microgrid to simulate is going to be introduced. Data is obtained from a real Microgrid installed in the United States of America, in Bloomington, Minnesota, called "OATI Microgrid Technology Center". Due to the lack of information, OATI Microgrid is only selected as reference. According to the California Energy Commission [20], the microgrid has the following characteristics:

Location	Bloomington, Minnesota
Utility	Xcel Energy
Developer/Vendor(s)	USA Microgrids, Inc. EnSync Energy Systems, Agile Hybrid Energy Storage, Capstone Turbine Corporation
Capacity	2,4 MW
Installation Timeline	April 2015 - April 2017
Total Cost	$ 1,5 million for the microgrid-specific costs, excluding the diesel generator

Table 3.1: OATI Microgrid Technology Center Project Overview

An outline of the connections of the Microgrid can be shown in the figure 3.1. As figure 3.1 shows, this microgrid has a Critical Load that can not be out of supply, that is the Data Center, and other that are less important as can be the offices.

Microgrid modelled is composed by the following elements, as the figure 3.2 shows.

- Natural Gas Turbines: 120 kW. Capstone C120 natural gas burning micro-turbine. Paired with absorption chiller and heat exchanger for CCHP (Combined Cooling, Heat and Power).
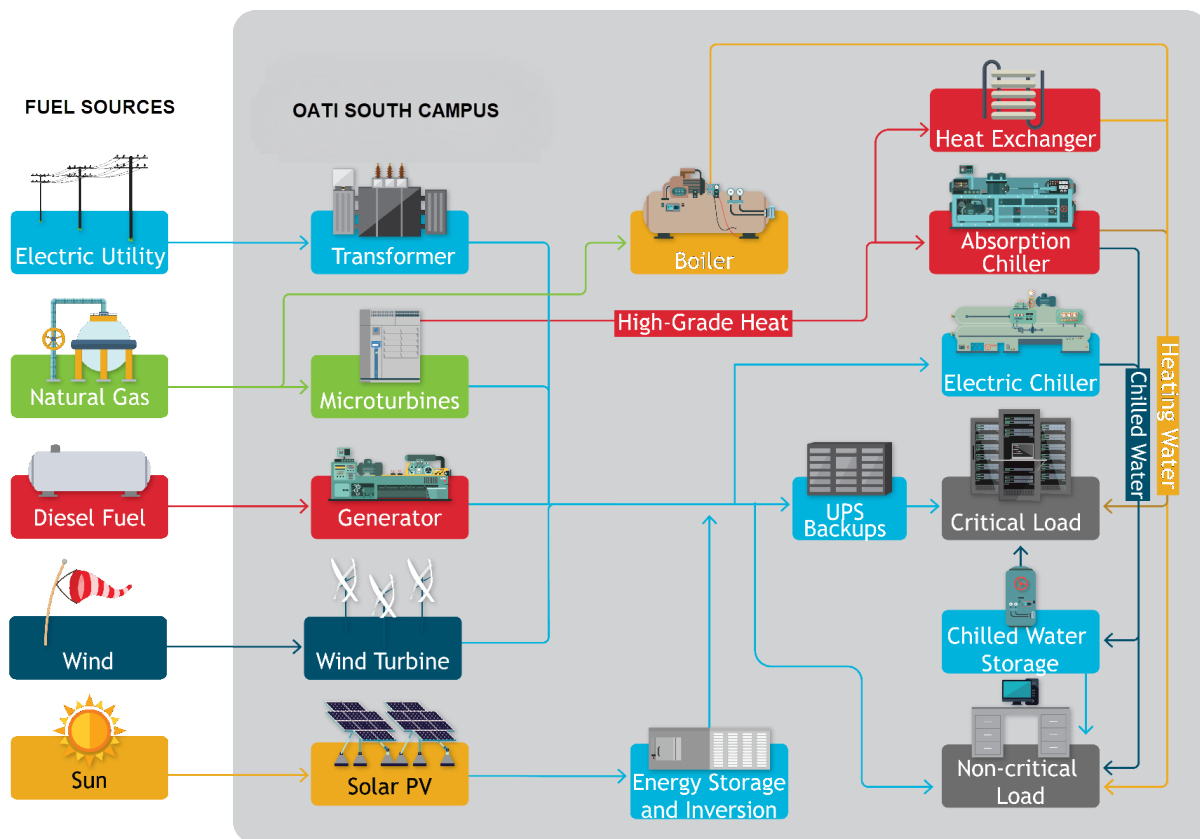
Figure 3.1: OATI Microgrid Technology Center Outline [21].

- Solar Photovoltaics: 150 kW rooftop solar array.

- Backup generator: 500 kW.

- Utility connection: Connected to local utility company.

In this chapter, microgrid modelling is done by modelling each element separately. Keeping this objective in mind, chapter is divided in several sections: Renewable sources modelling, Power sources modelling, Load modelling and Fault modelling.

3.2 Renewable Sources Modelling

Both solar and wind resources have to be modelled in order to complete a functional model of a photovoltaic panel and a wind turbine. In this category of resources PSCAD/EMTDC has both model for solar resources and wind resources.
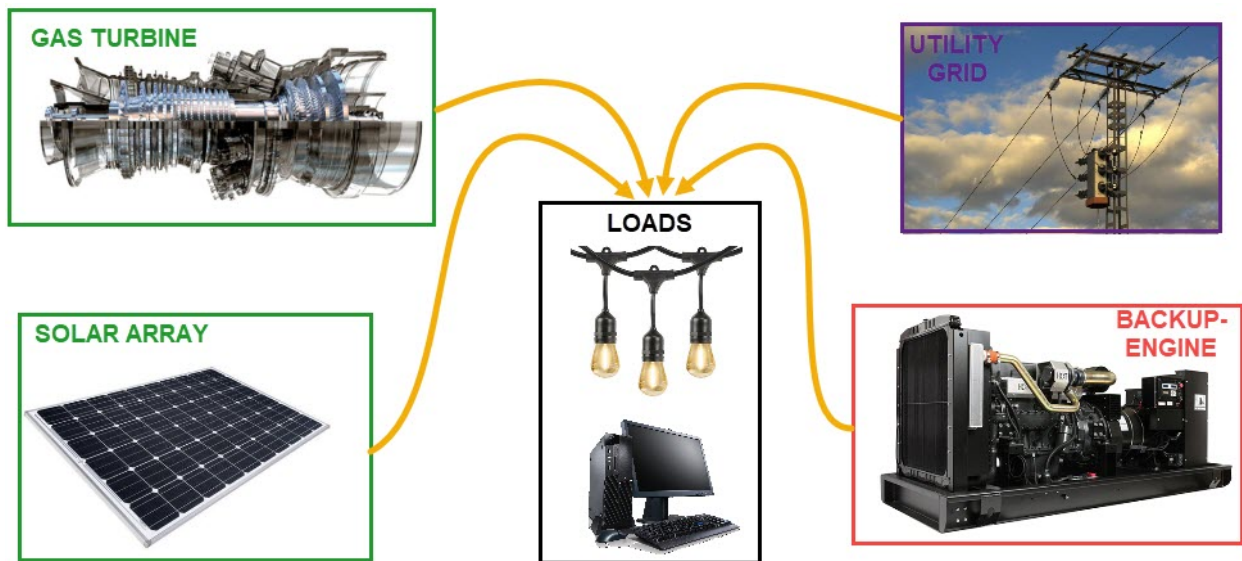
Figure 3.2: Microgrid General Scheme Connection

3.2.1 Solar resources

As figure 3.3 shows, PSCAD/EMTDC offers the possibility to use an functional photovoltaic source. This PV source is assumed to consist of several strings of modules connected in parallel configuration, where each string can consist of a number of PV modules connected in series. All PV modules in the array are assumed identical.
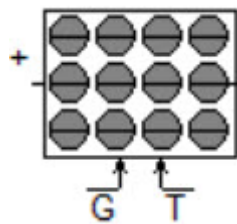
Figure 3.3: PSCAD/EMTDC Photovoltaic Source

Mathematical model used in the component were explained at 2.4.2. On the other hand, as figure 3.3 shows, there are two external inputs for this component:

- **G:** Instantaneous value of solar radiation on the panel (W/m^2).
- **T:** Instantaneous value of cell operating temperature (℃).

There are, also, internal inputs that allows to the user to defines the main characteristics

of the Photovoltaic Array and the Photovoltaic Cell, as: Number of modules connected in series per array, Number of module strings in parallel per array, Effective area per cell, Series resistance per cell, Shunt resistance per cell, etc.

3.3 Power sources

In this section, it is going to be described the different kind of power sources the microgrid has implemented. This is: Solar Photovoltaic source; Natural Gas Turbine; External Power Source and Backup Diesel Generator. Almost every power source need a inverter or a frequency converter to its functionality. For that reason, an separately subsection will be used to describe it.

3.3.1 Power Electronics

Power Inverter

A power inverter is a component of the power source that convert DC current into AC current. It is widely used in this type of applications and in the industry. It can be simulated using six IGBT's as figure 3.4 shown. At the very left of the figure a DC source is used and at the very right can be shown three phases, corresponding to the three phases of a three-phase line.
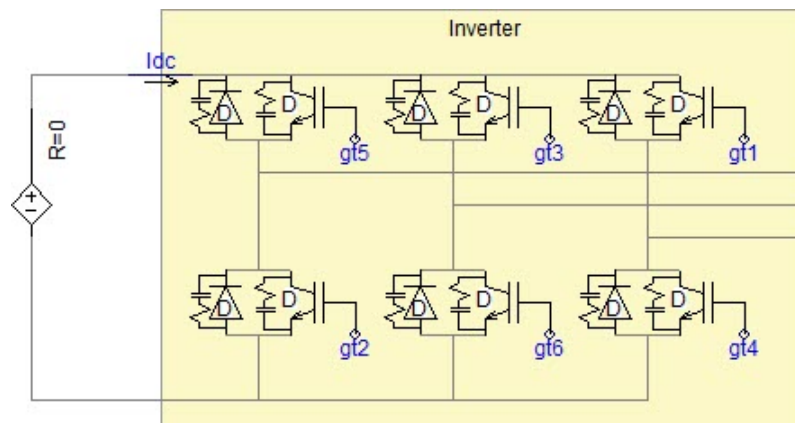

Figure 3.4: Power inverter implemented in PSCAD/EMTDC

In order to create an sinusoidal wave form at the output, IGBT's are pull on and off using a PWM technique. In the figure 3.5, is setted up this technique. This consist in compare a

high-frequency and low voltage sawtooth signal with a sinusoidal one and, by using a pulse generator, generate a signal that turn on and off the different IGBT's of the inverter.

If the power output has to be controlled, it is possible to do it changing the value of the "Modulation Order" m, this parameter has values between 0 and 1. The inverter inject more power as the value of the modulation order increases and inject less power if the value of this parameter decrease.
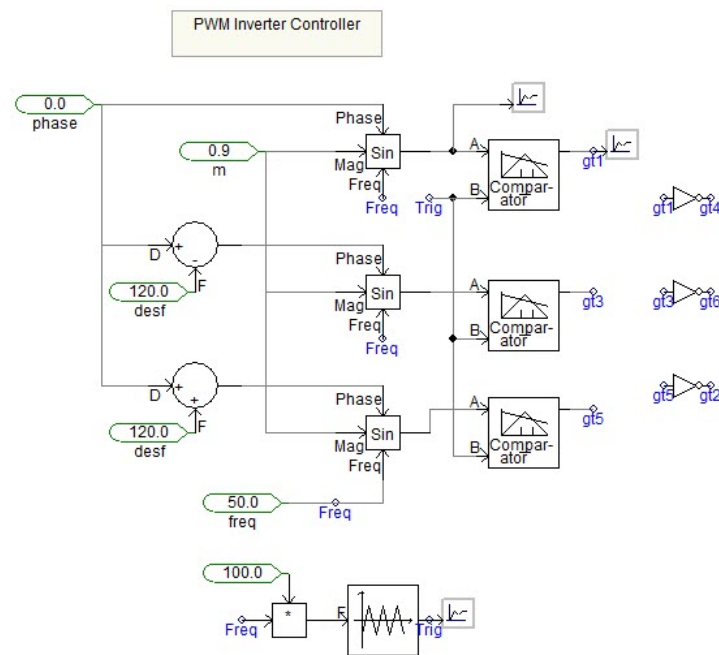
Figure 3.5: Fingering pulse generator using a PWM technique

Harmonics Filter

Due to the harmonics that the rectified signal will have, it is very important to use a LCL filter, just before the Point of Common Coupling. This filter absorb the harmonics generated and create a good three-phase sinusoidal signal. This type of filter is show in the figure 3.6.

Non-Controlled Rectifier

This element can create a DC signal using a three-phase AC signal. This type of rectifier is the simplest one, and it is not possible to change the output, and for that reason is named as "Non-Controlled". In the figure 3.7 this type of converter is shown. It is modelled using simple diodes.
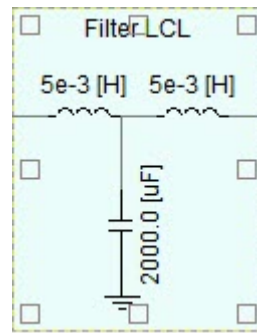
Figure 3.6: Harmonic Filter LCL
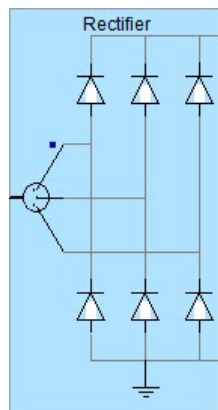
Figure 3.7: Non Controlled Rectifier modelled using diodes

DC-DC Converter

This component is used to change the value of the voltage of a DC signal without the losses that a resistor may have. It is implemented using only one IGBT, and the output voltage, at the right of the IGBT can be controlled by modifying the value of the "Duty cycle" of the signal $T1$. If the value of the Duty cycle is near to one, the voltage value of the output and input signal are similar.

As the figure 3.8 shown, it is possible to reduce the value of the voltage, that is $Vdc > dcVltg$. This is also called "Buck Converter". Output ripple is controlled by using a LC filter.

DC Link

Is a way of connecting two AC that have different values of frequency and voltage by an intermediate DC stage, it is generally used in converters and consist in a capacitor that storage the energy once AC is converted to DC. This capacitor usually has high ratings of nominal voltage and a low level of losses.
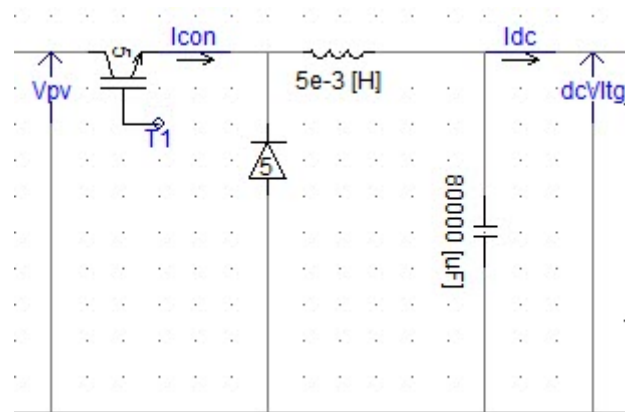
Figure 3.8: DC to DC Converter

3.3.2 Solar Photovoltaic Source

A solar photovoltaic system uses several power electronics element explained in the previous subsection. A general schematic for this set up is shown in the figure 3.9. It has the following components:

- Photovoltaic Panel: it has two inputs, one is the cell temperature, supposed constant as 25°C; the other is the solar radiation (SR) declared as variable in order to change it with a controller.

- DC to DC Converter: it modifies the output voltage of the solar panel using the duty cycle of the IGTB, in order to get as much power as possible of the PV panel using a MPPT controller (Maximum Power Point Tracker). This MPPT Controller gives the voltage when the output power is maximum analyzing the output voltage and current. Figure 3.10.

- DC link: used as a link between DC and AC stages. It consists in a 80 mF capacitor.

- Inverter: converts DC signal in a triphasic signal.

- Filter LCL: smooths the output signal once it is inverted.

- Isolation Transformer: used as electrical isolation of the rest of the grid. It is a 400/400 transformer.

- PCC: Point of Commom Coupling: is where Photovoltaic sonal system is connected to the rest of the grid
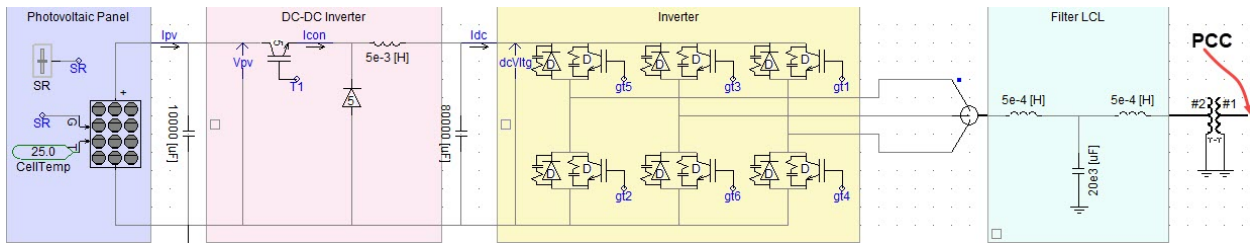
Figure 3.9: Solar Photovoltaic System
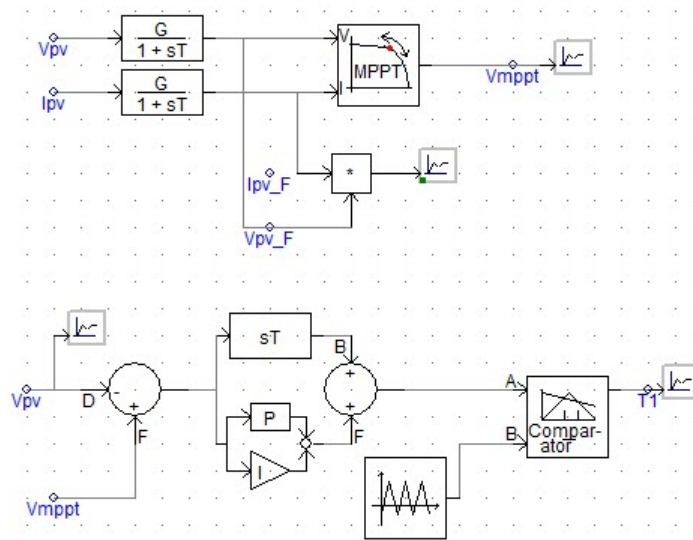
Figure 3.10: MPPT System

Solar Photovoltaic Array has been declared using technical data shown in table 3.2. This parameters are selected in order to obtain 400 V at the PCC, taking in mind the different parts of the installation. Rest of the parameters are selected by default.

Number of modules connected in series per array	4
Number of modules strings in parallel per array	114
Number of cells connected in series per module	72
Number of cell string in parallel per module	4
Effective area per cell	0,024 m^2

Table 3.2: Technical information about PV array

Then, once all the system is setted up, characteristics curves for the microgrid are done. In the figure 3.11 several curves are plotted for different Solar Radiations, this curves shown the behaviour of the photovoltaic source under different conditions. As can be shown, changing the voltage at the output of the photovoltaic module, it is possible to obtain more or less

power output. At this moment is when MPPT controller came into action as with it, it is possible to change the value of this value to obtain the maximum power output.

Figure 3.11: Power versus Voltage curves of the PV

In the figure 3.12, Voltage versus Current curves are shown. They shown the behaviour of the output voltage when current changes.

Figure 3.12: Voltage versus Current curves of the PV
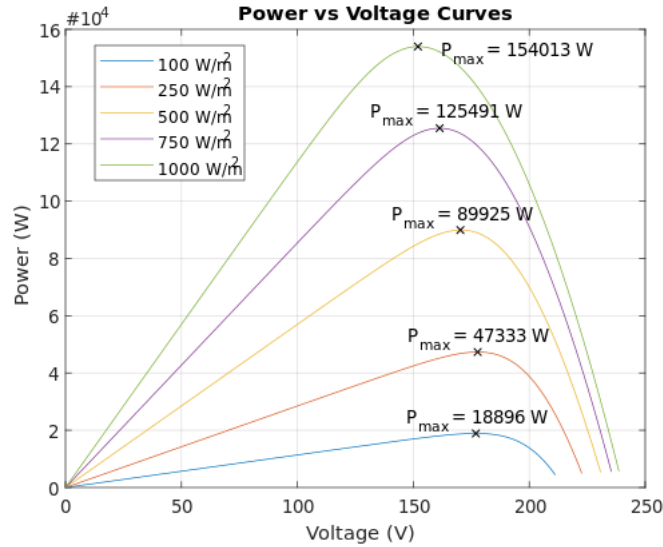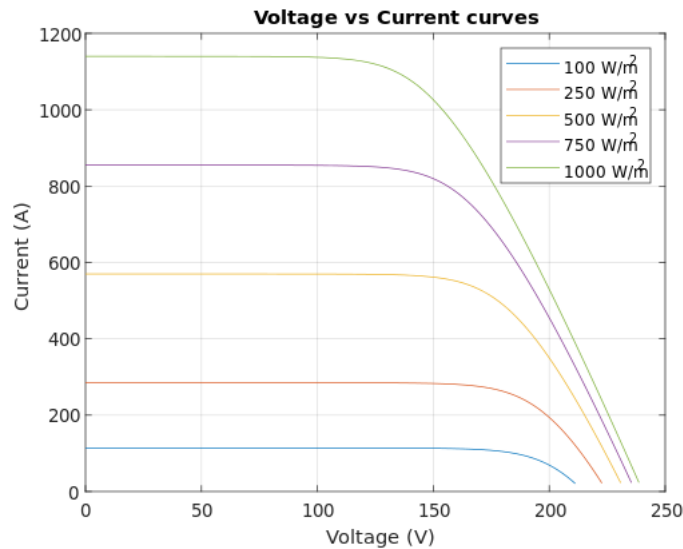
3.3.3 Natural Gas Turbine

Natural gas turbine are usually installed in most of the hybrid microgrids, they can produce heating, cooling, and electricity. In this study, only electricity generation is simulated. Following the work done by Gang Li about Micro-turbines modelling and simulation ([22]), this subsection is done.

Figure 3.13: Micro-turbine Model in PSCAD/EMTDC

The Microturbine simulated has several parts as is shown in the figure 3.13. It has several controls:

- Speed control: Measure the speed of the turbine and, using a Lead Lag compensator controls that parameters ensuring that the velocity is maintained near the rated speed of the machine.

- Acceleration control: Measure the acceleration of the turbine and ensure that this value is maintained in reasonable values, avoiding the over acceleration of the machine.

- Temperature control: As all the micro-turbines, this turbine follows a Brayton cycle and the temperature of the camber has to be maintained in a reasonable values.

With the signals of all this controls, a fuel control is made by taking the minimal signal of the three described. Then, the temperature of the gases at the exhaust is obtained and the Mechanical torque of the machine.

With this torque, using the mechanics dynamics (equation 3.1), angular speed is obtained. With this, a Permanent Magnet Synchronous Machine is feeded. It would be that machine that provides electricity to the microgrid.

$$T_m - T_e = J \cdot \frac{d^2\theta}{dt^2} \qquad (3.1)$$

After that, power electronics are used to condition the signal, that is, values of frequency and voltage are changed in order to be the same that in the other zones of the microgrid. This is done by using a rectifier, a DC link, and a Inverter controlled by a PWM signal and a LCL filter. This scheme is shown in figure 3.14.
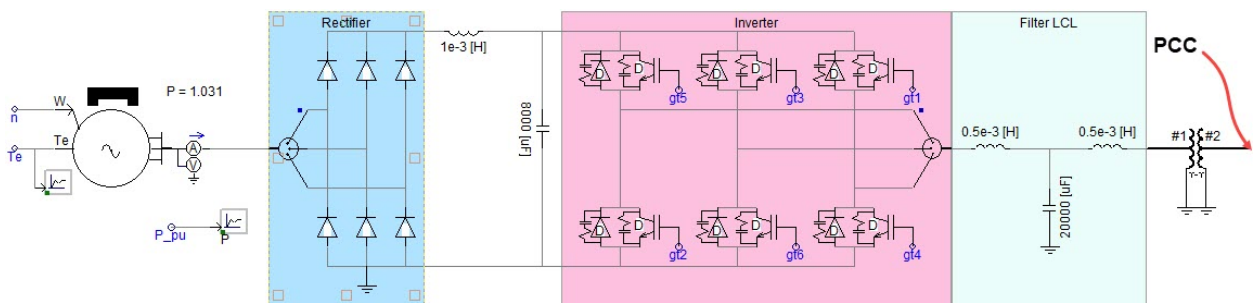

Figure 3.14: Microturbine PMSM and electronics

The main characteristics of the Microturbine are shown in the table 3.3.

Shaft velocity	72.000 rpm
Chamber temperature	950°C
PMSM rated power output	1 MVA
Output Line to line voltage	400 V

Table 3.3: Main Characteristics of the Gas Turbine system

3.3.4 Backup Diesel Generator

In this section, it is described how is modelled the Backup Diesel Generator used in the microgrid. This model is done by following the example model of the software. Complete model is shown in figure 3.15.

The working principle is simple, it only has a PI controller for the output torque of the Diesel generator and the PMSM machine. When both values are the same the PMSM maintain its velocity as the acceleration is zero. There is another PI controller for the output power. Due to the condition of backup generator, it is completely necessary the ability of power regulation, and this is done by acting over the input fuel rate.
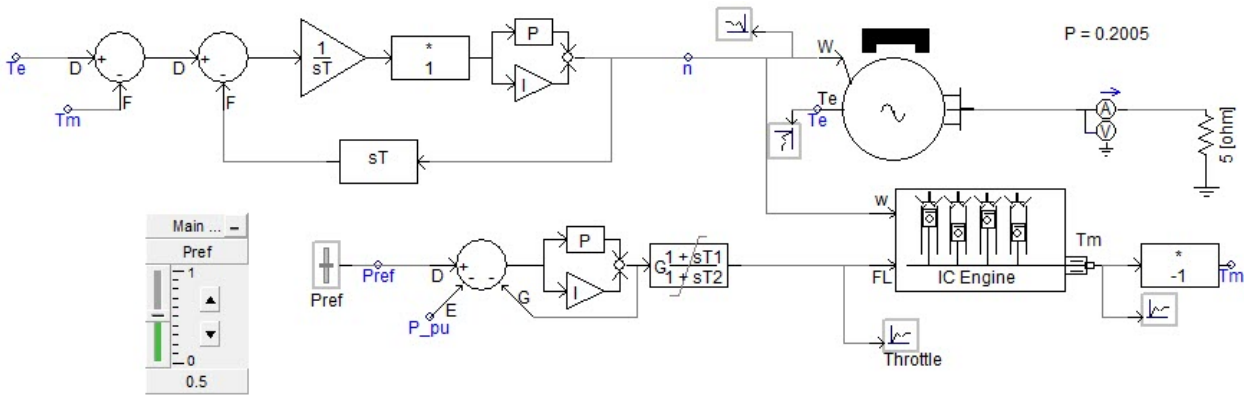
Figure 3.15: Modelling a Diesel Generator in PSCAD

It is done the simplification of considering that the speed of the Diesel Engine is constant and for that reason it is not needed power electronics to condition the output signal. The main characteristics of the backup system is shown in the table 3.4.

Power output	1 MW
Rated speed	1.500 rpm
PMSM pair of poles	2
Frequency	50 Hz
Output Voltage	400 V

Table 3.4: Backup Diesel Generator

3.3.5 External Source

Also, for a complete microgrid simulation, it is necessary to model an external power source, modelling the main grid. This source is used to simulate the microgrid when it is consuming power from its distributed sources and external grid.

Due to the difficult power regulation of the voltage and current sources available in PSCAD library, an external power source is modelled using a DC voltage source with a PWM inverter with power controller. That is what it is shown in the figure 3.16.

For the correct simulation of the external source, i.e., in order to be able to control the power output, it is necessary to act over the modulation order of the PWM signal, changing the value of this parameter, it is possible to regulate the amount of time current is flowing through the semiconductors, and, consequently, the amount of electricity generated.
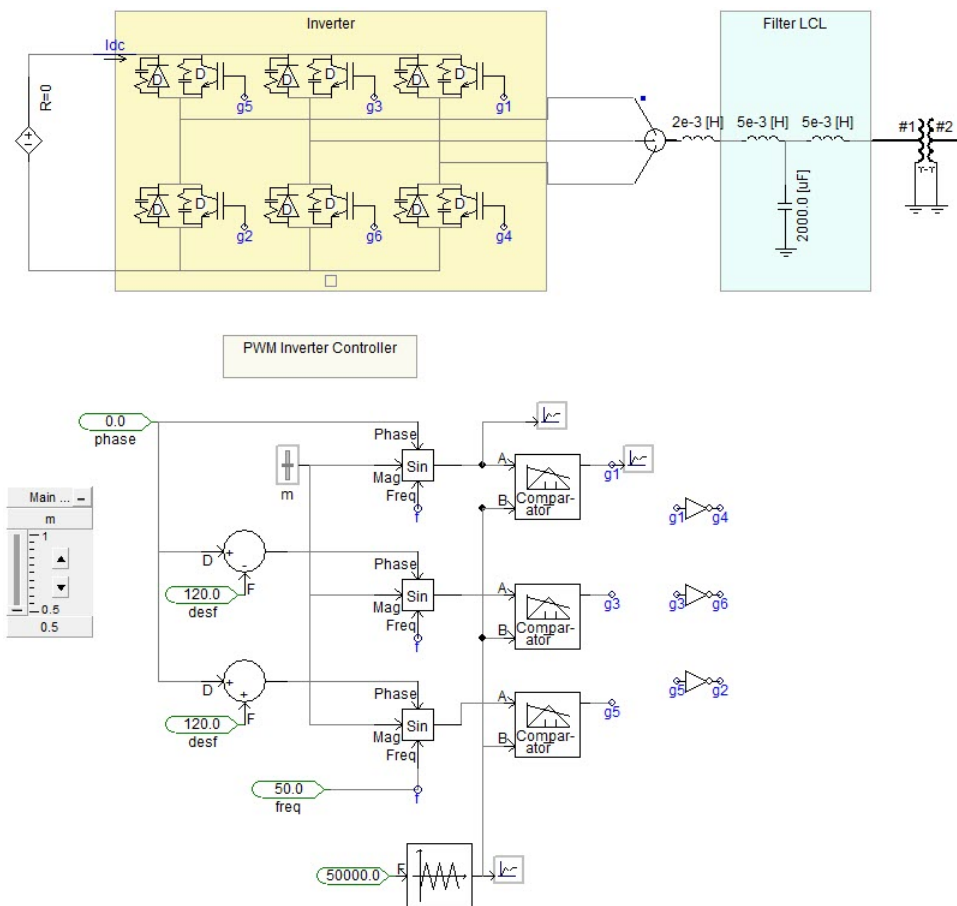
Figure 3.16: External Source Modelling

The model contains a DC source rated in 1 kV, a power inverter controlled by a PWM signal and a Filter LCL for signal quality. The output line to line voltage is about 400 V, and 50 Hz, being possible to control the power output.

3.4 Load modelling

In this section, loads are modelled. This is a much more simpler design comparing with the previous models. In this work, only active power is considered as in Low Voltage Distribution Grid most of the loads are resistive. For that reason, loads are modelling as a variable resistor, as is illustrated in the figure 3.17. The power demanded by the resistor is controlled by changing its value. As the voltage is supposed to be constant at that point, this power can be calculated using equation 3.2. Where $P(W)$ is the value of the power output in watts,
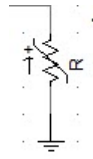
Figure 3.17: Resistive Load Modelling

V_f is the phase to ground voltage at the bus (230 V) and R the value of the resistance.

$$P(W) = \frac{3 \cdot V_f^2}{R} \tag{3.2}$$

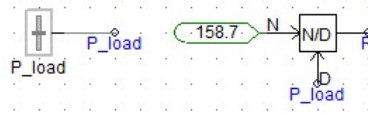That is the formula represented with the controller shown in figure 3.18.

Figure 3.18: Power Demand Controller

3.5 Fault Modelling

In this work, is also simulated the behaviour of the system when a fault occurs at the main bus. It is considered the phase to ground fault, as long as is the most common type of fault, and the triphasic fault, as is the most dangerous. In the figure 3.19 is shown how is modelled and simulated the fault.

The fault occurs at the moment t_{fault}, then is applied for $0,1\ s$ and the general circuit breaker is opened. The fault is supposed to occurs when the system is in steady state. Using the controller T_{fault} it is possible to control the type of fault applied (Monophase-ground, triphase-ground).

Fault is applied during $0,1\ s$ due to it is the largest time of actuation of the current circuit breakers (5 frequency cycles). On the other hand, the value of the Fault resistance is supposed $0\ \Omega$ as this is the most dangerous value, because the current that flows through the fault are greater than in any other case.
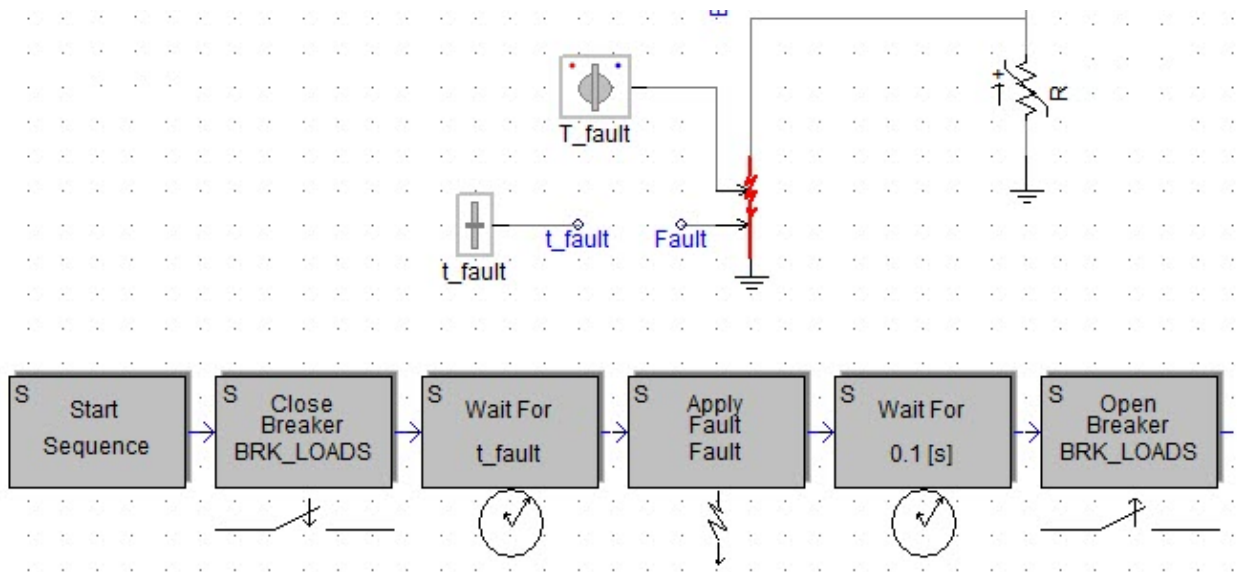
Figure 3.19: Fault system simulation in PSCAD

3.6 Complete Model

With all the models explain in the previous section of this chapter, complete microgrid model is done and it is shown in the drawing N°1.

Chapter 4

Microgrid Simulation

4.1 Introduction

In this chapter, the microgrid modelled in the previous chapter is going to be simulated. The microgrid modelled is based on the OATI Microgrid Technology Center, that is, there are only included in the simulation the most relevant elements of the microgrid, as: PV solar system, External source, Diesel backup generator, Gas Turbine and Loads.

Several studies will be made to the model created, first of all, it will be simulated the Microgrid working as an Island, in normal conditions of operation. Then, grid connected mode is simulated, in normal working conditions. After that, an emergency situation is simulated when only Diesel Engine is working feeding loads.

The second part of the study is done by simulating the whole system under fault conditions. There were made several studies: when the grid is connected, when is working in islanded conditions and when backup generator is working.

All this simulations are completely useful in order to select the different circuit breakers of the electrical installation, because is obtained the higher peak of current under that kind of conditions.

Each simulation is done only for one load condition, that is because the results of changing the value of the load consumed only affects to the transient stage, and the results, in steady stage would be the same. That is because of the control made that allow to the microgrid to have 400 V of line to line voltage with 50 Hz of frequency.

In the following sections will be done an resume of the simulation done. Technical parameters

of the simulation are shown in the table 4.1

Solution Time Step (μs)	10
Channel Plot Step (μs)	500
Duration of the run (s)	From 1 to 10 s

Table 4.1: Technical Parameters of the simulations

4.2 Islanded Mode. Normal Operation

In this section, three different simulations are done. Each one consider one kind of configuration of the Distributed Resources, that is, photovoltaic, gas turbine and both working together.

4.2.1 Photovoltaic power source

In this simulation, the only source that provides energy is the Photovoltaic system, as scheme of the figure 4.1, shown . Here the system is simulated with a solar radiation of $1.000\ W/m^2$ at the reference temperature of the Photovoltaic array ($25°C$).
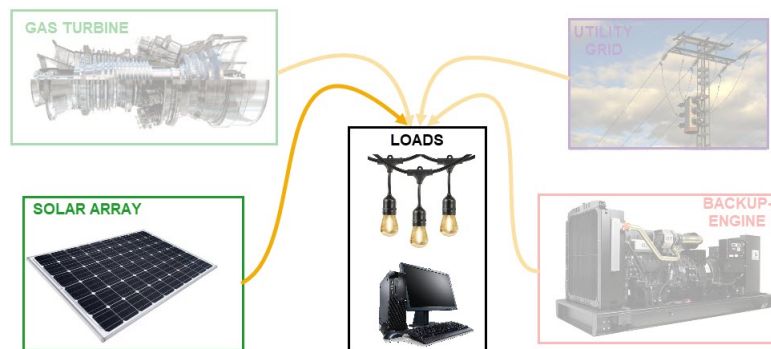

Figure 4.1: Schematic of the Case of Study 1

Load is adjust to consume 135 kW of active power, and output line to line voltage it is around 400 V. Steady state is reached very fast, about 0,1 seconds. As can be shown in the figure 4.2, the triphasical signal has a near perfect sinusoidal wave, that is due to the LCL filter.
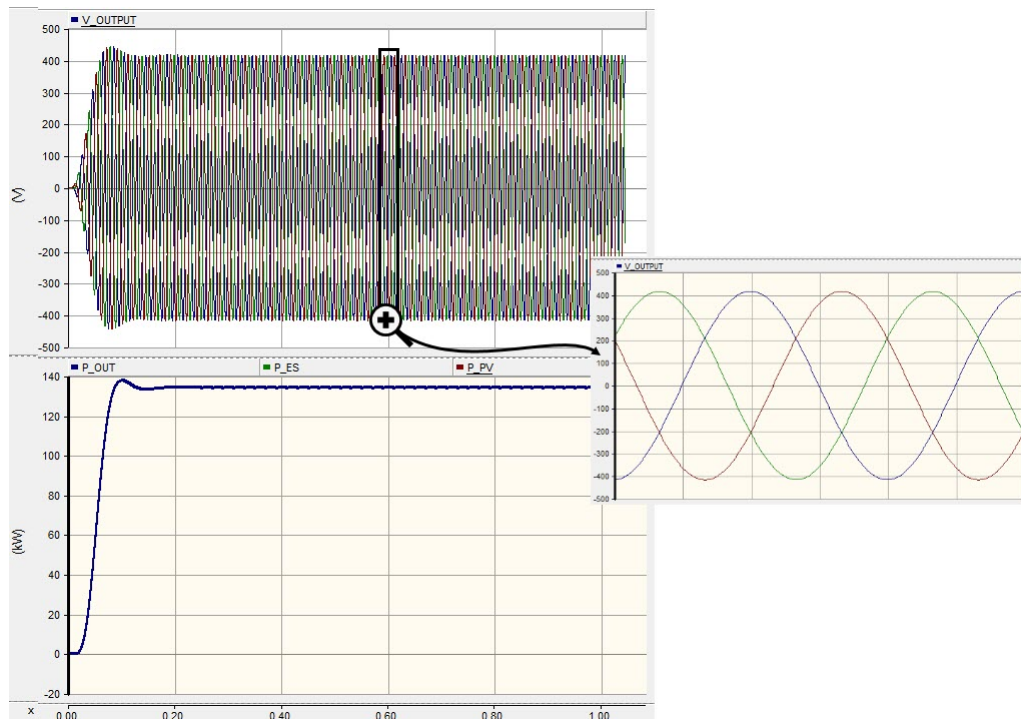
Figure 4.2: Islanded Mode. Photovoltaic Array Only

4.2.2 Gas turbine power source

In this simulation, there are only one source that generates energy, the gas turbine. Figure 4.3. The gas turbine is simulated with full input of fuel (1 p.u.). Load is adjust to 50 kW. The result is shown in the figure 4.4.

After a period of, approximately, 5 seconds, the system reach the steady state with the output voltage of 400 V and 50 kW of power output.
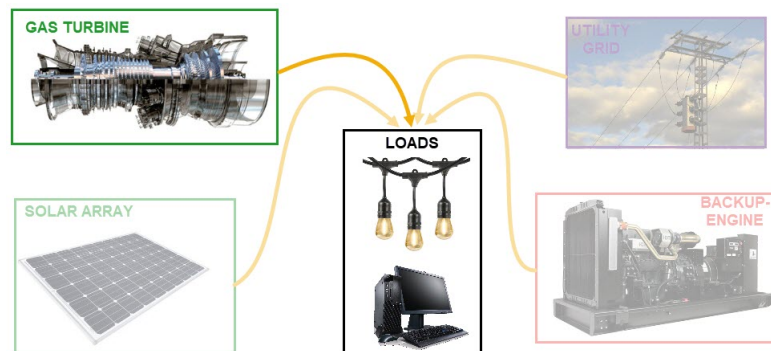

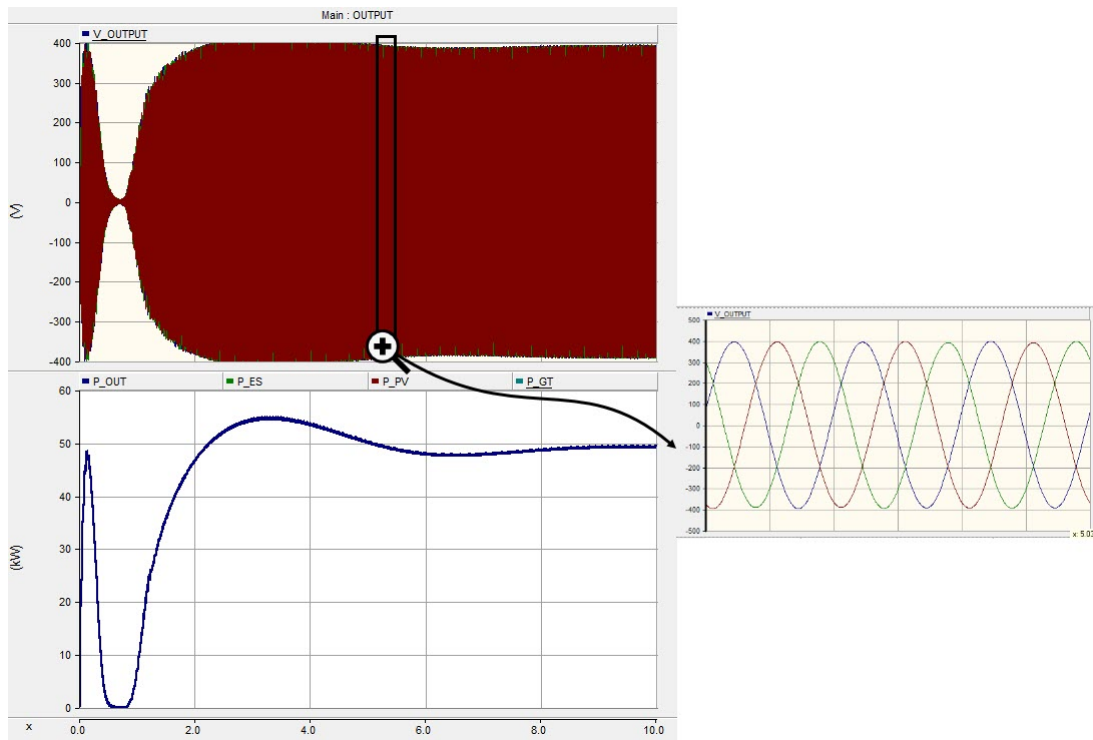Figure 4.3: Schematic of the Case of Study 2

Figure 4.4: Islanded Mode. Gas turbine working

4.2.3 Gas turbine and photovoltaic source

Here, generation are done both the photovoltaic array and the gas turbine. Figure 4.5. Both solar radiation and the fuel injection to the gas turbine are reduced, to observe the behaviour of the system with lower load consumption. As can be shown in the figure 4.6, in blue are
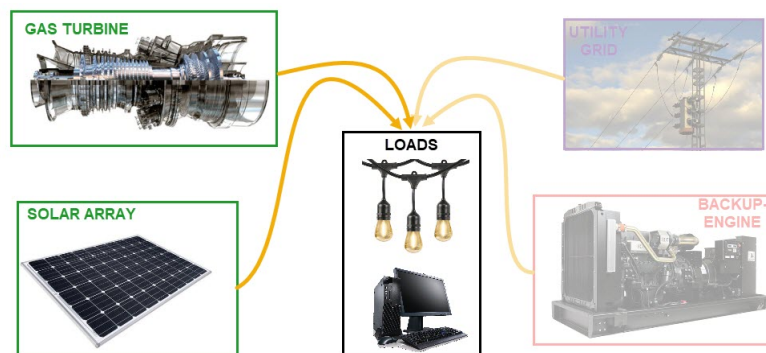

Figure 4.5: Schematic of the Case of Study 3

shown the power generated by the gas turbine, and in red, the power generated by the solar array. In deep blue are shown the output power of the microgrid.
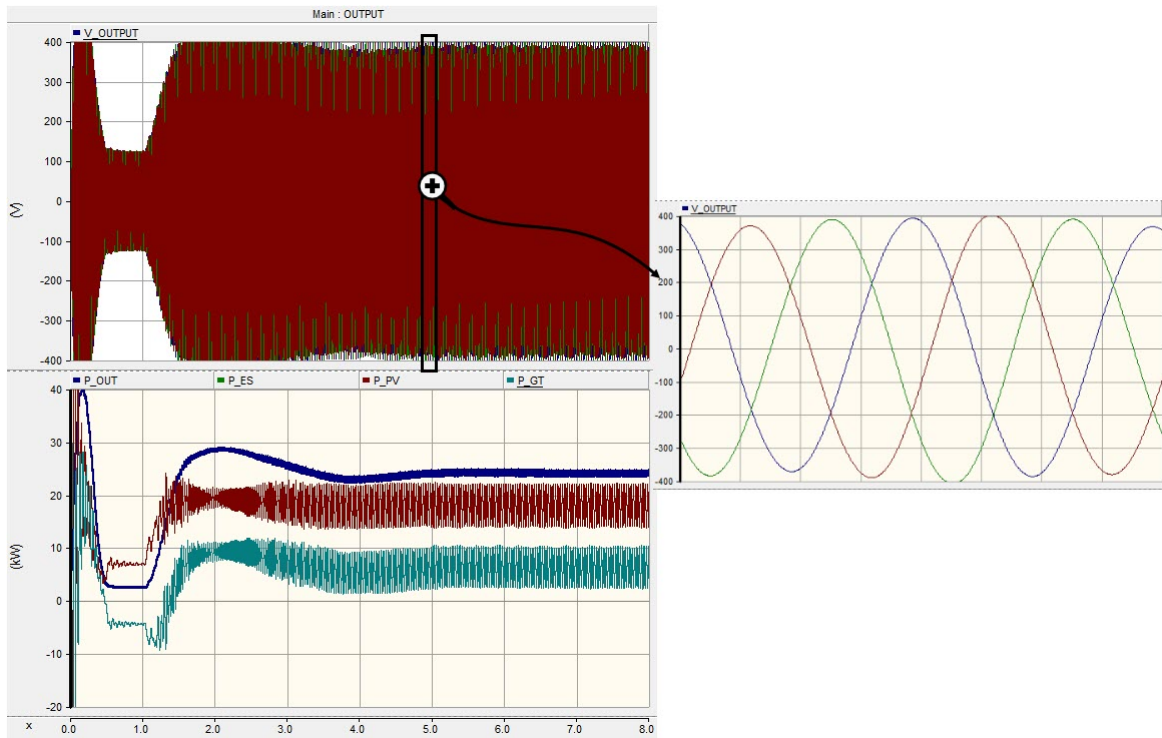
Figure 4.6: Islanded Mode. Gas turbine and solar array working

The settling time of the system is near when only the gas turbine is working, about 5 seconds, and the output voltage is about 400 V.

4.3 Grid Connected. Normal operation.

In this section, microgrid is simulated under grid connection conditions, that is, there are always present a external power source that generates the differences between what is produced by the distributed power resources and what is demanded by the consumption.

First, is simulated the system only with the photovoltaic array working, then with the gas turbine working, and, at the end, the whole system is simulated, that is, photovoltaic array, gas turbine and external source.

4.3.1 Photovoltaic power source

As can be shown in figure 4.8, output power is about 160 kW, what is demanded by the loads. In green are shown the amount of power generated by the external source and, in red the power generated by the photovoltaic array. Figure 4.7. Solar radiation is fixed to
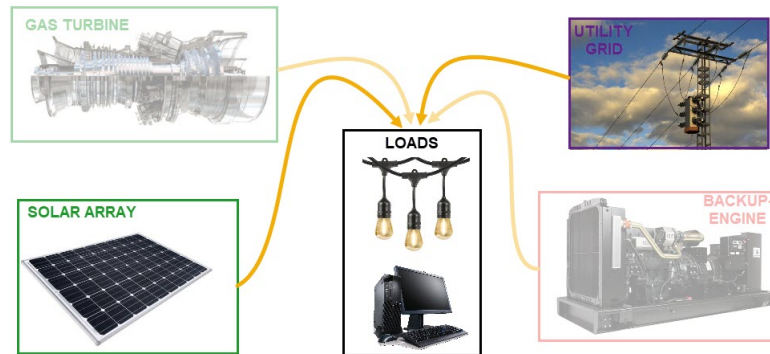
Figure 4.7: Schematic of the Case of Study 4

650 W/m^2, and under this conditions, solar array can produces, in grid connected mode, about 50 kW. Then the rest of the power needed is generated by the external source, that is, about 110 kW.

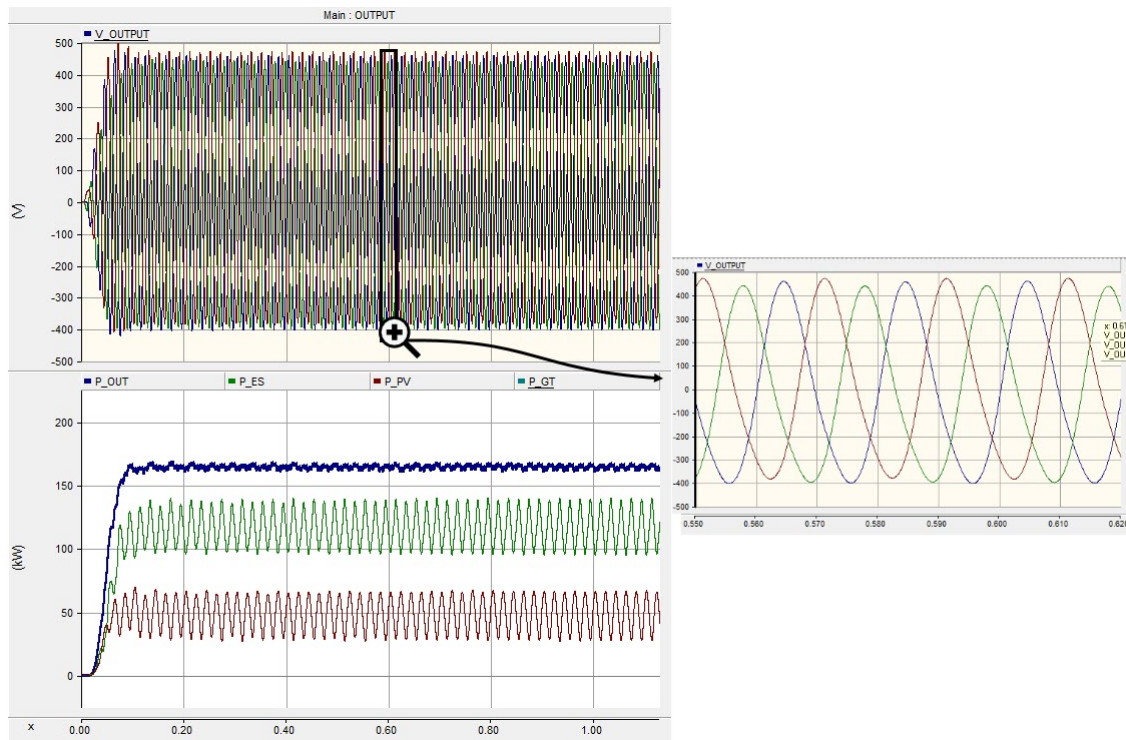Voltage output is near to 400 V, with a frequency of 50 Hz. Settling time is short, about 0,1 seconds.

Figure 4.8: Grid connected mode. Photovoltaic array working.

CHAPTER 4. MICROGRID SIMULATION

4.3.2   Gas turbine power source

As is shown in figure 4.10, there are several stages in the simulation. First, part of the energy produced by the external source is consumed by the gas turbine. This is used for the starting of the turbine. Figure 4.9. Then, gas turbine starts to produce energy and the power output
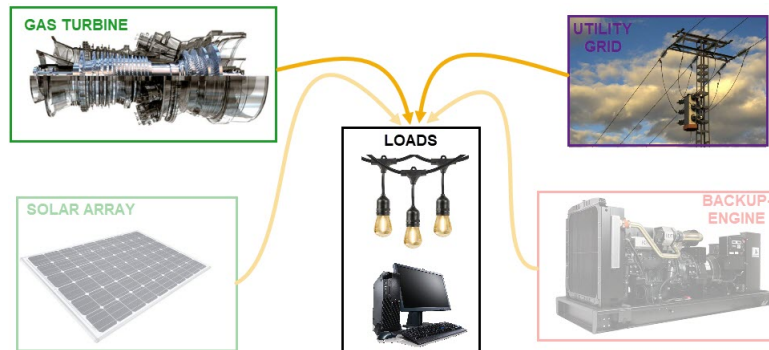

Figure 4.9: Schematic of the Case of Study 5

steady state is reached. Load consumption is about 110 kW, and the most of the energy is produced by the external source (100 kW), as the intake of fuel of the Gas Turbine is setted up to 0,6 p.u.
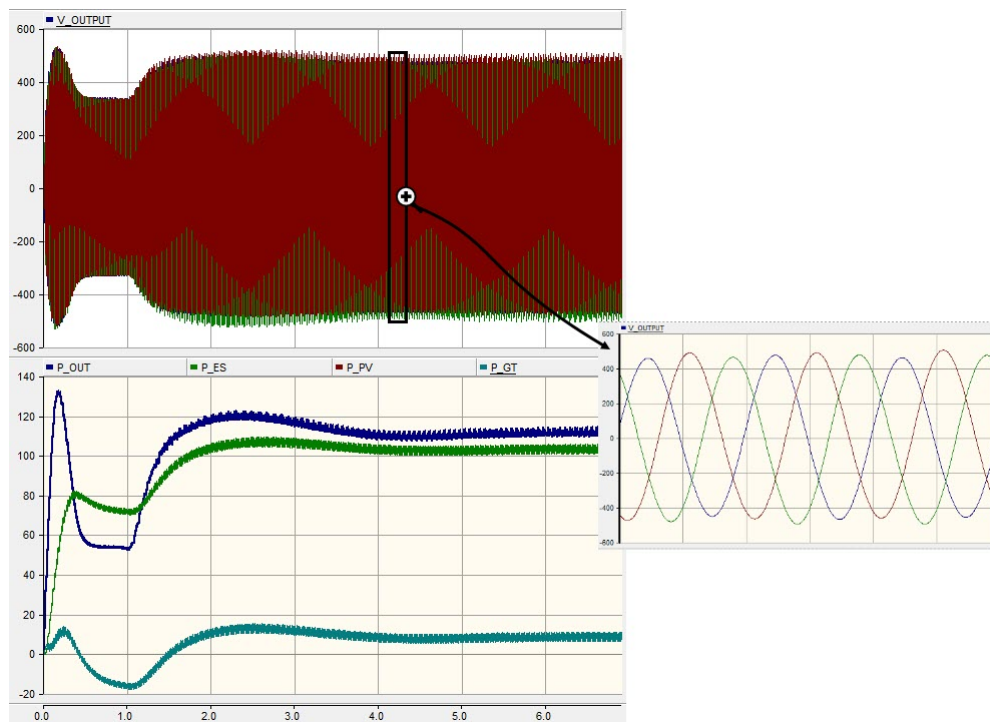

Figure 4.10: Grid connected mode. Gas turbine working.

The output voltage signal is about 400 V, and 50 Hz. Settling time is about 4 seconds.

4.3.3   Gas Turbine and Solar array power sources

Once, each power source is generated in grid connected mode, it is time to simulate the whole system under normal conditions of operativity. That is, solar array, gas turbine and external source working together. Figure 4.11.
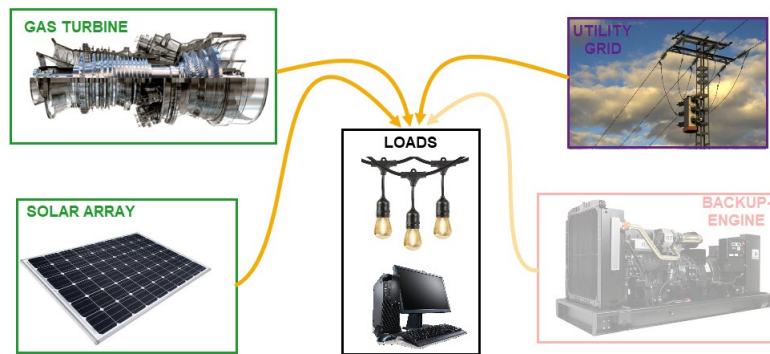

Figure 4.11: Schematic of the Case of Study 6

As can be shown in figure 4.12, the simulation progress very similar to the previous simulation, first of all, the gas turbine consume some energy in order to reach the steady state.

Here is simulated the microgrid when solar and gas turbine resources are generating low quantities of power, and the external source is needed to fulfill the power balance. Solar radiation was setted to 600 W/m^2, and the fuel intake for the Gas Turbine, 0.6 p.u.

Output line to line voltage is about 400 V and the frequency is 50 Hz, with a settling time of the whole system of about 3 seconds. Power generation is about 100 kW, generating 20 of them by the solar array and the gas turbine, and the rest by the external source.

4.4   Emergency situation. Backup Diesel Generator working

In this section, a emergency situation is simulated. A general scheme can be shown in the figure 4.13. Figure 4.14 shown the simulation of the whole microgrid when the distributed resources are not available, and there are a problem with the external source.

Diesel engine has to be able to generate energy for the whole microgrid, and for that reason is simulated when the power consumption is about 300 kW. As figure 4.14 shown, the settling
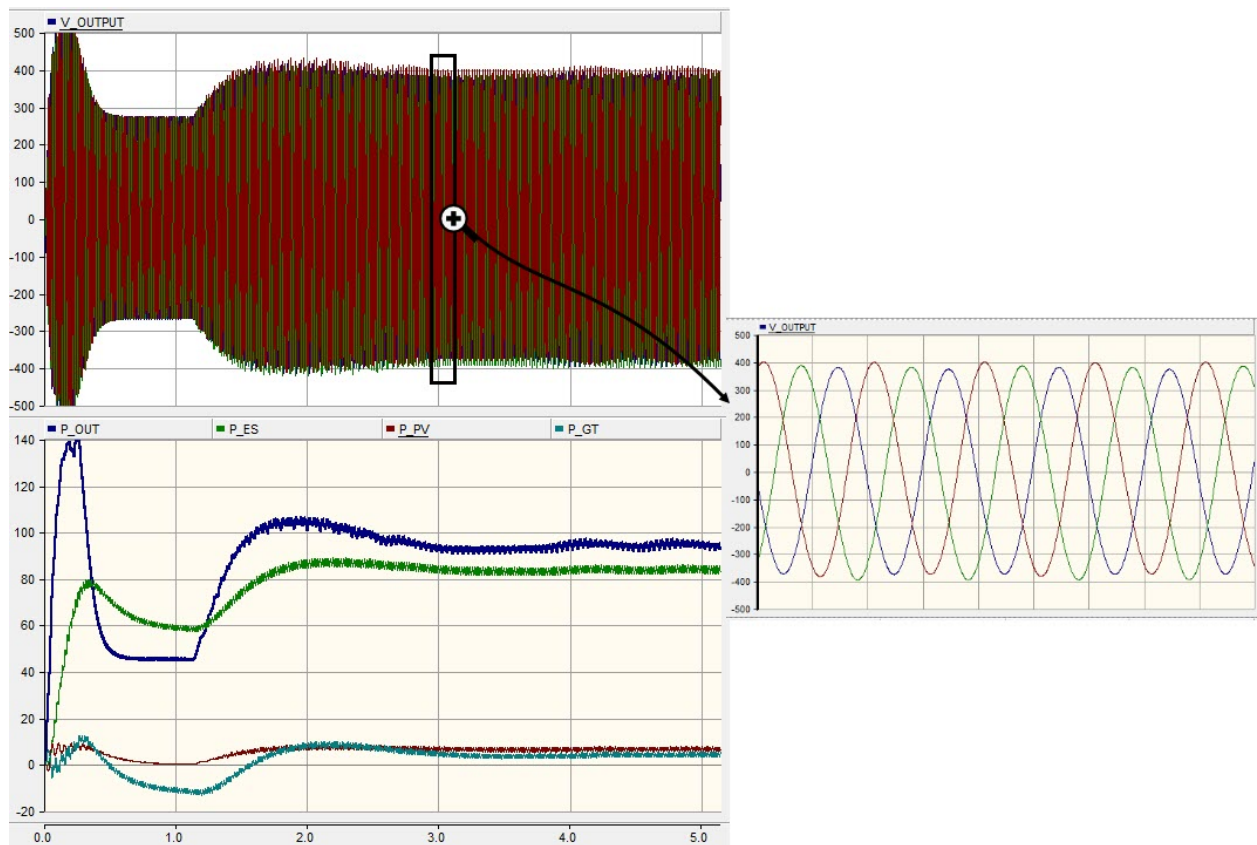
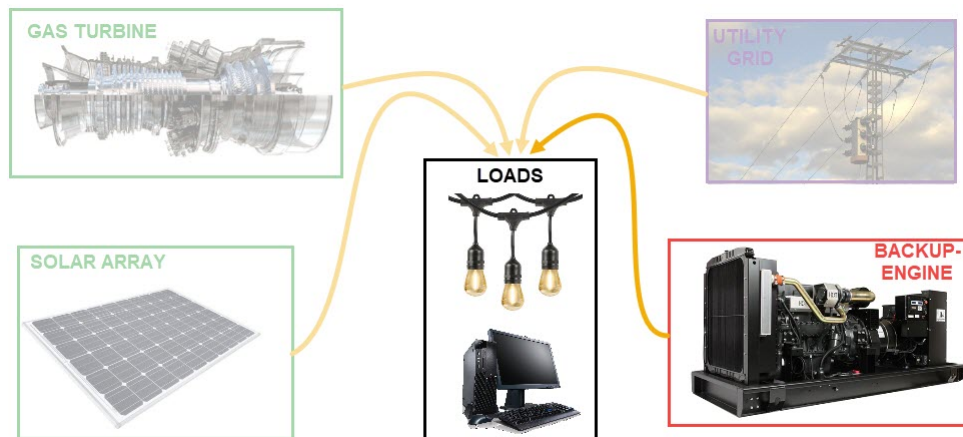Figure 4.12: Grid connected. Gas turbine and solar array working.

Figure 4.13: Schematic of the Case of Study 7

time is about 5 seconds and the output voltage is 400 V, with 50 Hz of frequency. This simulation show that the backup diesel generator works fine, and it is able to fulfill the power demand.
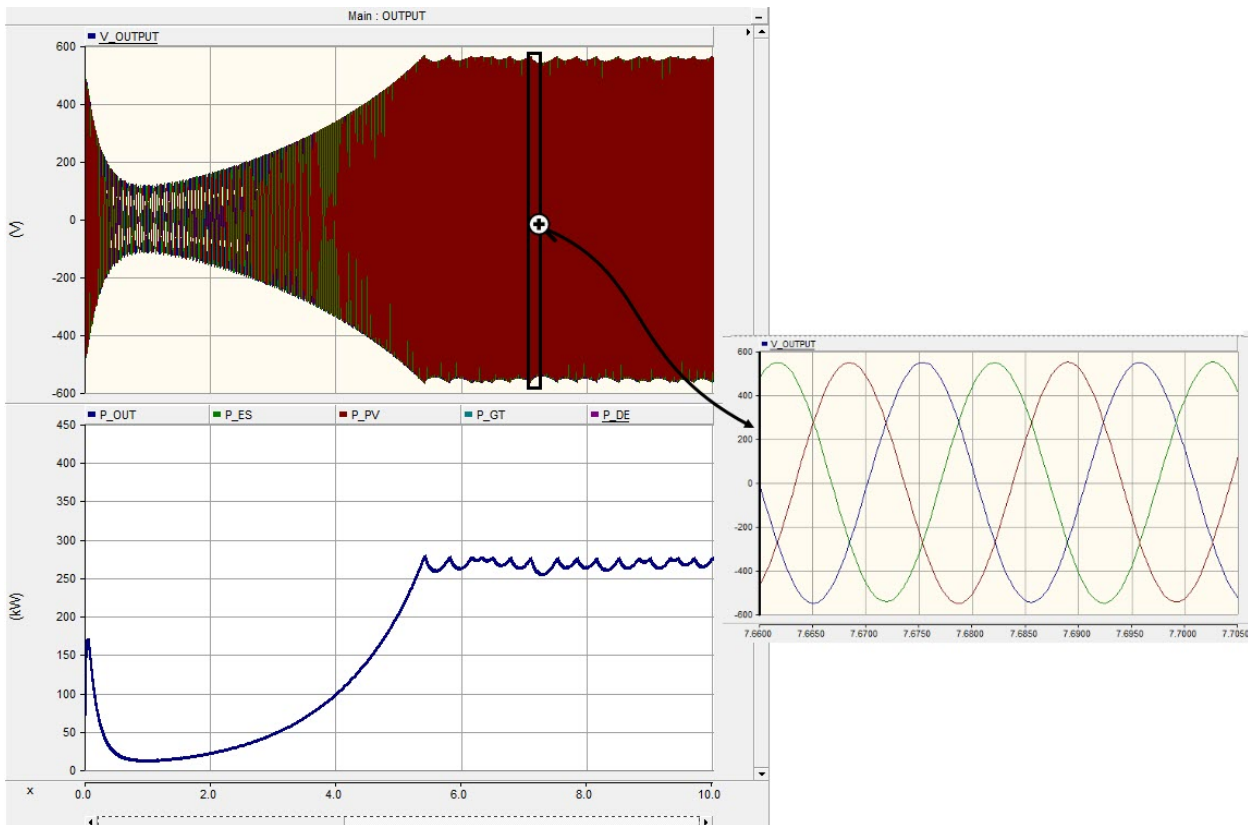
Figure 4.14: Emergency situation. Diesel engine working

4.5 Abnormal situation. Fault conditions

In this section, several faults are done at the main bus, where the loads are connected. There were simulated both the mono-phase to ground fault, and the three-phase to ground fault, as there are the most common and the most dangerous in a electric power system, respectively. Both types of faults are produced when the system work under islanded mode, grid connected mode and emergency mode.

4.5.1 Islanded Mode. Mono-phase to ground fault

Both photovoltaic array and gas turbine are running in this mode. Fault increases the speed of the gas turbine and the production of the electricity, this phenomena is recursive and, until the breaker does not open the circuit, fault current maintain at high values. Figure 4.15.

In this simulation fault is applied at $t = 5.0\ s$, when the system has reached the steady

Figure 4.15: Schematic of the Case of Study 8

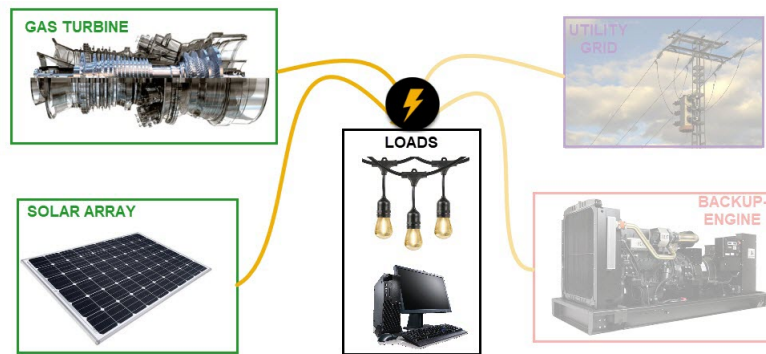state. Due to the condition of mono-phase to ground fault, phase A increase the value of the current that flows through up to 3 kA, as can be shown in the figure 4.16.

If voltage signal is observed, it is possible to observe two types of phenomena, one is the change of the phase of the signal, and the other is the change of the alue of the voltage. Frequency is maintained more or less constant.

4.5.2 Islanded Mode. Three-phase to ground fault

In this simulation, as is done in the previous chapter, both gas turbine and photovoltaic array are working. It is possible to observe in the figure 4.17, fault is applied at $t = 5.0 \ s$, and it is applied during 0,1 s. The value of the line to line voltage droops to values near to zero.

Output current increase to values near to 3 kA, in the three phases. As in the previous section, the fault phenomena is recursive, and, for that reason it is not until the circuit breaker opens when the current decreases.

4.5.3 Grid connected. Mono-phase to ground fault

In this subsection is described the behaviour of the system under grid connected conditions when a mono-phase to ground fault occurs. Fault is applied when the microgrid has reached the steady state, at time $t = 5.0 \ s$. Fault is applied during 0,1 s. Figure 4.18.

As figure 4.19 shown, the line to line output voltage changes in phase and rms value. The peak of current reached in the bus where fault occurs is about 3,5 kA. And the fault does
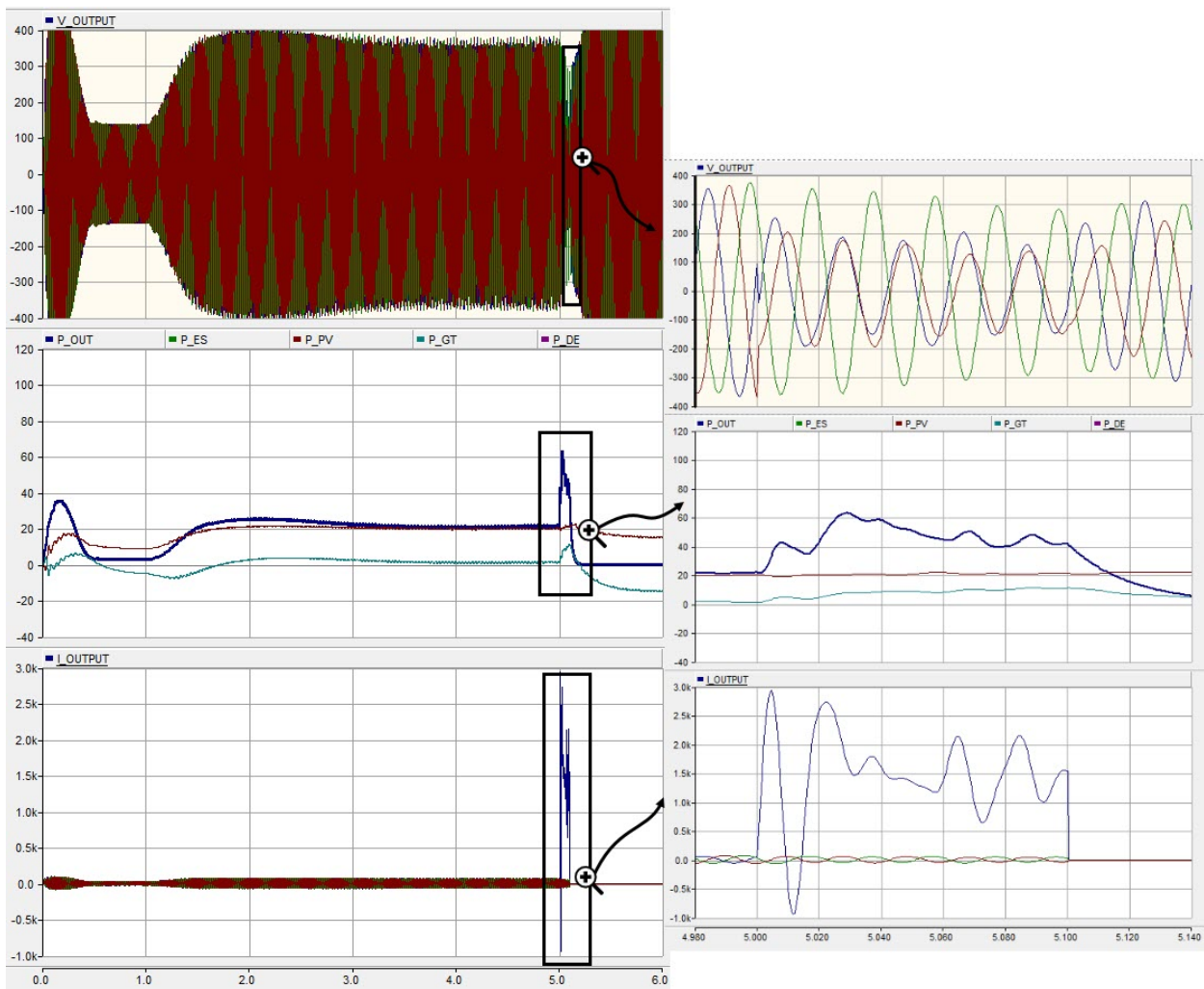
Figure 4.16: Islanded Mode. Mono-phase to ground fault

not extinguish until circuit breaker is opened.

4.5.4 Grid connected. Three-phase to ground fault

In this simulation, a three-phase to ground fault is applied at point of time $t = 5.0 \ s$, when the system has reached the steady state. Fault is applied during 0,1 s.

In the figure 4.20, is shown occurs an acceleration of the gas turbine qhen the circuit breaker has opened, because the power flow goes from the external source to the PMSM of the Gas Turbine. This produces a bad behaviour of the Gas turbine, and provokes a peak in the output power. For that reason, it is necessary in a fault to open all the circuit breakers in a fault, or to not allow the power flow from the external source.
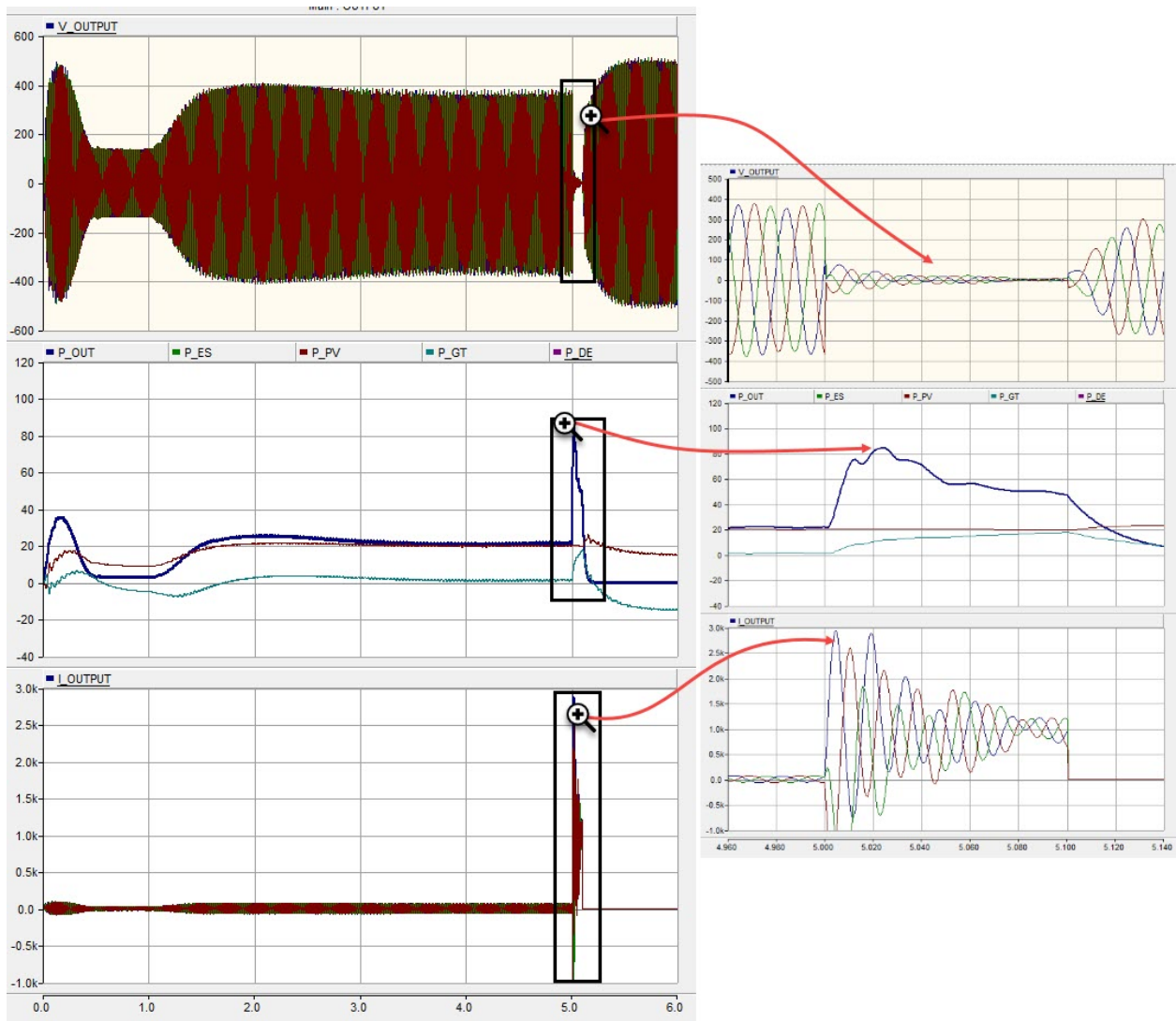
Figure 4.17: Islanded Mode. Three-phase to ground fault
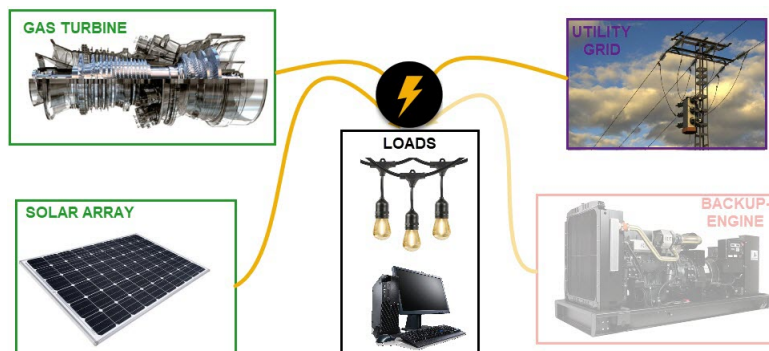
Figure 4.18: Schematic of the Case of Study 9
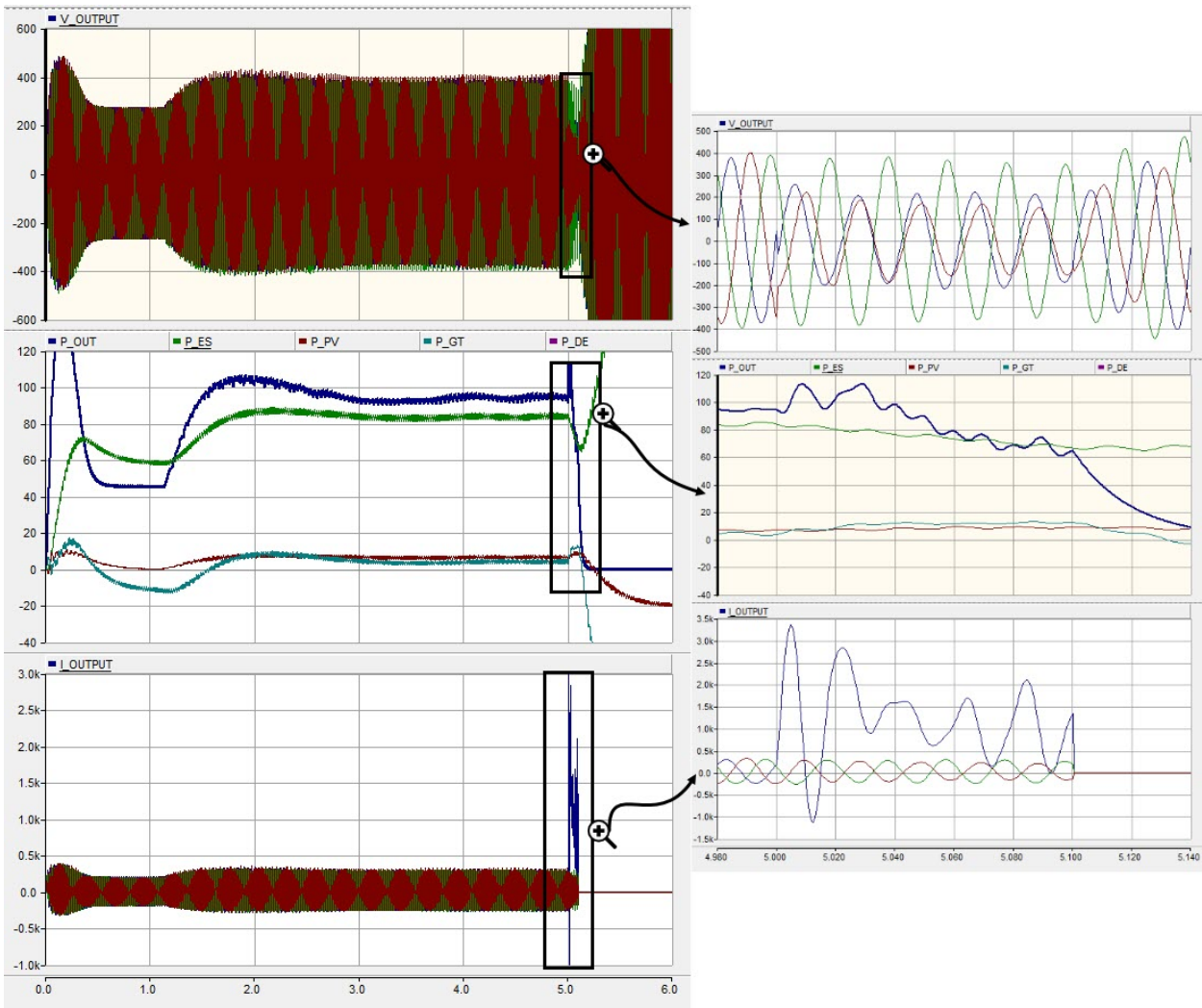
Figure 4.19: Grid connected Mode. Mono-phase to ground fault

Current peak is about 2.5 kA, in the three phases, the voltage droops, the phase changes.

4.5.5 Emergency situation. Mono-phase to ground fault

In this case, fault is applied when system is under emergency situation. Fault is applied during 0,1 s when the system has reached the steady state, at point of time $t = 7.0\ s$. Diesel Engine is supposing to be generating 275 kW of power. Figure 4.21.

The peak current generated by the fault is about 9,5 kA, and occurs 0.01 s just before the fault occurs. This peak is only produced in the phase A, the rest of the phases are maintained at lower values of the current. This is shown in the figure 4.22.
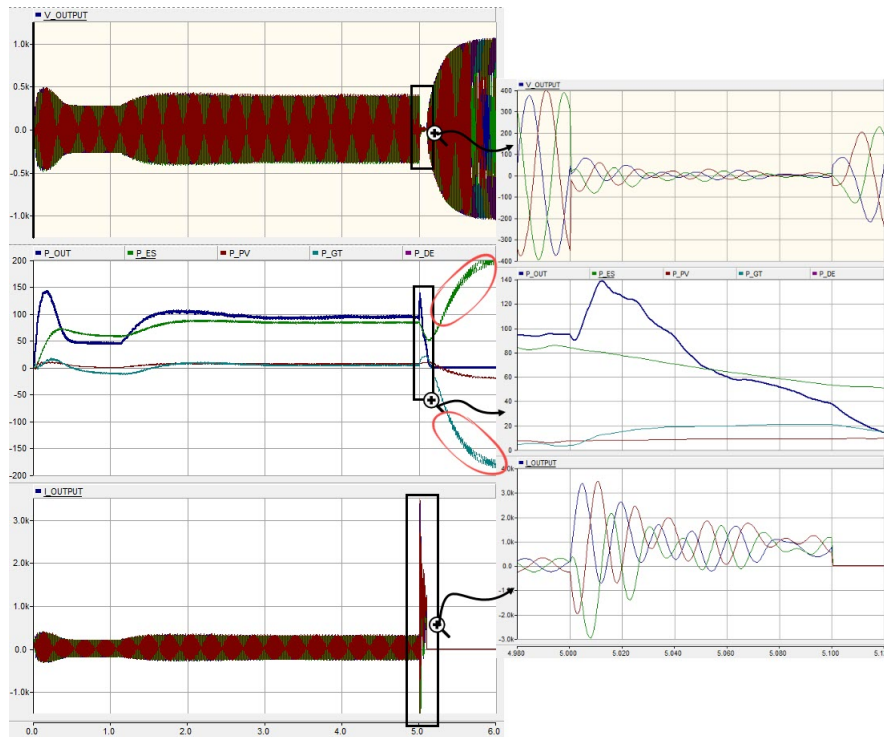
Figure 4.20: Grid connected Mode. Three-phase to ground fault
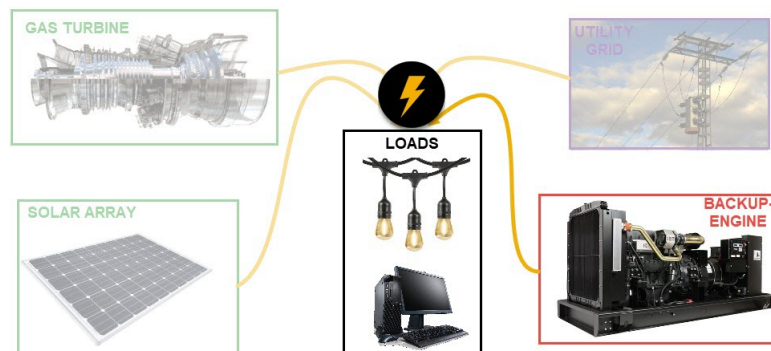
Figure 4.21: Schematic of the Case of Study 10

4.5.6 Emergency situation. Three-phase to ground fault

In this case, fault is applied when system has reached the steady state during 0,1 s at the time point $t = 7.0$ s. As can be shown in the figure 4.23, the peak of current in the three phases is about 6.0 kA, voltage droops rapidly as the values of current too.

This occurs due to the acceleration of the diesel engine when the fault occurs. Power output increases what increase the output current, provoking a peak current of about 6 kA.
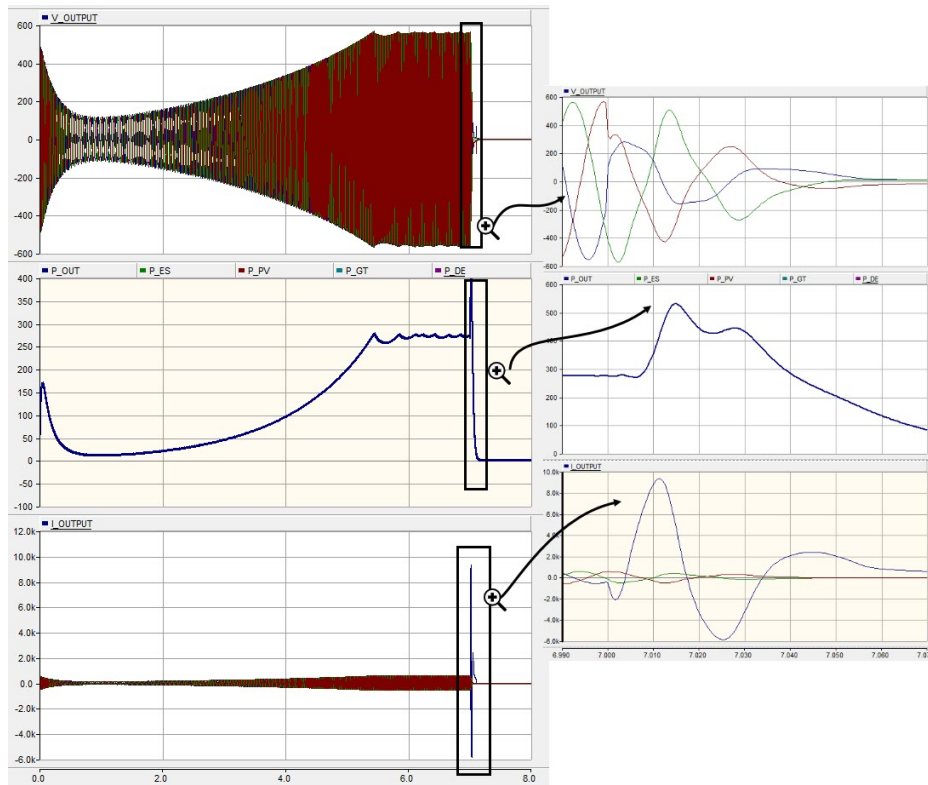
Figure 4.22: Emergency situation. Mono-phase to ground fault
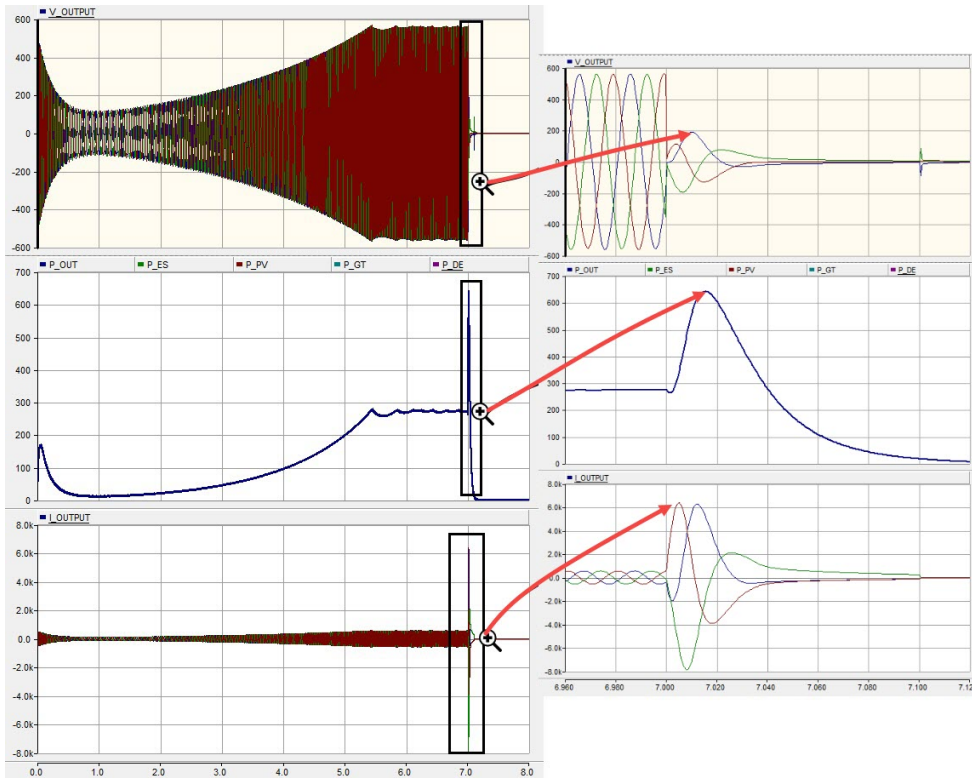
Figure 4.23: Emergency situation. Three-phase to ground fault

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Chapter 5

Results Analysis and Conclusions

5.1   Introduction

In this chapter is done a results analysis of the microgrid simulated in Chapter 4. After modelling all the system and simulate several working cases of the microgrid, it is necessary to done a Result Analysis over the data obtained.

First is going to be analyzed the results obtained when the system is simulated under normal working conditions. Then, an analysis of the results obtained under fault conditions is done. At the end of the chapter, conclusions are drawn, both in English and Spanish language. Then, some futures lines of work are explained.

5.2   Result Analysis

5.2.1   Microgrid working under normal and emergency conditions

Normal working conditions

In chapter 4 is shown how the systems behaves when is connected to the main grid and when works under islanded conditions. First is described the scenario simulated for normal conditions and then, emergency conditions.

The first case of islanded grid simulated correspond to the scenario when there are enough solar radiation to fulfill power demand, and no other source power is needed. In that case, settling time is reached in less than 1 cycle.

The second case of islanded grid correspond to the scenario when there is no solar energy available and the price of the external power is higher than the price of the gas turbine

generation. Settling time is reached in about 5 seconds.

The third case of islanded grid simulated correspond to the scenario when there are some solar radiation but it is not enough to fulfill the power demand. Then, if the price of producing energy with the gas turbine is lower than the price of the external electricity, gas turbine is turn on and power is generated. Settling time is reached in about 5 seconds.

Then, there are simulated another three cases considering the external source of power. Fist of that scenarios consider that solar radiation it is not enough to cover all the power demand and that it is cheaper to consume external electricity than produce it using the gas turbine generator. Then, another scenario is considered where solar energy it is no available and due to contract conditions it is not possible to consume all the energy from the external source. The last case consider that both solar energy and gas turbine is needed to cover the demand. All of the cases a 400 V line to line voltage is obtained in steady state with a frequency of 50 Hz, allowing the correct operation of the different loads connected in the microgrid. Figure 4.6 shown high rate of disturbance in the power output of the gas turbine and photovoltaic array, that is because of the "Smooth constant" of the multimeter. Output power is measured with a higher smooth constant.

On the other hand, results shown that there is much quicker to act over the Photovoltaic Array than doing it over the Gas Turbine. Fist exhibit a quicker settling time. This is because of the simpler functionality of the solar array. In the working principle of the gas turbine, there are much more elements involved, and this has consequences in the settling time of the whole system. Even, the PMSM can also consume power of the grid in the starting sequence.

Emergency working conditions

When there is no possibility of using any of the sources that microgrid has, a backup diesel engine takes into action. This allow to the system to recover from a failure. Figure 4.14 of the chapter 4 shown how the system is recovered from a zero. System reach the settling time in less than 6 seconds exhibits a line to line voltage of 400 V and 50 Hz. Fluctuations shown that this is not a solution for normal working conditions. Diesel engine has to be used only under this kind of circumstances and for short periods of time.

5.2.2 Microgrid working under fault conditions

The most relevant value that can be obtained of this simulation is the peak of the current in the fault. This is necessary in order to select correctly a circuit breaker. The value of the peak of the current has to be the minimum value of the power of the active current breaking capacity of the circuit breaker.

Table 5.1 shows the values of the peak of the current for all the case of the study considered in the chapter 4.

Case of Study	Type of fault	Peak current (kA)
Islanded Mode	Mono-phase to ground	3 kA
Islanded Mode	Three-phase to ground	3 kA
Grid connected	Mono-phase to ground	3,5 kA
Grid connected	Three-phase to ground	2,5 kA
Backup Generator	Mono-phase to ground	9,5 kA
Backup Generator	Three-phase to ground	6 kA

Table 5.1: Peak current for different simulations

In table 5.1 is shown that the situation when the peak of the current is greater is when a mono-phase to ground fault is applied to the microgrid when only backup generator is working. In this case, the peak of the current reaches value of 9,5 kA. Circuit breakers has to be selected taking this result in mind.

5.3 Conclusions

In this section, conclusions are drawn, first is going to be explained the general conclusions of the simulations done and about the software. Then specific conclusions are explained about different simulations done.

5.3.1 General Conclusions

- **About the software:** PSCAD is a software that can develop simulations solving differential equations, what is called Electromagnetic Transients including Direct Current (EMTDC). Also it is a visual programming software as it is possible to declare the different element using blocks. As advantages can be cited:

– Quickly simulations: Solve quickly large scale problems.

– Large element library: Has enough elements declared in the default library to accomplish most difficult and large scale problems.

– Customizable: It is possible to declare personal blocks in order to develop functionalities that are not set up by default in the software.

– Large examples library: It is possible to learn how to use the different libraries of the software using the examples library both online and offline.

But, on the other hand, the software has several drawbacks that has to be keeping in mind while simulating:

– Debugging: This software has almost no debugging tool, and the messages error are so complicated to understanding at first sigth. Debugging consumes the most part of the development of a functional model in this software.

– Aimed to large scale power systems: Most of the default parameters are aimed to simulate large scale power system, making harder the simulations when medium or short scale real problems are involved.

– Power Electronics: This part of the library is almost no developed, and it is difficult to simulate this part of the electrical engineering. It is necessary to develop every single part of a converter. This is very time consuming.

- **About the simulations:** It has been possible to accomplish several functional simulations that represent the different situations. In all this simulations has been possible to reach the steady state, with correct working conditions (400 V line to line voltage and 50 Hz). Also it has been possible to simulate fault system under fault conditions, analyzing how the system behaves when a mono-phase to ground and three-phase to ground fault are applied.

5.3.2 Specific Conclusions

- **Normal working conditions:** Both in islanded mode and grid connected, a quicker response in shown by the microgrid when only the photovoltaic array is working. When gas turbine is working, the settling time increases up to 5 seconds. It is necessary to say

that this is not implies a worst microgrid functionality, because with the gas turbine it is possible to control the power output and with the photovoltaic array it is not that easy.

- **Emergency working conditions:** Under this circumstances, microgrid reaches correct values of functionality in steady state. The settling time increases up to 7 seconds, and the value of the line to line voltage may vary between 0,95 and 1.05 pu. This is acceptable as far as the conditions are not maintained in the time during large periods of time, because of the durability of the different loads present in the microgrid.

- **Fault conditions:** After simulating the whole system under different fault conditions, results drawn that the top of the peak of the current occurs when system is under emergency situation and a mono-phase to ground fault occurs. The value of the higher peak of the current is 9,5 kA, and that is important in the selection of the minimum value of the active current breaking capacity of the circuit breaker.

5.4   Conclusiones

En esta sección se van a exponer las conclusiones del trabajo. En primera instancia se van a explicar las conclusiones generales sobre el programa y las simulaciones llevadas a cabo. Tras esto, se van a explicar varias conclusiones específicas sobre las simulaciones realizadas.

5.4.1   Conclusiones generales

- **Sobre el software:** PSCAD es un programa en el que se pueden resolver distintas ecuaciones diferenciales sobre sistemas eléctricos, lo que usualmente es llamado Electromagnetic Transient including Direct Current (EMTDC). Además, es un programa orientado a la programación visual en el que se puede modelar cada elemento como un bloques. Varias ventajas pueden ser citadas:

  - Simulaciones rápidas: resuelve con gran velocidad problemas de gran embergadura.
  - Amplia librería: las librerías por defecto del programa son suficientes para completar simulaciones de gran complejidad.

– Personalizable: Es posible la introducción de bloques customizables que desarrollen funcionalidades que no están disponibles por defecto en el software.

– Amplia librería de ejemplos: es posible aprender cómo utilizar las diferentes librerías del programa mediante el uso de los ejemplos que existen tanto online como offline.

Pero, por otro lado, este software tiene algunas desventajas que se citan a continuación, las cuales hay que tener en cuenta cuando se simula:

– Depuración: El software apenas tiene herramientas de depuración, y los mensajes de error son complicados de entender de un vistazo. Depurar el modelo realizado consume gran parte del tiempo invertido en la creación de un modelo funcional en este software.

– Orientado a sistemas de gran escala: la mayoría de los parametros por defecto están orientados a sistemas de gran potencia, lo que dificulta la simulación de sistemas a mediana o pequeña escala.

– Electrónica de potencia: esta parte de la librería del programa no está totalmente desarrollada, y es complicado poder simular esta parte de la ingeniería eléctrica, ya que es necesario desarrollar cada elemento de, por ejemplo, un convertidor. Consume gran parte del tiempo de uso del programa.

• **Sobre las simulaciones:** Ha sido posible completar varias simulaciones funcionales que representen distintas condiciones de funcionamiento. En todas estas simulaciones, ha sido posible llegar al régimen permanente con unas correctas condiciones de funcionamiento (400 V de línea y 50 Hz). También, ha sido posible simular distintas faltas bajo distintas condiciones de funcionamiento, analizando cómo se comporta el sistema cuando una falta monofásica tierra o trifásica ocurre.

5.4.2   Conclusiones específicas

• **Concidiones normales de funcionamiento:** Tanto conectado a la red principal como en modo aislado, se ha obtenido mejores tiempo de respuesta cuando únicamente funciona las placas solares y la turbina de gas no entra en acción. Cuando lo segundo

ocurre, el tiempo de establecimiento aumenta hasta los 5 segundos. Es necesario tener en cuenta que esto no implica un peor funcionamiento, ya que mediante el uso de una turbina de gas es posible regular la producción de potencia mientras que con el generador fotovoltaico no es tan sencillo.

- **Condiciones de emergencia:** Bajo estas circunstancias, la microrred alcanza valores correctos en cuanto a la funcionalidad en régimen permanente. El tiempo de establecimiento es de 7 segundos y la tensión de línea varía entre los 0,95 y 1,05 pu. Esto es aceptable siempre y cuando estas condiciones no se mantengan durante grandes periodos de tiempo, porque puede afectar a la durabilidad de las distintas cargas presentes en la microrred.

- **Condiciones de falta:** Después de simular el sistema completo bajo condiciones de falta, los resultados indican que el pico más alto de corriente ocurre cuando el sistema se encuentra bajo condiciones de emergencia y una falta monofásica tierra ocurre. El valor del pico de intensidad alcanzado bajo las condiciones expuestas alcanza los 9,5 kA. Este valor ha de ser tenido en cuenta a la hora de seleccionar el poder de corte del interruptor automático.

5.5 Future Lines of Work

In this section, future lines of work are drawn. This thesis open other lines of work, in the power system simulations:

- **Development of peer to peer controlling:** In this thesis, power output of the different parts of the microgrid are made without any automatically technique. There are several bedtests where this kind of control are tested obtaining good results. It is consist in create an interface that controls the amount of power generated by each element keeping in mind different operativity conditions, as economically options, predictions, etc.

- **Development of higher accuracy power converters:** In this thesis, power converters modelled and simulated are very simple, there are new techniques, as the vectorial

control, that allows better performance in this elements. It would be very interesting to do a comparison between PWM technique (followed in this thesis) and vectorial control.

- **Development of a testbed for a microgrid:** It is possible to complete a testbed for a simpler microgrid system. This would allow to the student to compare results between the reality and the simulation.

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Appendix A

Budget

A.1 Introduction

In this appendix is going to be explained the budget necessary to achieve all the objectives setted up in the first chapter. Budget is decomposed in several parts: Computer equipment, Human resources, Material resources.

A.2 Computer equipment

In this section is detailed the part of the budget related to computer resources, both software and hardware. This detailed budget is shown in the table A.1.

Concept	Units	Unity price(€/unit)	Total base price (€)
Overleaf license	1	0	0
PSCAD/EMTDC license	1	10.000	10.000
Computer (MSI GP70 2QF)	1	825,62	825,62
Windows 10 license	1	113,31	113,31
Total price			10.938,93
IVA(21%)			2.297,18
Total			**13.236,11**

Table A.1: Computer equipment

As shown in table A.1, this part of the budget ascend to THIRTEEN THOUSAND, TWO HUNDRED AND THIRTY SIX EUROS AND ELEVEN CENTS.

A.3 Human resources

In this section is detailed the part of the budget related to the human work hours, considering both the student work and the mentor and co-mentor work. This is an orientation of the number of hours worked to complete this thesis:

Concept	Units	Unity price(€/unit)	Total base price (€)
Student	300	10	3.000
Mentor	20	50	1.000
Co-Mentor	20	30	600
Total price			4.600
IVA(21%)			966
Total			**5.566**

Table A.2: Human resources

As shown in table A.2, this par of the budged ascend to FIVE THOUSAND, FIVE HUNDRED AND SIXTY SIX EUROS.

A.4 Material resources

In this section is detailed the part of the budget related to the material cost of implementing the whole. This is, the printing price of the thesis, approximately.

Concept	Units	Unity price(€/unit)	Total base price (€)
Printing pages	150	0,4	60
Blueprints	1	5	5
Cover	1	10	10
Total price			75
IVA(21%)			15,75
Total			**90,75**

Table A.3: Material resources

As shown in table A.3, this part of the budget ascend to NINETY EUROS AND SEVENTY FIVE CENTS.

A.5 Resume

In this section, a general resume of the whole budget is done:

Concept	Total price (€)
1. Computer equipment	13.236,11
2. Human resources	5.566
3. Material resources	90,75
Total	**18.892,86**

Table A.4: Complete Budget

As shown in table A.4, complete budget of the thesis is EIGHTEEN THOUSAND, EIGHTY HUNDRED AND NINETY TWO EUROS AND EIGHTY SIX CENTS .

Sdg. Ángel Paredes Parrilla.

APPENDIX A. BUDGET

Appendix B

PSCAD User Guide

B.1   Introduction

In this appendix is going to be introduced the software used for modelling and simulating the microgrid. Fist of all, most important features of this software is going to be introduced by explaining the different aspects of the user interface: How to create a new workspace, a new project, how to deal with the different libraries, etc. And then, how to carry out a complete simulation of a simpler schematic.

B.2   User interface. The basics

Opening PSCAD, by clicking in the top right menu, it is possible to access to the option that are shown in figure B.1. It is possible to select one of the three options that are shown.
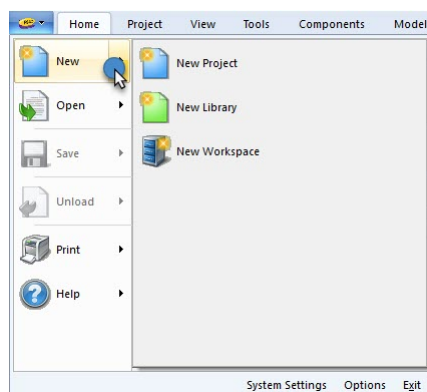
Figure B.1: Creating a new project and workspace in PSCAD

By clicking in "New Workspace", it is possible to obtain the window shown in figure B.2. First tab that appears is "Master library tab", from here it is possible to access to the different

libraries available on PSCAD/EMTDC.
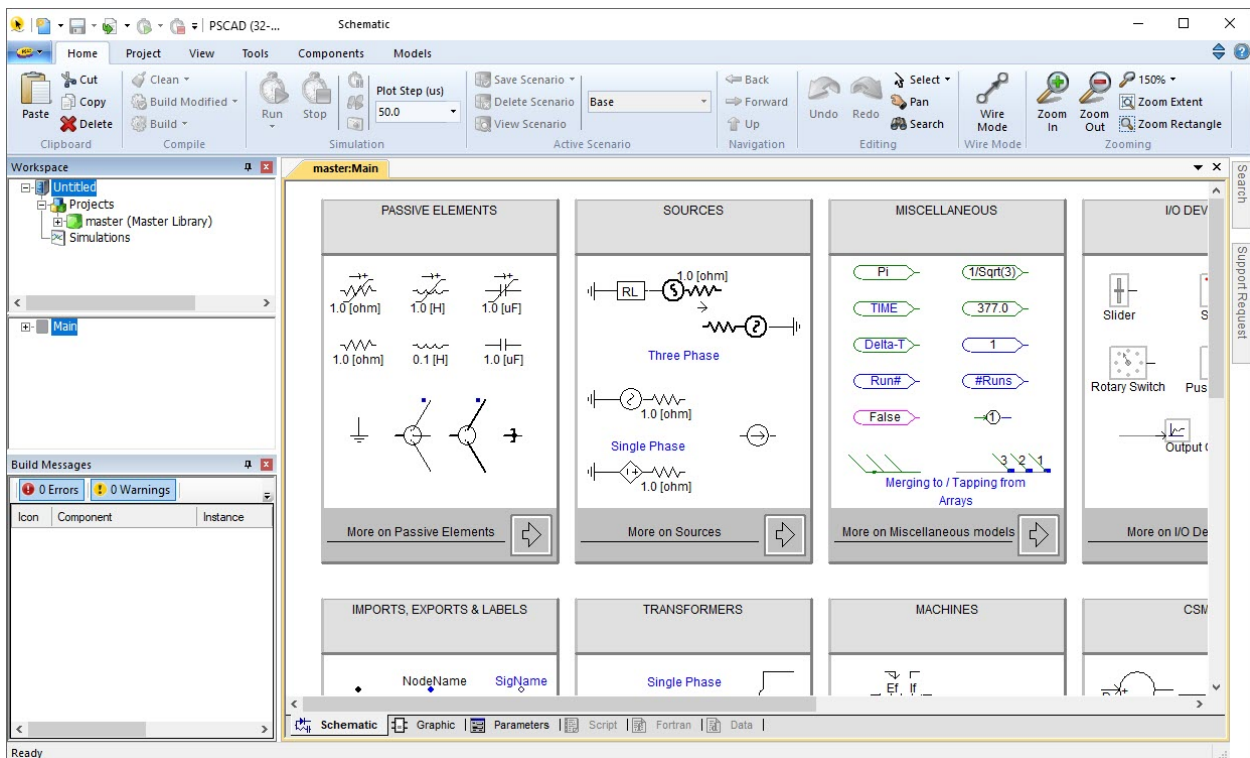
Figure B.2: New Workspace window on PSCAD

There are several libraries available on PSCAD, as can be shown in the figure B.2.

- Passive elements: Resistors, inductors, capacitors, etc.

- Sources: AC Voltage source, DC Voltage source, AC current source, DC current source, etc.

- Miscellaneous: Number π, number of runs, etc.

- I/O Devices: Meters, switches, elements that allow to the user to interact with the system while system is running.

- Breaker and faults: Circuit breakers, fault control, etc.

- HVDC, Facts and Power Electronics: Diodes, IGBT's, etc.

- Import, Export and labels.

- Transformers: three phase transformer, etc.

- Machines: PMSM, DC Machine, etc.

- CMSF: And, or, multiplier, etc.

- Transmission Lines: Modelling of aerial electric power lines.

- Cables: Modelling of cables.

- Meters: Current meter, Multimeter, etc.

- Protection

- External Data Recorders and Readers

- Sequencers: Elements that allows to execute a sequence when, for example, a fault occurs.

- Logical: AND, OR, XOR, XNOR Gate, etc.

- Pi sections: Pi circuit of a power transmission line.

By clicking twice on the arrows of each library, it is possible to access to the complete list of elements available. In order to use one element of the library, it is necessary to start a new project by clicking in "New Project". Figure B.1. Then, a dialogue window like shown in figure B.3 appears, and it is necessary to type the name the project will have, in this case "Example", and the path where it would be saved.
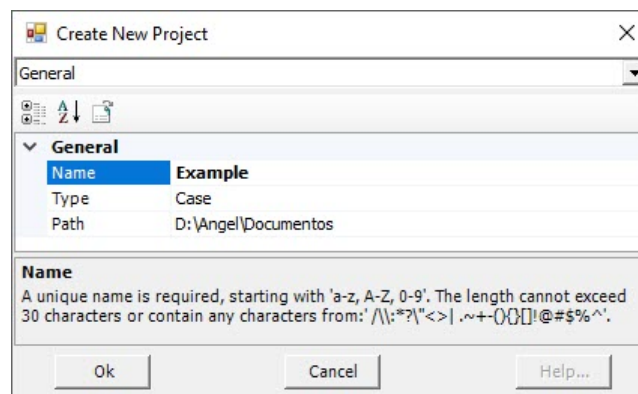
Figure B.3: New Project

Then, it will appears a blank window, like shown in figure B.4. In this window it is possible to interact with the principal toolbar which have six tabs: Home, Project, View, Tools, Component and Models.

- Home: In this bar tab it is possible to interact with the most relevant tools of the programme: Zoom, Run a simulation, Stop a simulation, build a project, etc. Figure B.5.
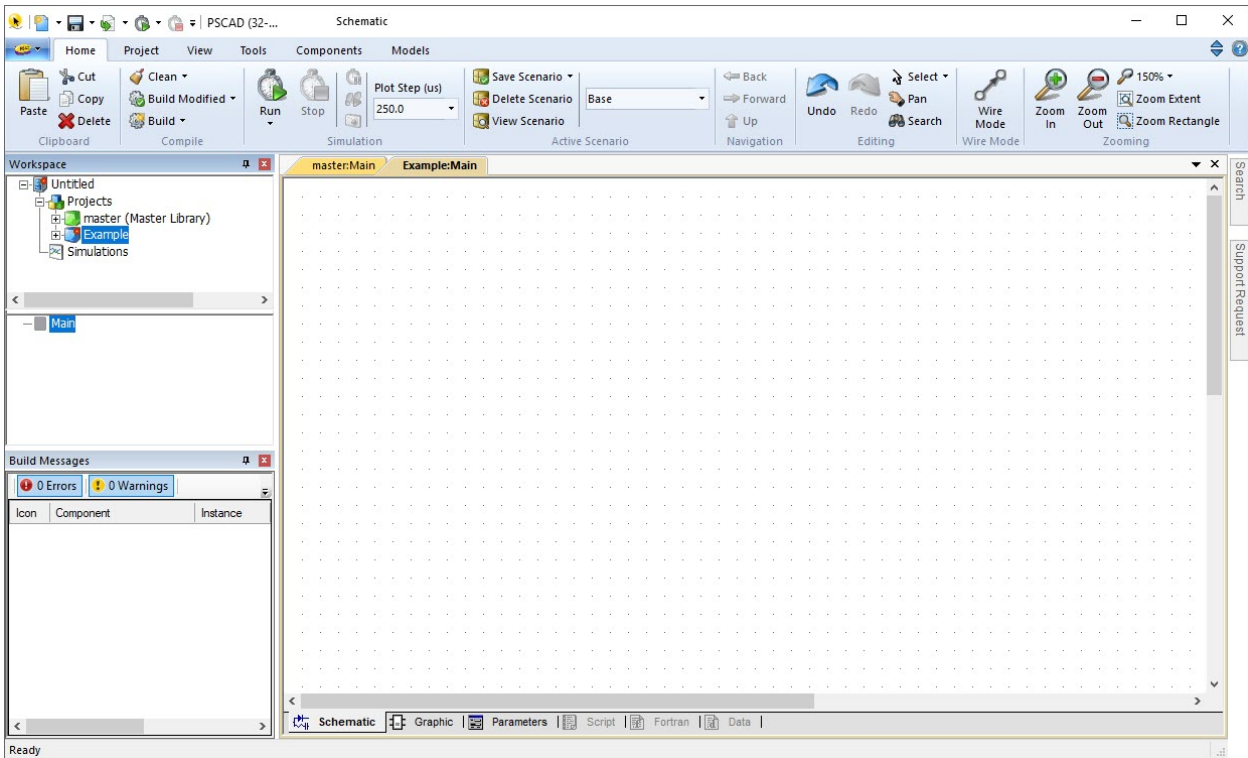
Figure B.4: New Project blank window
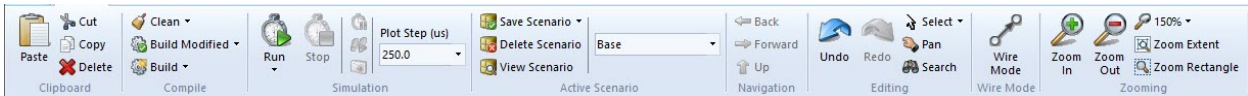
Figure B.5: Home tab

- Project: In this tab it is possible to modify the duration of the run, step time plot or step solution time. Figure B.6.
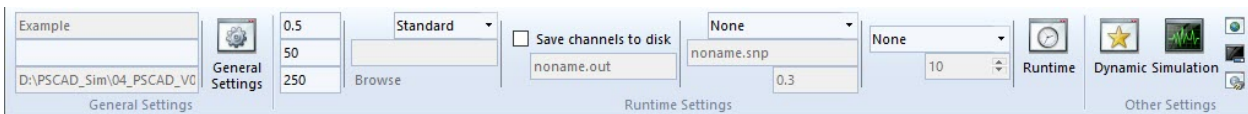

Figure B.6: Project Tab

- View: In this tab it is possible to modify the aspect of the window and the blank workspace. Figure B.7.

Figure B.7: View Tab

- Tools: Only have two low used tools: Medic and LiveWire.

- Component: In this tab it is possible to find the basic component of the PSCAD default library. Figure B.8.

Figure B.8: Component Tab

- Models: In this tab it is possible to find the complete PSCAD default library sorted by categories. Figure B.9.

Figure B.9: Models Tab

To introduce any of the models available in PSCAD in the project just started the only thing to do is selecting it, copying it and paste it into the project. Figure B.10
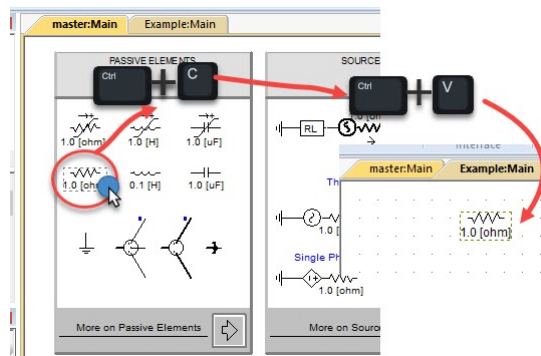
Figure B.10: Introduction of a component into the project

B.3 How to set up an simple simulation

In this section a simple simulation is going to be setted up. The circuit that will be simulated is shown in the figure B.11.

The current I that flows through the resistor is easy to calculate:

$$I = \frac{V_{source}}{R} \tag{B.1}$$
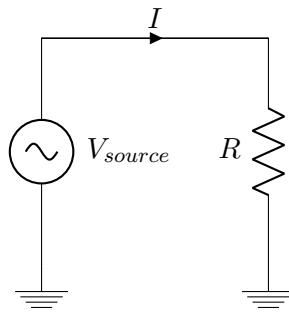
Figure B.11: Schematic of the circuit to be simulated

If $V = 1kV$ and $R = 1\Omega$, then the current $I = 1kA$. In order to complete this simple simulation on PSCAD the process done in the figure B.12 has to be done. It is necessary to copy a Voltage Source from the Sources Library, an Ammeter and the Ground from the tool bar. Then, all is wired using wire mode.
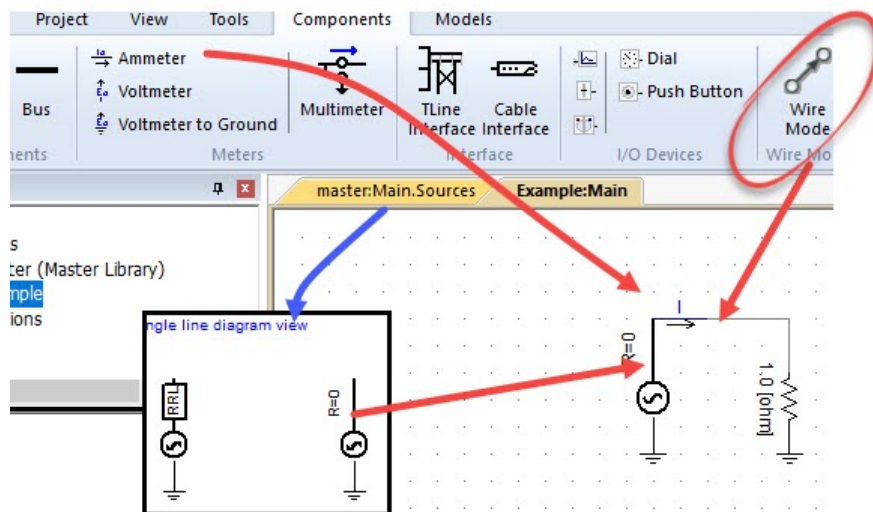

Figure B.12: Construction of the circuit

Then, it is necessary to set up the voltage source as shown in figure B.13.

Then, in order to observe the system respone it is necessary to set up the running time, step time and plot time, all of them available in the Project Tab. They are set as default, for this simulation it is okay. On the other hand, it is necessary to create what it is called an "Output Channel" in order to see how the value of the signal changes. Also, it will be created a plot.

How to set up the Output Channel and the Plot is shown in the figure B.14. First of all
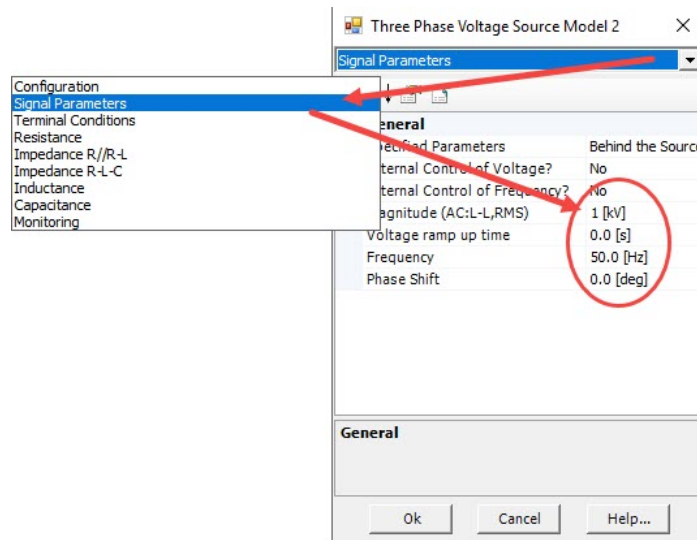
Figure B.13: Characteristic of the voltage signal

it is necessary to copy a Data label from the tool tab. Second step is to copy the Output Channel, and rename it with the name I. Third step is to copy a Graph Panel and instert the grid by clicking on it and push "Insert". Last step is to "Add as a curve" the previous defined Output Channel as shown in the figure B.14.

Figure B.14: How to set up an output channel and a plot

Then, in order to simulate this system it Run button has to be clicked. The output shown in the figure B.15, are in terms of RMS value, and for that reason, the voltage value has to be input as $V = \frac{1}{\sqrt{2}}\ kV$.
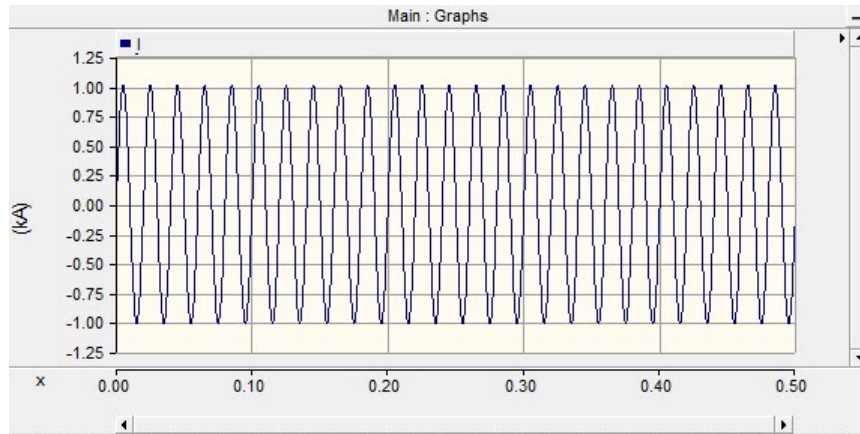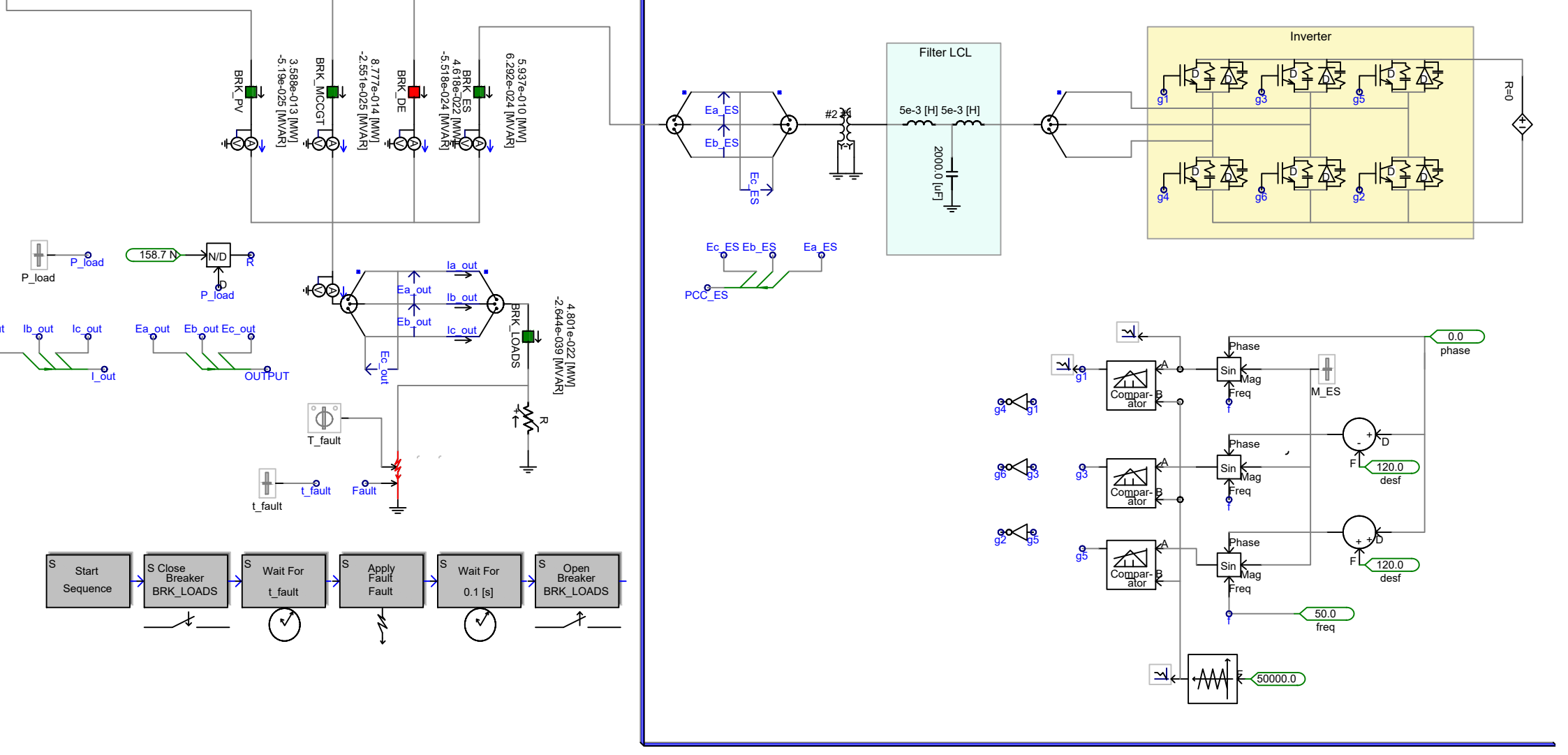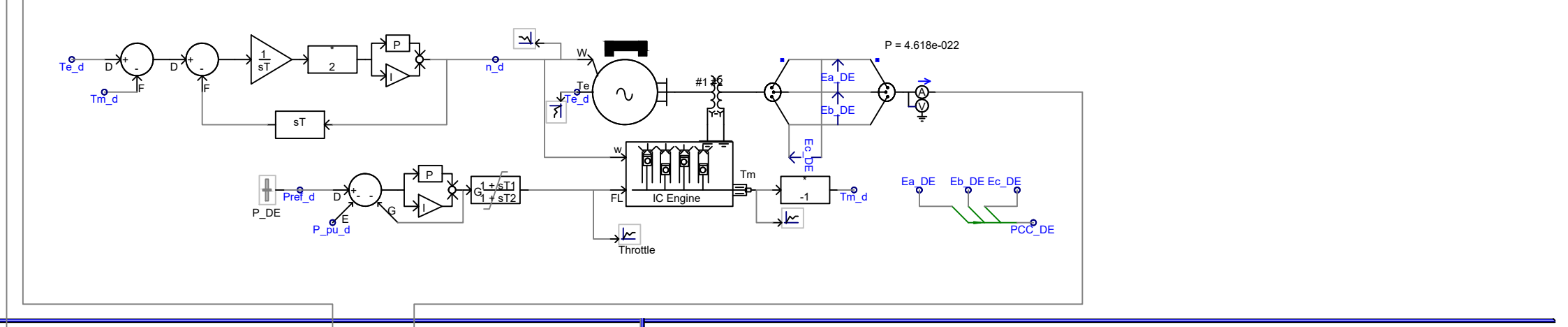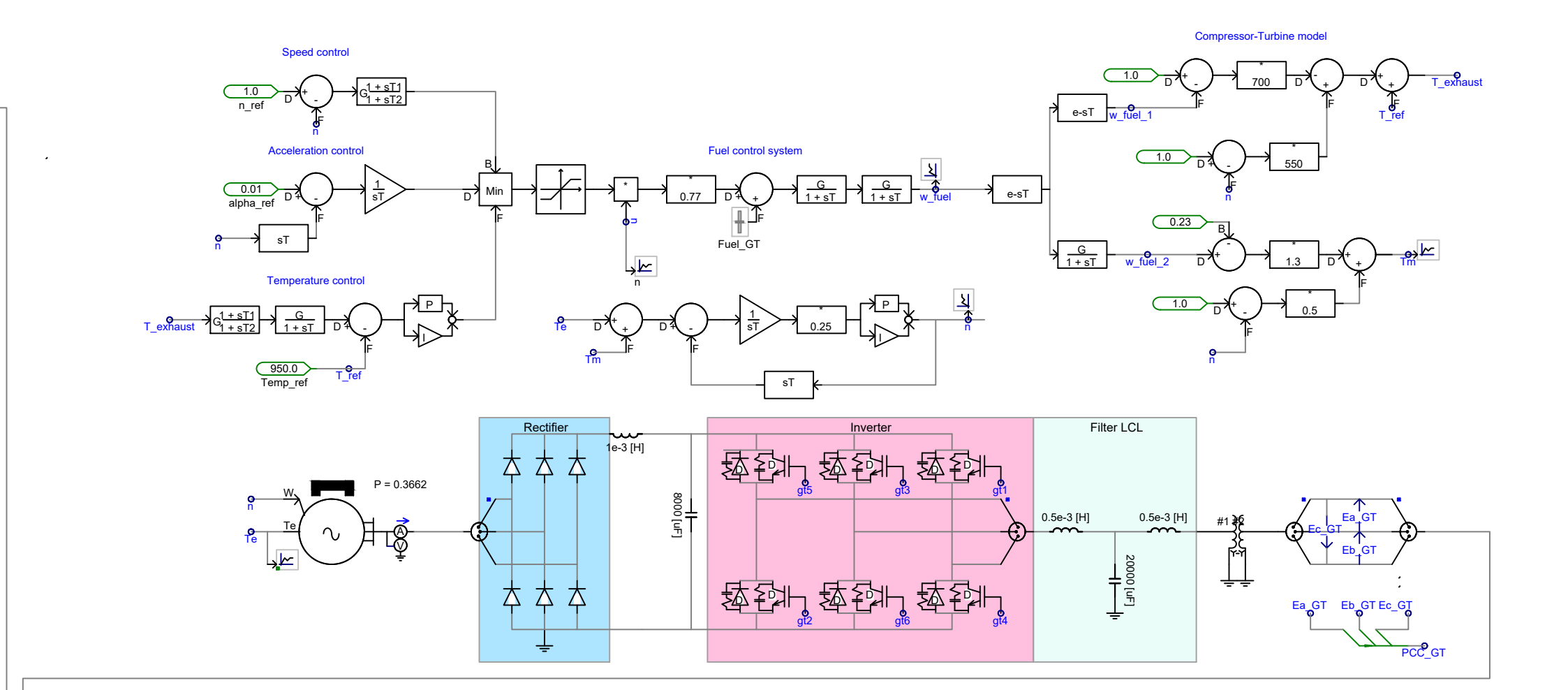

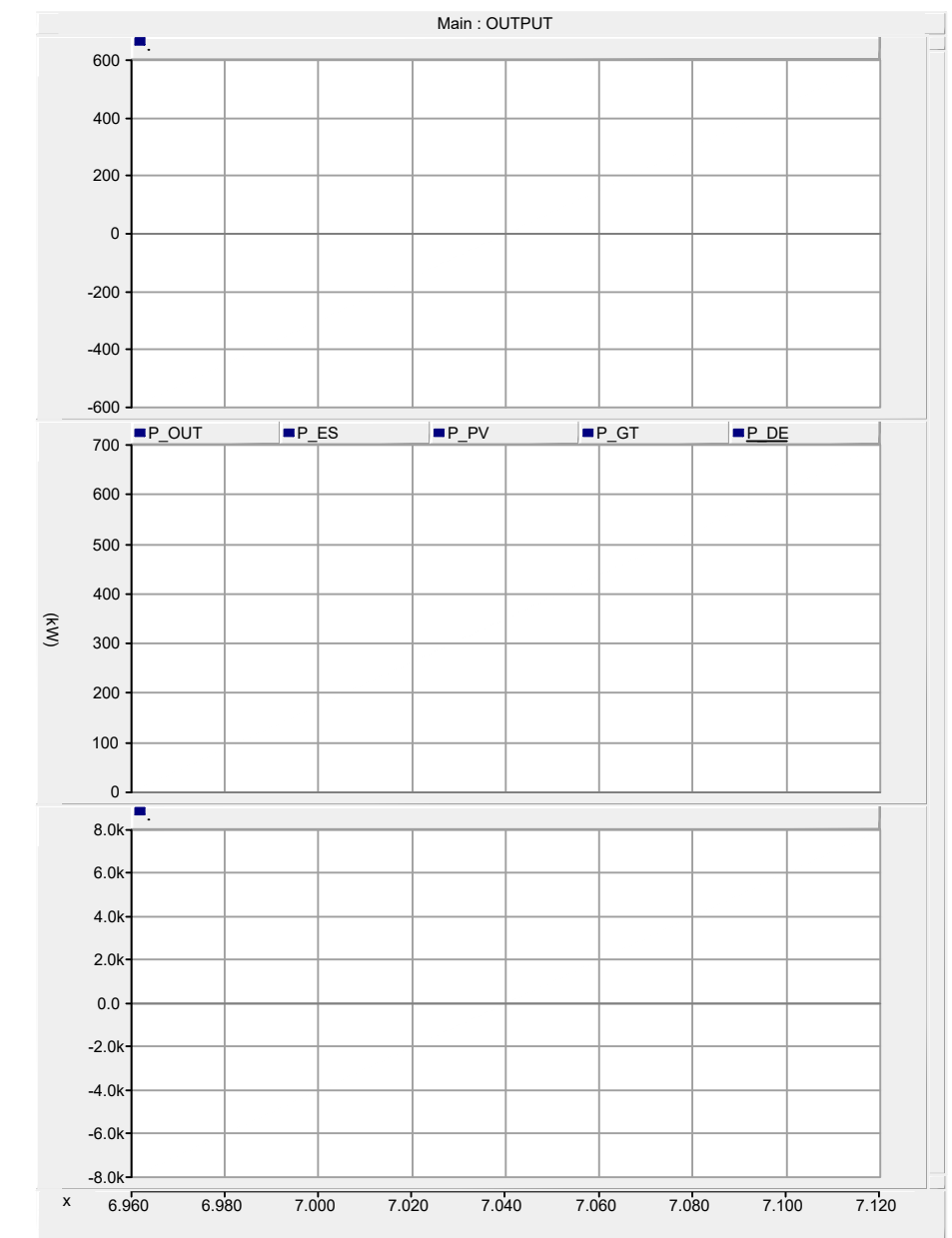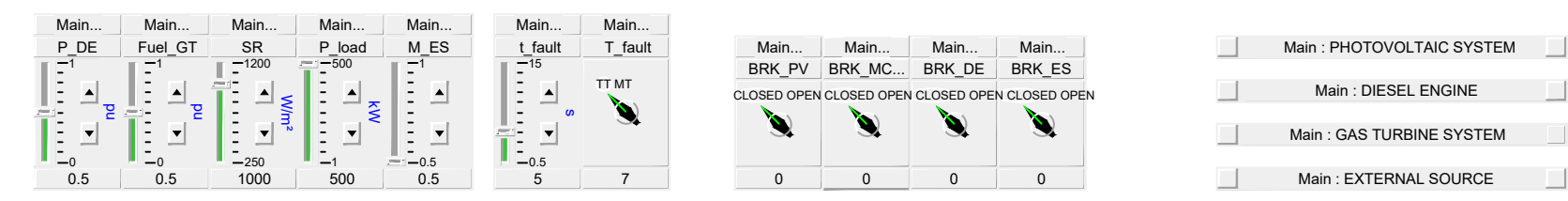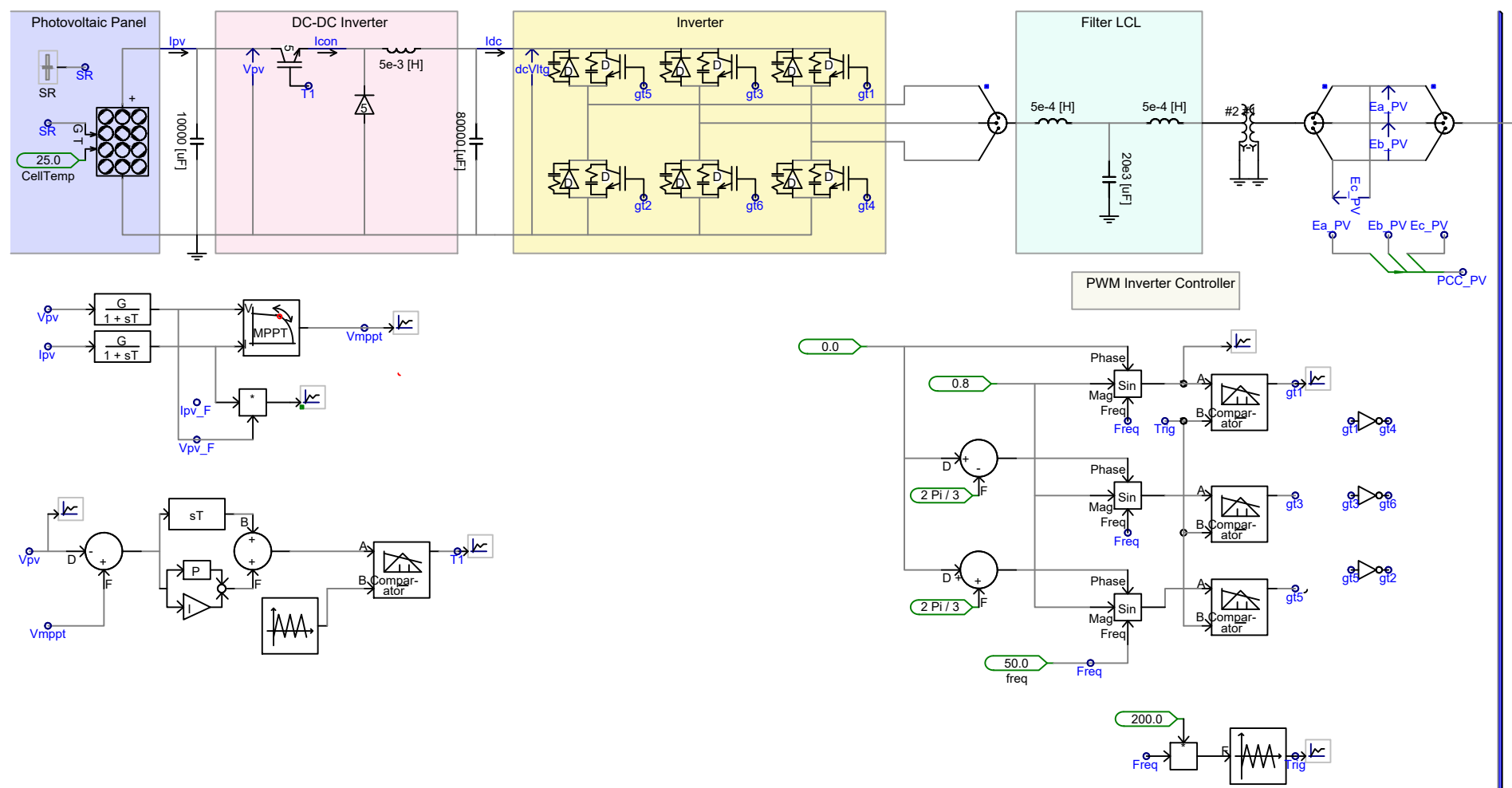Figure B.15: Example simulation

Appendix C

Drawings

C.1 Introduction

In this last appendix drawings are listed. There are only one drawing that represent the whole microgrid system.

1. Drawing N°1: Complete Microgrid Model.

Photovoltaic Panel

DC-DC Inverter

Inverter

Filter LCL

Compressor-Turbine model

PWM Inverter Controller

Speed control

Acceleration control

Fuel control system

Temperature control

Rectifier

Inverter

Filter LCL

Main : PHOTOVOLTAIC SYSTEM

Main : DIESEL ENGINE

Main : GAS TURBINE SYSTEM

Main : EXTERNAL SOURCE

Main : OUTPUT

IC Engine

Start Sequence

Close Breaker BRK_LOADS

Wait For t_fault

Apply Fault

Wait For 0.1 [s]

Open Breaker BRK_LOADS

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Sign

ESCUELA DE INGENIERÍAS INDUSTRIALES
UNIVERSITY OF MÁLAGA

Scale

MODELLING AND ANALYSIS OF HYBRID
MICROGRIDS USING PSCAD/EMTDC

COMPLETE MICROGRID MODEL

DRAWING NUMBER-1