



# GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

Modelling of a fuel cell in a Micro-Grid and its  
respective control algorithm

Autor: Jorge Andrés Roch

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Madrid



Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título Modelado de una pila a combustible en una Micro-Grid y de su respectivo algoritmo de control

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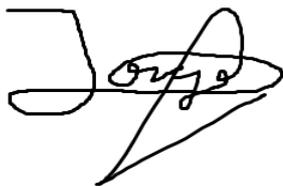
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# GRADO EN INGENIERÍA EN TECNOLOGÍAS INDUSTRIALES

TRABAJO FIN DE GRADO

Autor: Jorge Andrés Roch

Director: Amir Arzandé

Madrid

# Agradecimientos

En primer lugar, quiero agradecer a mi familia y a ICAI por la enorme posibilidad que me han brindado con el doble diploma París-Madrid y también por apoyarme en todo lo que he necesitado.

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Por ultimo muchas gracias a mis amigos, tanto los de Francia como los de España que me han dado el apoyo necesario estos años y que siempre me han ayudado a desconectar.



# MODELADO DE UNA PILA A COMBUSTIBLE EN UNA MICRO-GRID Y DE SU RESPECTIVO ALGORITMO DE CONTROL

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## RESUMEN DEL PROYECTO

A lo largo de este proyecto se ha logrado modelizar el funcionamiento y control de una pila a combustible para que tenga una respuesta estable a una tensión concreta. Además, se ha analizado el sistema de control general de una Micro-Grid y se ha propuesto un modelo sencillo de Matlab que representa el funcionamiento de la Micro-Grid en las diversas situaciones que se puede encontrar. Por último, a través de un análisis económico se discute la viabilidad de estas estructuras en la actualidad y en un futuro cercano.

**Palabras clave:** Micro-Grid, micro-red, pila de combustible, energía, electricidad, suministro, Simulink, Matlab, control, renovables, energía limpia.

### 1. Introducción

Actualmente nos encontramos dos problemáticas muy graves que son necesarias resolver y que acaparan la atención de la ONU. La primera de ellas es la contaminación y el calentamiento global (en gran medida por las emisiones de CO<sub>2</sub>) y la falta de bienes considerados básicos en algunos países como es la electricidad. El Banco Mundial considera que las Micro-Grids pueden ser claves para poner fin a estos dos problemas [1].

### 2. Definición del proyecto

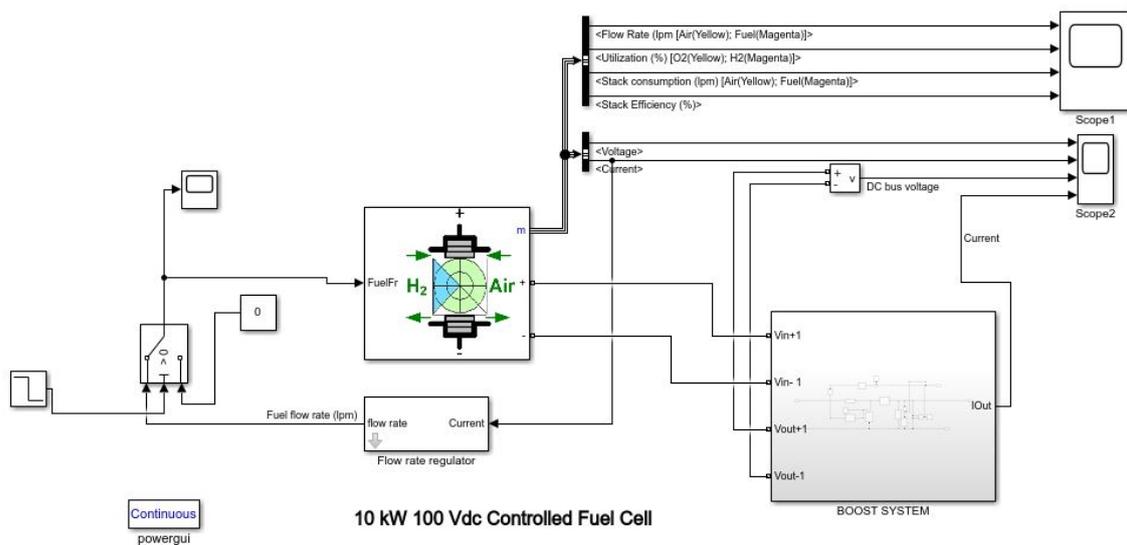
Mediante el programa de modelización “Simulink”, se ha realizado la modelización de una pila a combustible de una potencia concreta y su correspondiente sistema de control para obtener una respuesta rápida, estable y a un valor definido. Posteriormente, se ha analizado los sistemas de control de una Micro-Grid y nuevamente mediante Simulink se ha diseñado un modelo que controla y reproduce su comportamiento ante las diversas situaciones que se pueden dar: producción de energía inferior a la demanda, carga de las baterías con el exceso de energía etc. Además, un estudio económico muestra la versatilidad de las micro-grids y su capacidad de adaptación al entorno y a las necesidades.

### 3. Descripción del modelo/sistema/herramienta

El primer modelo consiste en el acople de una pila de combustible con un sistema de regulación, uno de control y un convertor DC-DC que permitiera aumentar la tensión de salida a los 400V de la red fijados. Para ello, ha sido necesario representar el sistema a la salida de la pila con un sistema de ecuaciones de “Small Signal Variation” [2] del convertor elevador según este en modo abierto o cerrado. Gracias al método de “state-averaging” realizado con el ciclo de funcionamiento, se logra un modelo matemático que representa el comportamiento del sistema. Posteriormente se busca un

punto de equilibrio cercano a las condiciones de trabajo en las cuales va a operar la pila de combustible (100V de entrada al conversor y 400V de salida). Posteriormente, el sistema se linealiza alrededor del punto de equilibrio. Finalmente, se obtiene el bode que relaciona el ciclo de trabajo del conversor con la diferencia entre una tensión referencia (400V en este caso) y la tensión a la salida del sistema y a partir de este, se construye un sistema de control que se asegurara de que exista un buen compromiso estabilidad/rapidez/precision en la respuesta del sistema. En resumen, el controlador diseñado, toma la diferencia entre la tensión de referencia y la tensión de salida del sistema y varía el ciclo de trabajo del conversor para que la salida se mantenga constante a la tensión elegida.

También se ha llevado a cabo un modelo en Simulink de un algoritmo de supervisión, que recibe la demanda esperada cada 15 minutos y es capaz de cambiar el régimen de trabajo de cualquiera de los componentes presentes en la Micro-Grid en cualquiera de las situaciones previstas.



*Ilustración 1 – Esquema en Simulink del sistema completo de la pila de combustible*

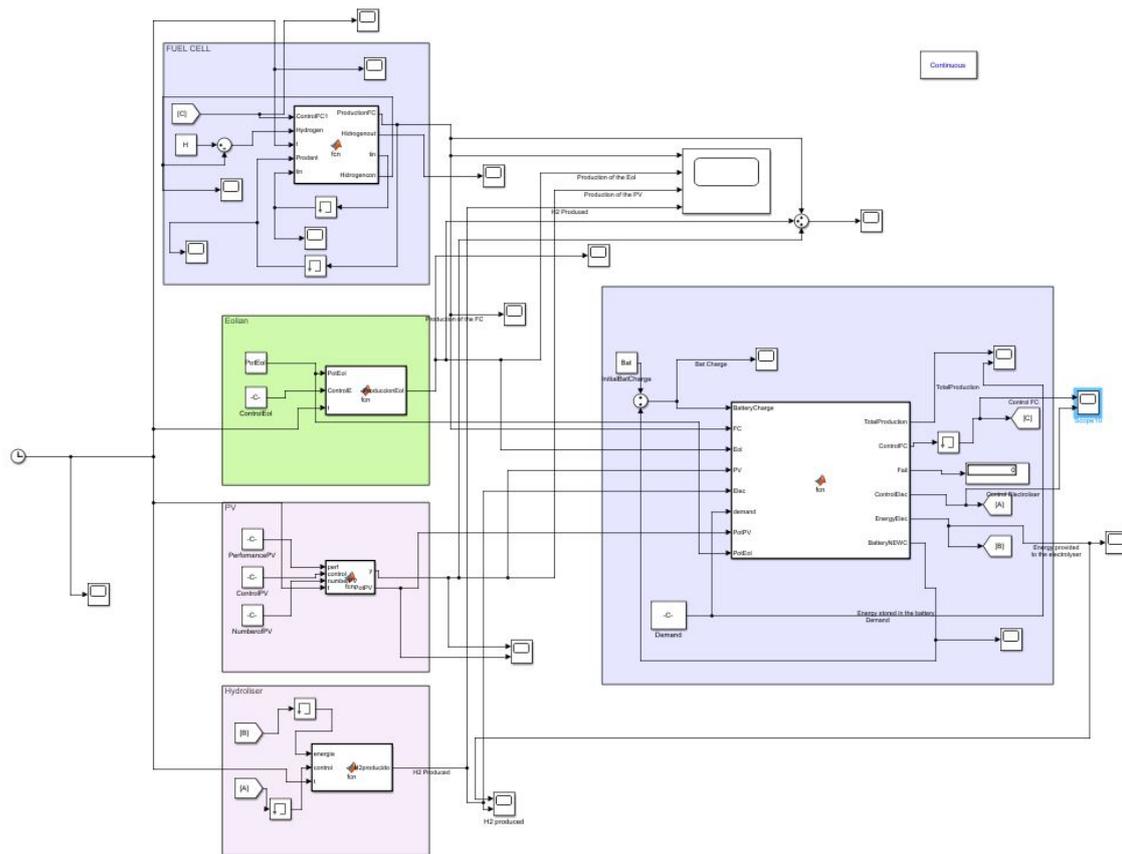
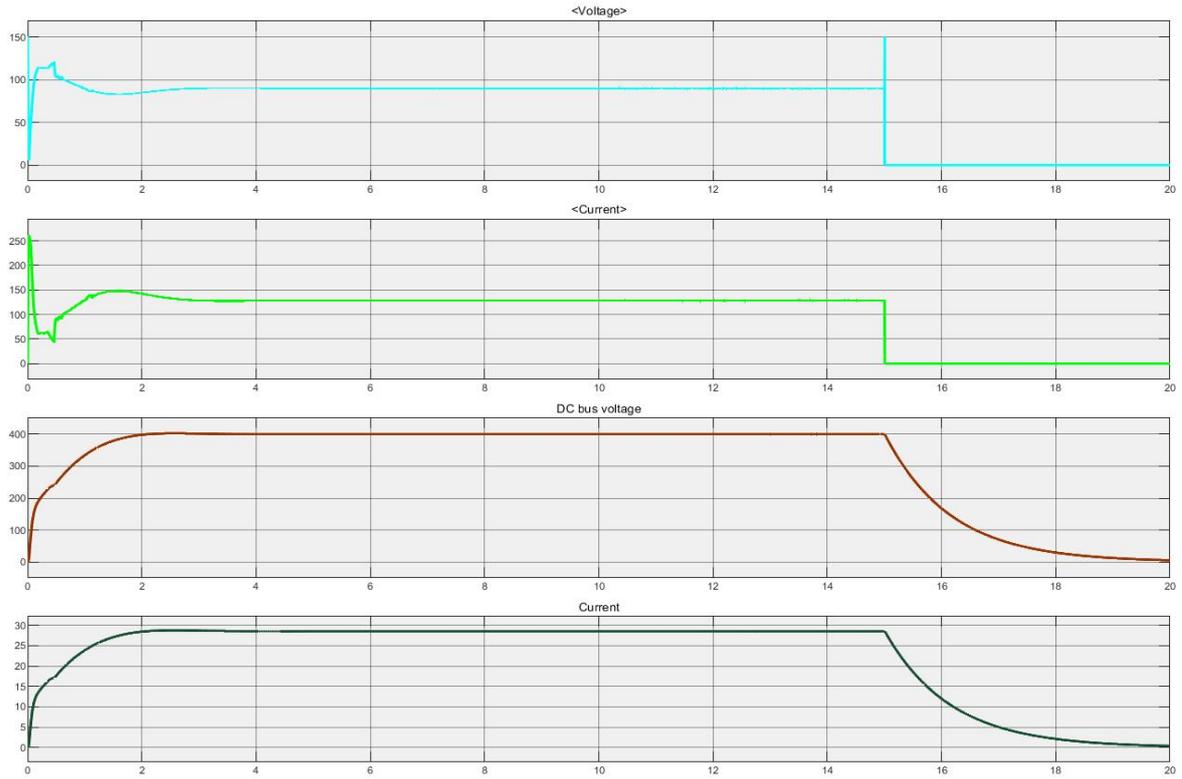


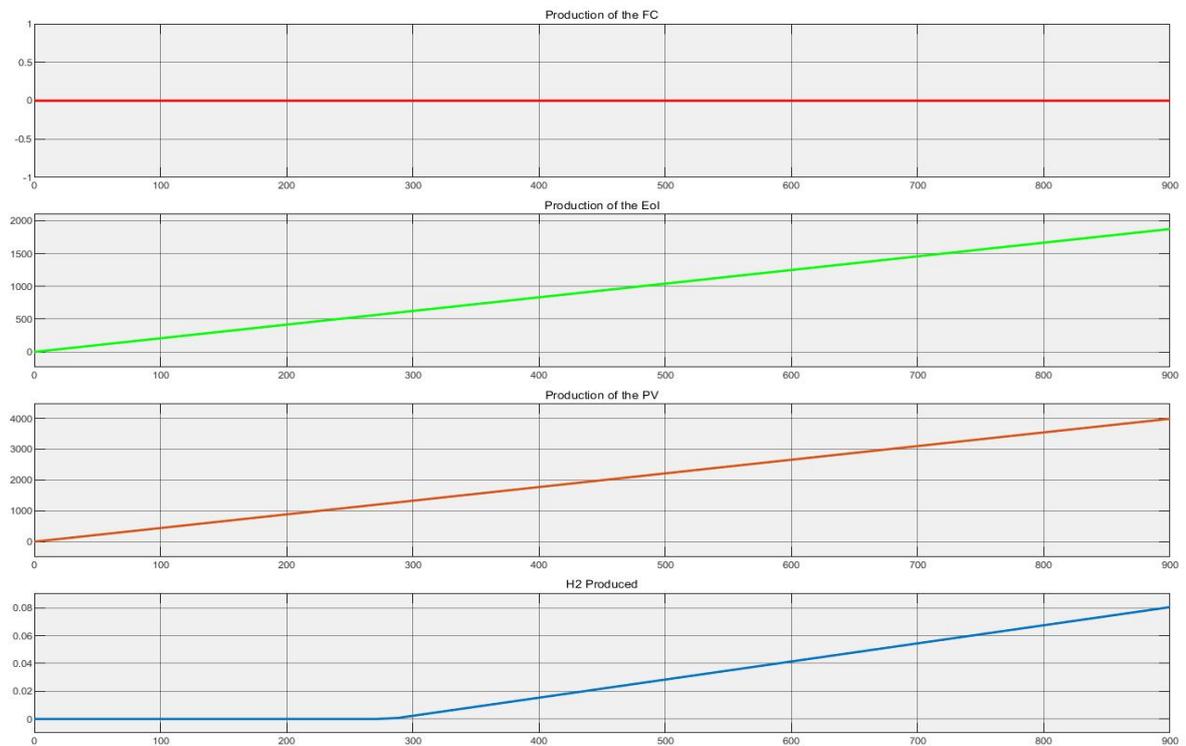
Figure 2 – Modelo en Simulink del algoritmo de supervisión (control) de una Micro-Grid.

#### 4. Resultados

- En cuanto al modelo de la pila que incluye el sistema de control y regulación, se ha logrado hacer funcionar la pila a 400 V estables de salida mediante la utilización de dos sistemas de control diferentes.
- El algoritmo de supervisión regula correctamente la Micro-Grid siguiendo el diagrama de flujo que indica como deben actuar los componentes en cada situación.



*Ilustración 3 – Resultados del sistema pila + convertor + PID (Primer modelo de control). En  $t=0$ , la pila de combustible se pone en funcionamiento y en  $t=15$  se apaga. Las dos figuras superiores muestran la tensión y corriente a la salida de la pila y las dos inferiores, a la salida del convertor DC-DC*



*Ilustración 4 – Aquí se muestra la producción de cada uno de los bloques en el caso en el que la producción energética sea superior a la demanda y las baterías estén a un nivel máximo.*

## 5. Conclusiones

- En cuanto al sistema de control del sistema pila + convertidor, se ha logrado encontrar dos modelos que funcionan: un PID y un PI con dos elevadores de fase. Ambos están diseñados para buscar un buen balance y equilibrio de la respuesta, pero pueden ser optimizados para satisfacer unos requisitos concretos debido a la utilización o condiciones del sistema (mayor velocidad de respuesta o mayor estabilidad). No obstante, esto también afectará al resto de propiedades. Es por ello, que una correcta modelización de las características del sistema nos permitirá seleccionar el controlador adecuado para un mejor rendimiento.
- En cuanto al sistema de supervisión de una Micro-Grid, es importante señalar que al igual que esta, no tiene una configuración fija. El algoritmo que ha sido modelizado se trata de uno muy general y fácilmente adaptable a la mayoría de los casos. No obstante, podemos encontrar diferentes algoritmos adaptados a una rentabilidad o necesidad específica. Por ejemplo, en el caso de un Micro-Grid conectado a una red general, puede ser interesante comprar automáticamente energía a la red general siempre que esté por debajo de un determinado coste y los niveles de carga de la batería se mantengan inferiores a unos límites fijados.

## 6. Referencias

- [1] Mini-Grids for half a billion people. Energies renouvelables. ESMAP, 2019.
- [2] Small-Signal Modeling of the Boost Converter Operated in CM. "On Semiconductor".

# MODELLING OF A FUEL CELL IN A MICRO-GRID AND ITS RESPECTIVE CONTROL ALGORITHM

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## ABSTRACT

Throughout this project, it has been achieved to model the operation and control of a fuel cell that presents a stable response with a specific voltage. In addition, the general control system of a Micro-Grid has been analysed and a simple Matlab model has been proposed to represent the operation of the Micro-Grid in the various situations it may encounter. Finally, through an economic analysis, the viability of these structures at present and in the near future is discussed.

**Keywords:** Micrp-Grid, electricity, energy,supply, fuel cell, supervision, control, Simulink, Matlab, renewable, clean, green.

## 1. Introduction

We are currently facing two very serious problems that need to be resolved and that are attracting the attention of the UN. The first is pollution and global warming (largely due to CO<sub>2</sub> emissions) and the lack in some countries of something considered a basic need: electricity. The World Bank considers that Micro-Grids can be key to putting an end to these two problems [1].

## 2. Project definition

Using the "Simulink" modelling program, a fuel cell of a specific power and its corresponding control system have been modelled to obtain a rapid, stable and accurate response at a defined value. Subsequently, the control systems of a Micro-Grid have been analyzed and again using Simulink, a model has been designed that controls and reproduces the behavior of the Micro-Grid in the various situations that may occur: energy production below demand, battery charging with excess energy, etc. In addition, an economic study shows the versatility of Micro-Grids and their ability to be adapted to the environment and needs.

## 3. Description of the model

The first model consists on the couple of a fuel cell with a regulation system, a control system and a DC-DC converter that allows increasing the output voltage to the 400V of the fixed network. To do this, it was necessary to represent the system at the output of the battery with a system of equations of "Small Signal Variation" [2] of the boost converter according to his open or closed mode. Thanks to the state-averaging method carried out with the duty cycle of the converter, a mathematical model representing the behaviour of the system is achieved. Subsequently, the nearest point of equilibrium to to the working conditions in which the fuel cell will operate is found (100V input to the converter and 400V output). Later, the system is linearized around the equilibrium

point. Finally, a bode that relates the work cycle of the converter with the difference between a reference voltage (400V in this case) and the voltage at the output of the system is obtained. Taking this bode into account, a control system is built that will ensure that there is a good compromise between stability/rapidity/accuracy in the response of the system. In summary, the designed controller takes the difference between the reference voltage and the system output voltage and varies the duty cycle of the converter so that the output is kept constant at the chosen voltage.

A model of a supervision algorithm has also been carried out in Simulink. It receives the expected demand of electricity every 15 minutes and it is capable of changing the working regime of any of the components present on the Micro-Grid in any of the foreseen situations.

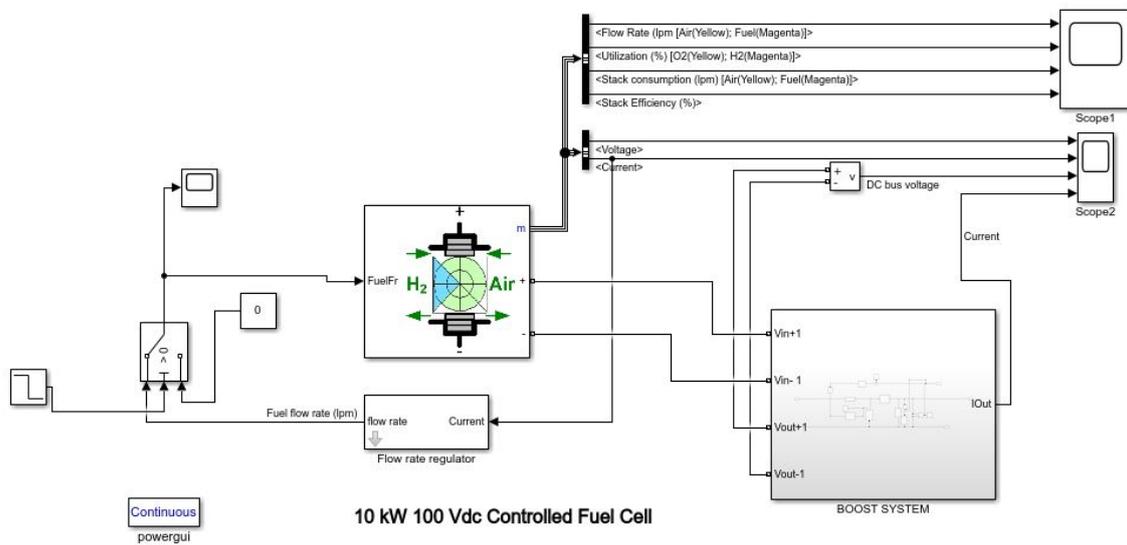


Figure 1 – Fuel Cell full system Simulink schema

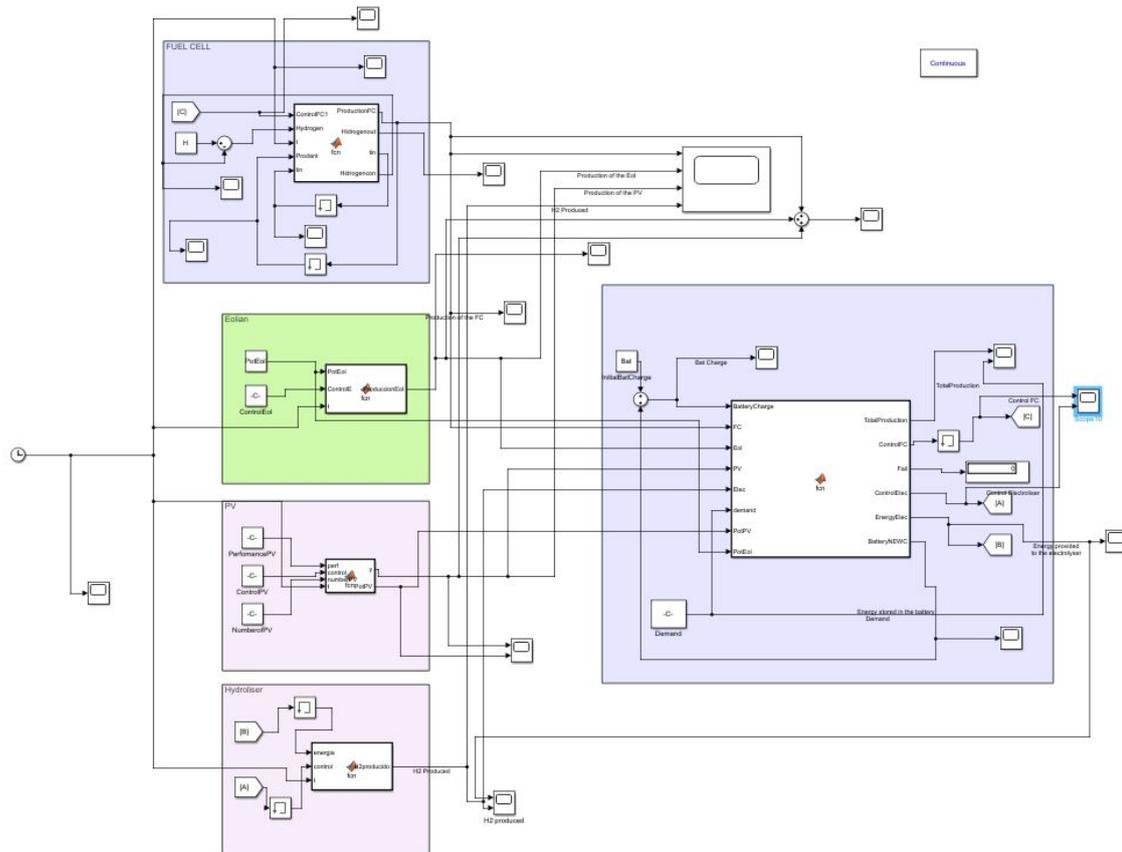


Figure 2 – Simulink model of the Supervision Algorithm of a Micro-Grid.

#### 4. Results of the project

- In the case of the fuel cell, it has been achieved, thanks to the control and regulation system, to operate the fuel cell with a stable voltage output of 400 V t by using two different control systems.
- The supervision algorithm correctly regulates the Micro-Grid following the flow chart that indicates how the components should act in each situation.

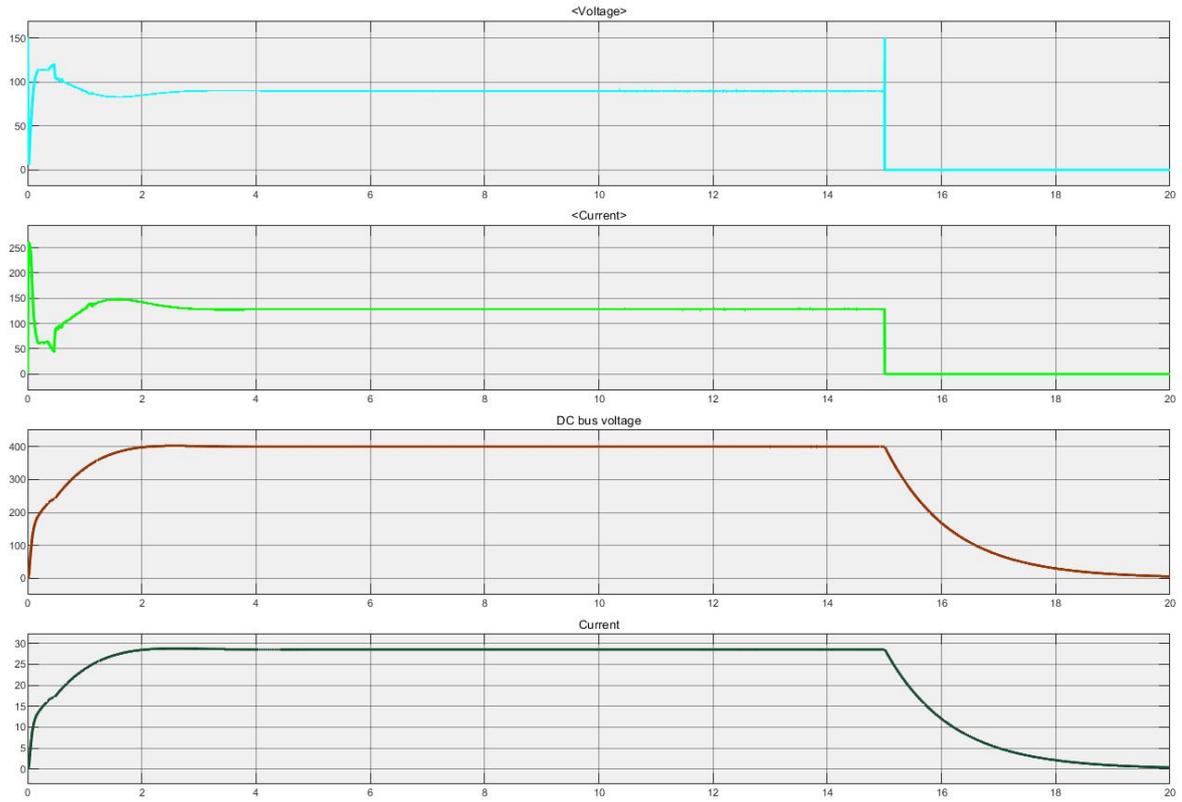


Figure 3 – Results of the fuel cell + boost system. At  $t=0$  the fuel cell is turned on and at  $t=15$  the fuel cell is turned down. The two superior plots represent the current and voltage in the output of the fuel cell and the inferior ones the current and the voltage at the output of the boost.

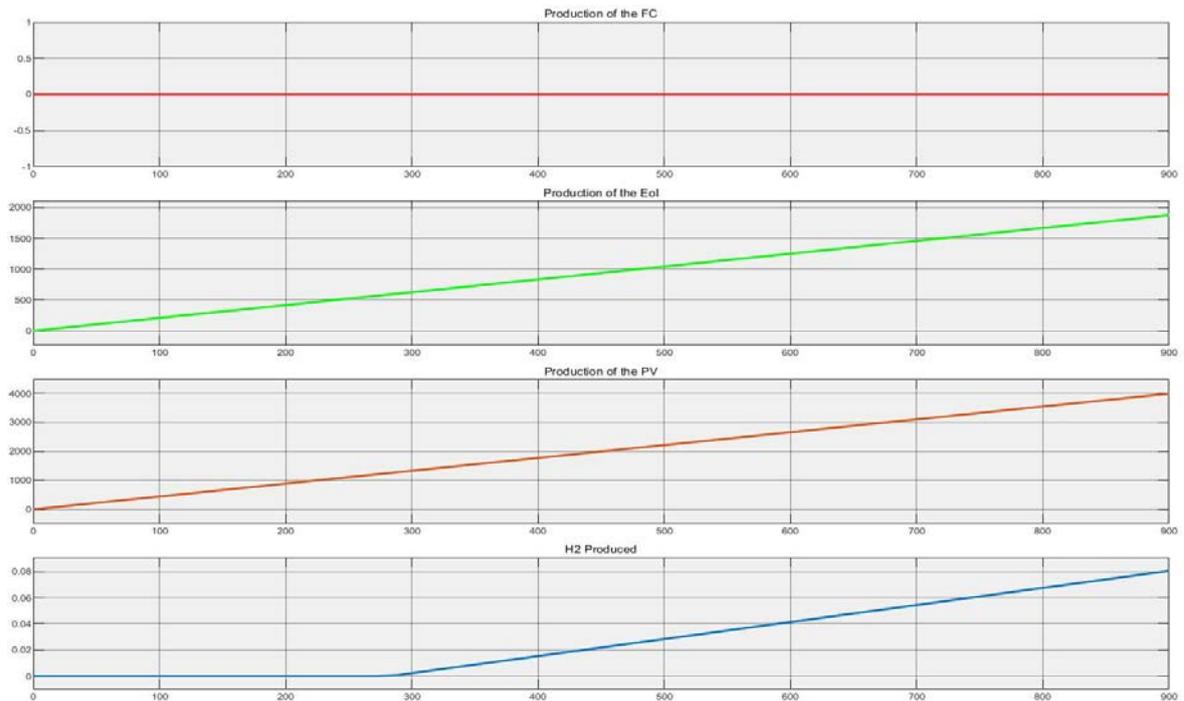


Figure 4 – Energy production of each system of the Micro-Grid if the production is higher than the demand and the batteries are full (surplus of energy used in the production of  $H_2$ )

## 5. Conclusions

- Regarding the control system of the fuel cell + converter system, two models have been found to work: a PID and a PI with two phase lead controllers. Both are designed to seek a good balance and equilibrium of response but both can be optimized to meet specific requirements in function of the use or the conditions of the environment (to reach higher response speed or greater stability). However, this will also affect the other properties. Therefore, a correct modelling of the system characteristics will allow us to select the appropriate controller for a better performance.
- About the supervision algorithm of the Micro-Grid, it is important to point out the fact that it does not have a fixed configuration. The algorithm that has been modelled is a very general one and easily adaptable to most cases. However, it is possible to find different algorithms adapted to a specific profitability or need. For example, in the case of a Micro-Grid connected to a general grid, it may be interesting to automatically buy energy from the general grid as long as it is below a certain cost and the battery charge levels are kept below fixed limits.

## 6. References

- [1] Mini-Grids for half a billion people. Energies renouvelables. ESMAP, 2019
- [2] Small-Signal Modeling of the Boost Converter Operated in CM. "On SemiConductor".





Degree in Industrial Technologies

Bachelor's final project  
Annex B

”Modelling of a fuel cell in a Micro-Grid and its respective  
control algorithm ”

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Madrid  
May 2020

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# 1.Introduction

## 1.1 Context

The main objective of this work is to investigate and model a new type of electrical network, **Micro-Grids**, focused on the fuel cell, a system that individually can solve many energy problems. This electrical construction can help the world to improve in two of the most problematic points at present:

- The pollution and deterioration of the planet
- The access to basic needs for all human beings (among which we can find access to electricity)

Starting with the pollution topic. Nowadays we live in a world that is starting to be more and more concerned about the problem that the pollution levels of last years is becoming. If we talk about Europe, it intends to be the first energetically neutral continent by 2050. In order to achieve this ambitious objective, a lot of important measures have been fixed in the Paris climate agreement of 2019 that will enable citizens and business of the United Nations to take advantage of different sources and technologies with less environmental impact such us hybrid/electric vehicles, renewable and clean sources of energy etc.

## 1.2 Global Warming

First of all we must understand what  $CO_2$  emissions are and why they represent a danger to the planet[1][2].  $CO_2$  already exists on our planet as the result of the cycle in which animals, plants and nature in general, participate. However, we,

human beings, interfere in that process and generate a much higher concentration of  $CO_2$  than there would be in a normal way. This is largely due to the fossil fuels that are used for so many activities in our daily lives: transport, energy production, heat systems etc. These fossil fuels have a high concentration of carbon which, when mixed with oxygen (as it happens in a combustion process), becomes  $CO_2$ , which is one of the main greenhouse gases that are causing climate change. This climate change can be more specifically identified as an increase in temperature that can have such terrible repercussions in a not too far future.

And perhaps it might be believed that global warming is not exaggerated considering that since 1906 the temperature has "only" increased by 0.9 degrees Celsius according to data published in "National Geographic" [3], an amount that makes almost no difference to humans... or so we might think. However, this increase has already had repercussions that have been recorded as the melting of the glaciers that, at the same time, causes an increase in sea level. This increase makes that there is territory that is disappearing and that is already posing great problems. For example, in Indonesia, where there exists already a plan to build a new city to convert it into the new capital and to move its inhabitants, since the current capital Jakarta is at high risk of flooding.

These changes also alter the cycle of life as we know it and can lead to numerous plagues and extinctions as changing livelihoods can wipe out some species and change the entire life cycle of multiple animals and plants.

Nowadays people is being more and more concerned about the critical situation that our world is living in terms of pollution. However, taking into account the more and more consumerist society that we have become, the forecasts about the future of the resources and the general health of the planet are not very encouraging.

In this context many meetings and conventions are taking place in Europe and also all over the world in order to fix new goals for reducing the  $CO_2$  emissions and other pollutant substances.

As we can check in the following graph provided by the scientific magazine "Futura-Science"[4], the energy and electric production represented in 2016 a 41.5% of the total emissions and that has not changed a lot in the last 4 years.

That's why the development of greener energies that do not imply the combustion of a fuel (excepting the biomass that against all intuition is also  $CO_2$  neutral as the quantity released is the one that the material has absorbed in its lifetime) such as the photovoltaic, hydro and wind energy would suppose a reduction in the

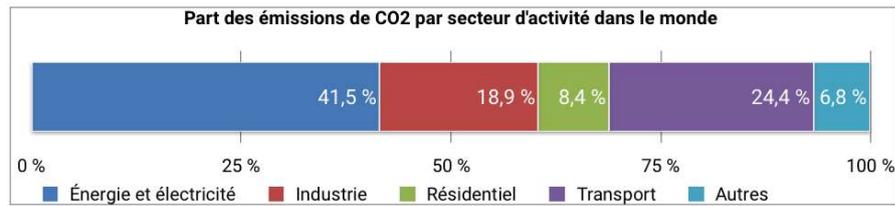


Figure 1.1: Share of CO<sub>2</sub> emissions by sector

total emissions and in the share represented by the energy production.

In the following graph provided by [5] it is possible to appreciate an estimation of the quantity of energy produced by renewable sources (renewable sources is not the same as green but in cases as solar, wind, hydro includes both of them) by each country and the objectives intended to achieve in 2020 (the study was made in 2018)

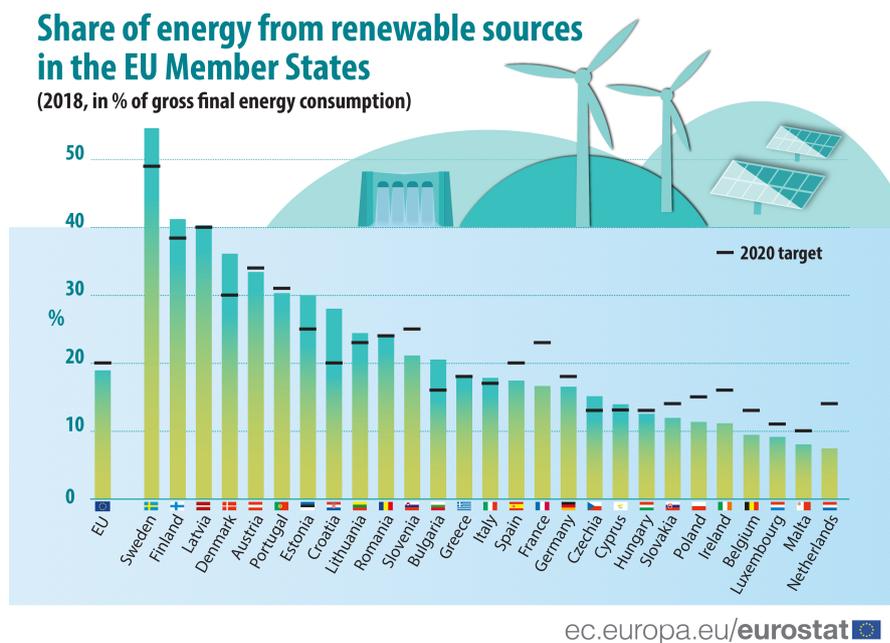


Figure 1.2: Investment in renewable sources of energy

It is already a fact that there is a problem with the carbonization of the world. Regarding some charts we can appreciate that the CO<sub>2</sub> emissions have increased constantly since around 1800. We achieved in 2014-2016 to stabilize these emissions giving hope to the objective. However, emissions began to rise again in 2017 as well as in 2018 and 2019. This slow-down maybe took place caused by the economic

crisis that began in 2012 and that paralyzed the economy of a lot of countries. Analyzing this fact it can be concluded that more sacrifices and measures must be taken.

In the following graph it is possible to see that countries are investing in this kind of technology but as it has been shown these efforts are not enough yet. That's why each year new conventions take place to check if the progress of the last year is satisfactory. As it can not be considered it a satisfactory result, it must be analyzed what is going wrong (mainly that the global production is not decreasing and even if we produce more green energy, the carbon-based production is not reduced as it cost a lot to close a coal central and to build new green installations) and to develop new ways to try to reduce the amount of  $CO_2$  not only in the energy production but in the whole daily life.

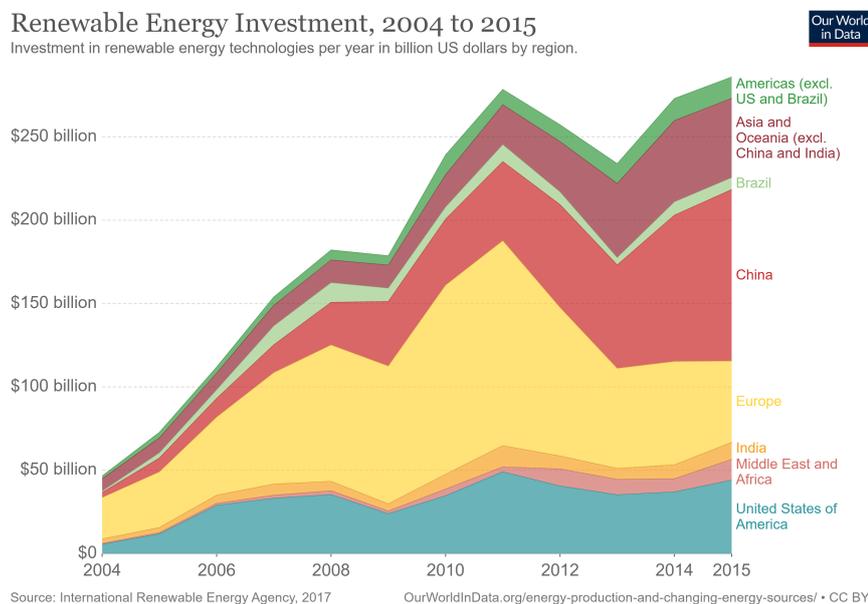


Figure 1.3: Investment in renewable sources of energy

### 1.3 Access to basic needs: Electricity

Studies show that approximately one billion of people [6] do not have access to electricity and that is one of the facts that the United Nations, through its sustainable development goals is trying to solve. The SDG 7 propose "the global goal of ensuring basic energy access for the 100% of the world's population by 2030"

It seems impossible that so many people do not have access to a resource that we consider basic like electricity. Furthermore, electricity will allow the application of agricultural techniques, medical services, etc. in these territories, which will increase their quality of life and production capacity. This is why access to electricity is considered essential in order to finish with poverty in the world.

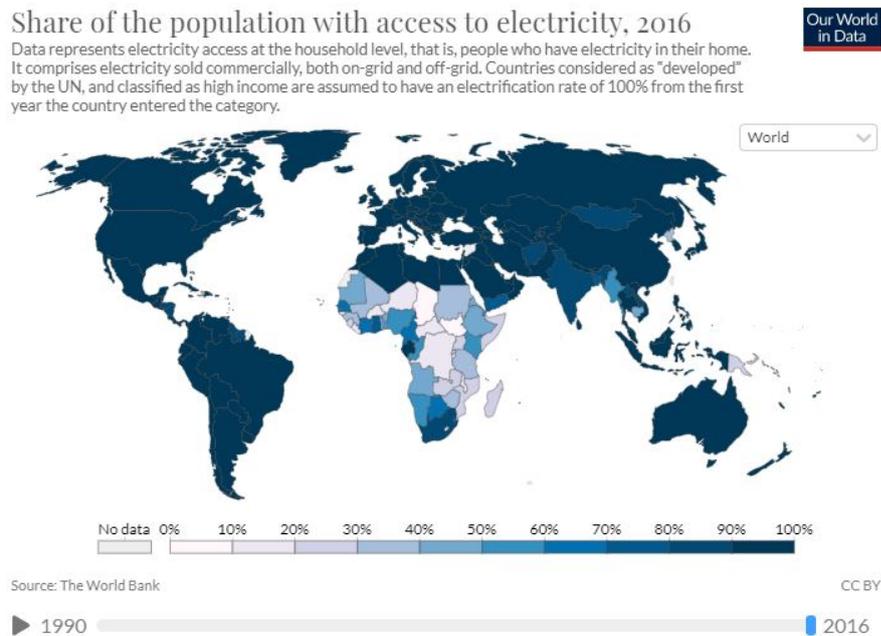


Figure 1.4: World Bank's map with the shares of "access to electricity" of each country

## 1.4 Summary of the content

Throughout the document different aspects of Micro-Grids are going to be discussed. In chapter two the solutions that currently exist for these problems are being commented. In chapter three, the general functioning of a Micro-Grid, and the technology of each of the renewable electricity sources it includes, will be explained. In chapter 4, the model of the fuel cell and its results will be shown. Suddenly, In the chapter 5 it will be shown the operation of a model of the Micro-grid supervision algorithm. Chapter 6 will consist on an economically analysis of this type of installations and finally in the chapter 7 some conclusion about the results will be given (another analysis of all the results will be presented also at the end of each one of the chapters about the models and the economic analysis)

## 2.State of the question

### 2.1 Green energies

#### 2.1.1 Renewable energies

Taking into account the context explained before, the world has tried to supply energy coming from renewable sources in order to reduce the  $CO_2$  emissions and at the same time trying not to deplete non-renewable resources like coal. As 28,2% of the  $CO_2$  emissions [7] come directly from the energy production sector (and another high percentage represents the energy produced by users for heating systems etc.), a reduction in the share of energy production based on coal would have a direct impact in the global emissions. This phenomena has taken place mainly in the recent years as the humanity has taken a lot of years to realize that the pollution made by carbon and oil-based centrals is really a huge problem for the world.

Currently more and more invests are being directed to renewable energies which have experimented an important growth in the recent years as for example: the production cost of 1 W produced with photo-voltaic panels has been reduced a 77% since 2010 [8] (data presented in the 2019 Climate Convention) and some other studies even assure that the difference is bigger than this 77%. Nevertheless, this tendency is thanks to two important factors: the investments in I+D and also the fiscal benefits that are being fixed by the governments with the clear objective of encouraging users to take part of this energetic evolution. Among these decisions it is possible to find for example, the liquidation of the sun tax that existed until 2018.

Each country studies which kind of source of energy will be better in terms of performance taking into account the different characteristics of the territory: average wind speed, hours of solar irradiation, rivers analysis etc.

A lot of different sources can be used to produce this energy, being the most developed the following ones: solar, wind, hydro and the biomass power. According to the statistics provided by "Eurostat" [9], The electricity production of Europe provided by renewable sources reached the 32% of the consumption of electricity (taking also into account the transport and heating systems, the use of renewable sources just reach a 18,88%). From this electricity provided by renewable sources, the **hydro-power** represented the 36,6%, the **wind power** the 33,9%, the **solar power** 12,2%, **biomass** 8% and the 9,2% left is produced by all the rest renewable sources. However there are also other kind of sources of energy that are clean in terms of  $CO_2$  emissions and with very good performance levels but who are not a renewable source as it happens with **nuclear power**.

In the following pages, some explanations about the operation of these sources of energy that can be considered the solution to the gas emission in this moment, will be presented.

### 2.1.2 Wind Power

Wind Power is the use of the mechanical power extracted by the movement of the blades thanks to the force of the wind, used to make an electrical generator rotate in order to obtain electrical energy.

There are different designs such as designs of two or three blades and with vertical or horizontal rotation axes. The most typical ones and the most implemented in the world are those ones of horizontal rotation axis and three-blades system.

The size of the wind farm and the eolic system is variable depending on the quantity of energy intended to produce (there exist eolic installations for a home and others to supply the main network of a country).

It is one of the more developed renewable source of energy with a growth of 9,6% in 2018 and its costs have been reduced in a 25% since 2010[10].

### 2.1.3 Solar Power

Solar energy is based on the use of the light energy provided by the sun to generate electrical energy. The experts use as a reference that the Earth receives  $1000 \text{ W/m}^2$  as radiation from the sun. There exist two types of installation based on solar power that work in different ways.

Firstly, the solar thermal power plants, that have as objective, to transform the luminous energy into thermal energy that in a second step can be used for the production of energy. For example: by means of a fluid that thanks to this heating, will be able to move an alternator to produce electrical energy.

In second place and the most known at present are the photovoltaic panels that convert directly the luminous energy into electrical energy by means of the use of semiconductors. It is possible to find different types of photovoltaic cells that in turn have different performances (between 12-16% and arriving to 20% with the last technology) depending on the material used and its mode of manufacture (the Si is the most used material). The performance may seem very low but we have to understand that there are many losses due to reflection, diffusion, dirt, orientation, temperature etc.

### **Classification of photovoltaic solar panels**

- Mono-crystalline solar modules: they are the ones with the best performance but they are also the most expensive ones (around 16% of performance).
- Poly-crystalline solar modules: nowadays the most used ones as they have the best quality/price ratio (around 14% of performance).
- Amorphous solar modules: this panels are really interesting even though their performance is lower than the other technologies (around 12%). That's because they are flexible so they can be installed in areas where the others are more difficult to implement. Besides they have better energy production than the others when the light is low what gives them a big advantage with respect to the others.

### **2.1.4 Hydraulic power**

Hydraulic energy is obtained from the kinetic energy and potential of a large body of water coming from rivers, waterfalls, rain, etc. On its fall the water passes through a turbine, transmitting the energy to an alternator that converts it into electrical energy.

Hydro-power is the most efficient way to generate electricity as they can reach efficiencies near the 90% and it is very used in Norway where hydro-power accounts for the 95% of the total energy consumption of the country [11], being one of the countries who has invested the most in renewable sources of energy.

### 2.1.5 Biomass power

Biomass deals with the combustion of wood (in its dead state), waste, and other materials for energy production. It is a complex form of production since each of the materials has different chemical properties that must be studied before being subjected to energy production and may require pre-treatment before being used. Some of these resources like wood are burned directly. However, others are converted into gases and fuel before they are burned (they are called "Biofuels"). With this combustion we get hot water or steam that turns a turbine, producing electricity.

As it is a kind of combustion, it might seem strange that it is considered a neutral energy source in terms of  $CO_2$ . It is considered neutral because the only  $CO_2$  released is that which the material has absorbed in its lifetime and that normally is released when the material is decomposed in a normal way. That is what differentiates it from other fuels used for energy production.

Three types of biomass exist:

- Natural, which is produced naturally without the participation of humans. (e.g. branches of fallen trees)
- Waste: from the residues of certain activities such as agriculture.
- Energy crops: intended for the production of biofuels.

## 2.2 Non-renewable energies

### 2.2.1 Nuclear Power

Nuclear energy has been separated from the previous ones because although it is considered a clean energy, the resources of uranium and plutonium are not unlimited and that is why it is not considered a renewable energy source.

Nuclear energy is based in most cases on the fission of uranium or plutonium atoms, a process that releases a lot of heat. Subsequently, it uses water (heated with this released heat) and the steam formed to drive turbines which, when connected to a generator, are capable of producing electrical energy. In this process, as no carbon-based fuel is being burned to supply the heat, no  $CO_2$  is released, so

it can be considered a "clean energy" (It is in terms of gas emissions but not in other kind of wastes created in the process).

However, nuclear energy has certain disadvantages, such as the high level of safety that must be implemented due to the seriousness of nuclear accidents and the production of radioactive waste, whose storage is a great challenge for some countries. This risk and wastes make nuclear power not very well regarded by some countries such as Italy or Austria but on the other hand we can find countries where this source accounts for a high proportion of their energy production, such as France, where nuclear power represents the 71.7% of total energy consumption. [12]

Public opinion on this type of energy production is very varied and that is why there are countries that clearly bet on it and others that do not consider it so safe or environmentally friendly. In Spain, for example, the construction of this type of plant has posed multiple problems, since the villages near the plant refused to live so close to a plant because in the case of an accident (no matter how remote the possibilities are) it would have catastrophic results for their families. Supporters of nuclear energy, on the other hand, highlight its performance, its "cleanliness", the safety of today that makes a nuclear accident very unlikely, the jobs that would be created, the development of the area and that there are countries that have it incorporated as part of their energy footprint and it works very well.

It is also necessary to take into account that it is not a clean energy in terms of  $CO_2$  emissions at 100% since the process of obtaining the necessary materials are not 100% free of this gas emissions.

## 2.3 Problems to expand the electrical network

As I said before, there are approximately 1 billion of people who has no access to electrical energy. To get electricity to these people, the most intuitive solution would be to extend the existing electricity grids. However, most of these people live in developing countries (most of them in Afrinca). But not only that, the large majority of the population who has not access to the electricity (up to 85%) reside in rural areas according to the info provided by [13]. This is why extending the electricity network represents a huge cost for these countries. A cost that for the moment they are not able to afford as the lack of electricity is often related with the poverty of the country.

Renewable energy can be the key to putting an end to this situation. However,

many Africans do not place the access to electricity among their priorities, being these: employment, effective health care, water supply and agriculture. The world must succeed in transmitting the idea that access to electricity would have a direct impact on these previous aspects so that the governments of these countries truly prioritize access to this energy. Some countries of North Africa, Mauritius and Cape Verde have made great improvements in this area in recent years and have greatly increased access to electricity even to 100% in countries such as Egypt and Morocco. However, the geographical distribution of these countries facilitates the growth of grids since people are more concentrated in large cities and the territory is not as big as in other countries of the Sub-Saharan Africa where the population density is much lower and more distributed. Under these conditions it is much more complicated to guarantee a quality energy supply through a common electricity grid. The lower economic development of these countries also poses a problem when it comes to developing this type of facility. Paying attention to all this, many experts think that renewable energies with its variable size and that do not need such big investments as big electrical installations can be the key to get out of this situation. And more specifically, as it is explained in the annex dedicated to the "Sustainable Development Goals", Micro-Grids are considered to be the best placed among the potential solutions to this problem.

## 2.4 Transport

Talking about the state of the art of a MicroGrid, the transport would not be normally touched as they are dedicated to the energy supply and not to transport. However as the main topic of the work has been the Fuel Cell in Micro-Grids, another important aspect where fuel cells are taking importance and may be the solution in the future is the transport thanks to the FCV (Fuel Cell Vehicles).

FCV are vehicles whose source of energy comes mainly from a fuel cell (which can be accompanied by batteries and supercapacitors to improve its operation). This FC takes oxygen from the air and compressed hydrogen. This makes possible to speak of a zero-emission vehicle since it only releases water and heat. The vehicle market is a complex world and while it seems clear that electrification is the future, each company decides to bet on a type of technology: hybrid, electric batteries, fuel cells, etc. Several important automotive companies have bet on this type of technology. Hyundai has just launched a spectacular Hyundai Nexus that works with this type of technology. However, its also spectacular price (not less than 70 000 euros) despite having "only" 163 CV and the tiny amount of refueling stations cause that fuel cell vehicles are still not too interesting for the average

people. Nevertheless, they have strong points such as their autonomy (600-700 km in the case of Hyundai Nexus) and a recharging speed clearly superior to the ones known as "electric vehicles" (battery based) since the hydrogen vehicles are capable of filling the tank in approximately 5 minutes. Recently, the vice president of hydrogen technology of BMW, Jürgen Guldner probably one of the largest companies that is betting on this type of technology today, when he was asked about its disadvantages (positions of load and price), answered that he does not think the price will be comparable to gasoline models until 2025 but thereafter and until 2030 we should be able to equal the cost of both technologies [14].

It is also possible to see that this technology could have a real future when Nikola, a fairly new company dedicated to electric (battery based) and hydrogen vehicles is going to launch the first hydrogen pick-up in the United States in 2021. The recent announcement of this model has made the company acquire an impressive stock price of 30 billion dollars over a car giant like Ford. This company that aims to revolutionize the world of batteries and hydrogen is resulting very attractive to investors who see in this company a lot of potential for the future. It is a good sign to see that investors consider as attractive a company that intends to implement a worldwide network of hydrogen distribution and that has even water boats (available for reserve) that would be driven by this technology.

# 3. Micro-Grids

## 3.1 Introduction

In this part some important concepts of Micro-Grids will be resumed and also the different technologies that are used in them will be explained for a better understanding of this installations .

## 3.2 Concept

### 3.2.1 Definition

Micro-Grids are facilities of variable size whose main objective is to supply energy to a given area based mainly on renewable energy sources. Each Micro-Grid is variable, it has neither a concrete design nor a specific size. They are adapted to the needs of the area and at the same time they are designed to take advantage of the types of energy that are the most efficient in that region (if it is a region where it is very sunny, solar energy will be prioritized, while if it is the case of Norway where there are many possibilities to use hydroelectric energy, it will be used).

Micro-Grids can be connected to a larger, general electric grid, which allows the energy exchanges between them. Once they are connected to the grid, they can be disconnected at any time, so that if there is a power cut in the grid, it will not affect the Micro-Grid, which will work autonomously as a self-supply Micro-Grid. It is also possible that in the area where we build our Micro-Grid there are no general networks (this is one of the cases that makes Micro-Grids very interesting in economic terms) and they have to work uninterruptedly in an autonomous way (also called isolated Micro-Grid). This is the case that is going

to be studied more deeply because if you achieve to make an isolated Micro-Grid who is capable to work autonomously, you will be able to ensure that it is going to work also connected to the general electrical network (with a few adaptations and with the possibility of optimizing some performances as there are functions that are no longer necessary) but not vice-versa.

A micro-grid is formed by a local generation system, an energy storage system, a control system, some users (consumers) and a connection point to the general grid, which may not be there if the micro-grid is isolated as it has been already mentioned. Due to the intermittence of renewable energy sources, it is necessary to include this storage system that allows us to accumulate energy when production exceeds demand and to supply this stored energy when demand exceeds production. The control system is necessary to operate with efficiency and to be able to have a stable supply of energy. This, is one of the big challenges of micro-grids

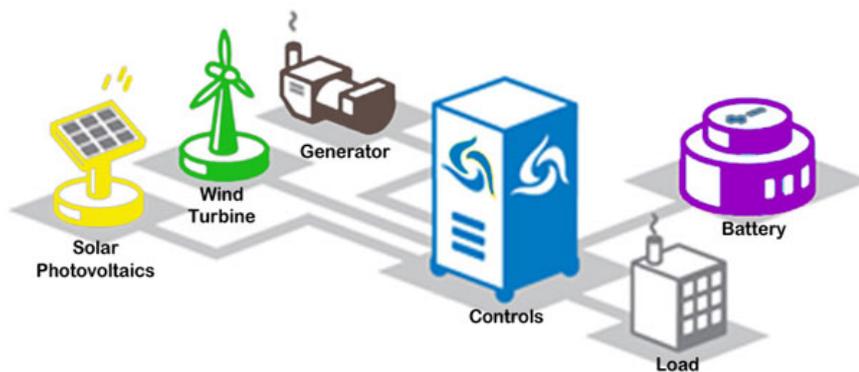


Figure 3.1: Simplified schema of a Micro Grid

### 3.2.2 Advantages

The advantages of Micro-Grids can be found in many sources. Some of them, taken from [15] [16][17] are being summarized in this section:

### **Increase reliability and cybersecurity**

Micro-grids increase the reliability of the energy supply. Reliability can be defined as "the ability to be relied on or depended on, as for accuracy, honesty, or achievement" [18]. With this definition, it is possible to apply the term reliability to the electricity supply to define the capacity of providing a stable and secure supply of energy.

A power failure can be fatal for some types of buildings such as hospitals, fire stations, police stations, etc. They would not be able to contact others, receive alerts or use their equipment.

In Micro-Grids the energy production is implemented as close as possible to the consumers to try to avoid as much as possible interruptions in the network.

In an era where computer attacks are becoming more and more frequent, electrical grids have to look for solutions to possible computer attacks. Micro-Grids, thanks to the possibility of isolating itself from the network and working autonomously or, conversely, making use of the network's energy, generates a clear increase in the system's resilience since it would not have to fall "only" the general network or the "micro-grid" itself, but would have to fall both at the same time to stop the supply of electricity to its clients.

That is why Micro-Grids have a plus of security against anything that can cause an electrical failure (storms, hackers etc.)

### **Resilience**

While reliability is about keeping the power on, resilience is about the ability of the system to recover quickly from an outage. In the case of Micro-Grids, there exists a very interesting possibility. This consists on the ability to choose which buildings are receiving the energy supply. Thanks to it, it is possible to prioritize some facilities to assure some specific activities such as laboratories on a university campus or surgery rooms in hospitals in the event that the full power supply cannot be restored immediately. Places where a loss of energy and a power failure could have fatal consequences for both the equipment being used and patients etc.

## Money Saving

Money can be saved building Micro-grids in many ways. Firstly, if the Micro-Grid is connected to a general grid money can be saved, buying the energy in the period of time when it is cheaper (normally at night) and store it in the storage system to be supplied when it is needed. Also, in case of a huge production, bigger than the demand, there exist the possibility to sell the excess of energy to the nearest network (the national networks usually buys this excess of energy).

However it can be considered as a money saving in the case of isolated Micro-Grids built in remote areas where there are not a big electrical grid to be branched can be considered as money-saving . In these cases the cost of extending the main network to a residence are unaffordable in many cases and it is more efficient economically to build a Micro-Grid.

## Promote clean energies

Micro-Grids are mainly focused on renewable forms of energy production. They try to use and to make profit from this clean energy. For example, on many of these grids that include a fuel cell, the heat energy released, it is used to heat water and to save energy. But it is not just that, it is even possible to configure the micro-grid to prioritize energy sources with lower pollutant emissions, higher performance, etc. In addition, this storage capacity avoid the lost of energy due to a surplus of production.

## 3.3 Solar Power

### 3.3.1 Introduction

Solar power is about the energy production made with the irradiation provided by the sun. As it has been already explained, there exist two types of solar power: the photovoltaic one and the thermal one. In this case just the photovoltaic one is going to be analyzed as they are the ones that are normally used in Micro-Grids. Now, the operation and its regulation system to extract the maximum power [19] are going to be explained.

### 3.3.2 Operation

The panel receives an irradiation that comes from the sun. Normally, experts take  $1000 \text{ W/m}^2$  as a good average value of the radiation arriving to the Earth that will allow us to quantify the performance of our technology. This value is going to be considered the reference one for the whole project.

Semi-conductors can be considered the key in this kind of technology. A type of material that occupies an intermediate position on the conductivity scale between conductors and insulators. It is an element that functions as one or another depending on some factors, such as the electric or magnetic field, radiation, pressure or temperature of the environment in which it is found [20]. The most used ones in photovoltaic panels are the **Si** and the **Ge**.

The technology is based on the assembly of a "P" type conductor and an "N" type conductor. On the N side, the semiconductor, is doped so that there is an excess of electrons, unlike on the P side where we are interested in having holes. Some of the electrons can move to occupy these holes.

Thus, the so-called depletion region appears, where there are no holes and no electrons. The P-sided edge is slightly negatively charged and the N-sided edge is slightly positively charged.

When the solar radiation hits the depletion zone, it causes holes and electrons to appear there. As the edges are slightly charged, the electrons move to the part P and the holes to the part N, creating now an electromotive force that causes that the electrons circulate from the part P, follow an electrical circuit and join with the holes of the part N producing a current DC.

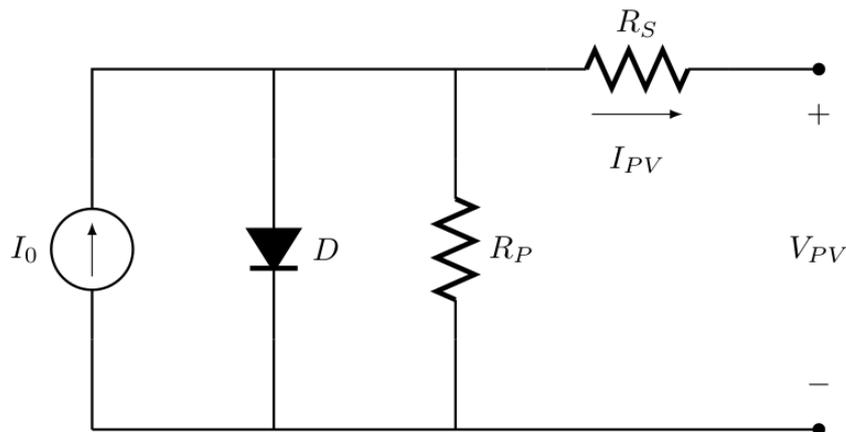


Figure 3.2: Equivalent Schema of a PV

Its operation is in fact comparable to that of a diode and its equivalent scheme is presented in 3.2, where  $R_p$  and  $R_s$  model losses that depend on the material and that generally have to be calculated experimentally since the manufacturer does not usually provide this information.

The photovoltaic panels can be in series (3.3 see on the left) and in parallel (3.3 see on the right)

As it can be checked in the image 3.4 in solar panels a curve I-U and P-U can be traced. In those curves, there is a point of maximal power where the voltage and the current will be called  $U_c$  and  $I_c$ . With those values, it is possible to calculate the equivalent resistance 3.1.

$$R_c = \frac{U_c}{I_c} \quad (3.1)$$

This equivalent resistance value would be the one that would extract the best performance for the system as the power supplied will be the biggest one. That is why the performance of a solar panel is made with the following formula 3.2 as it represents the maximal power that the panel can supply for a given irradiation that will be normally  $1000\text{W}/\text{m}^2$

$$\eta = \frac{U_{cc}}{\text{Irradiation}} \quad (3.2)$$

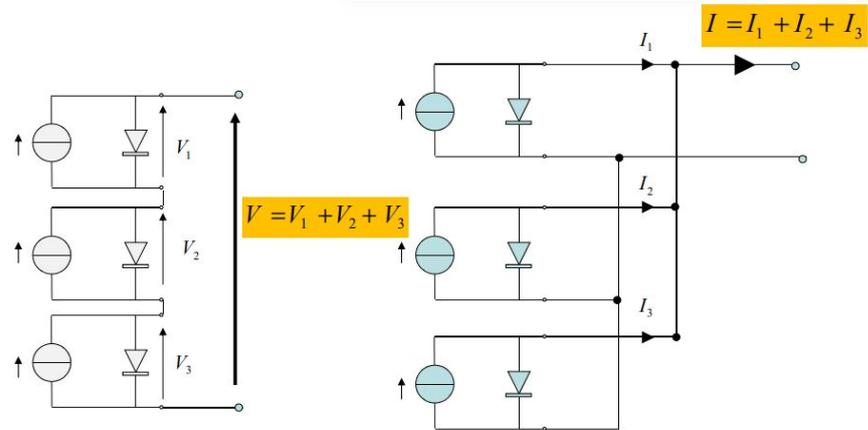


Figure 3.3: PV panel in series (left) and in parallel (right)

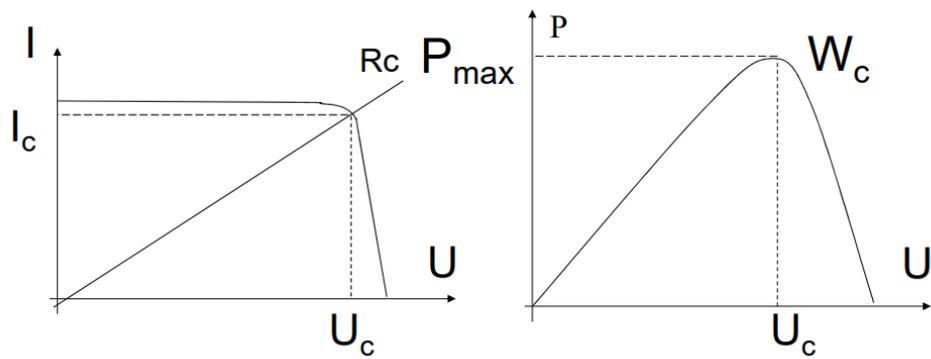


Figure 3.4: PV I-U and P-U curves

### 3.3.3 MPPT

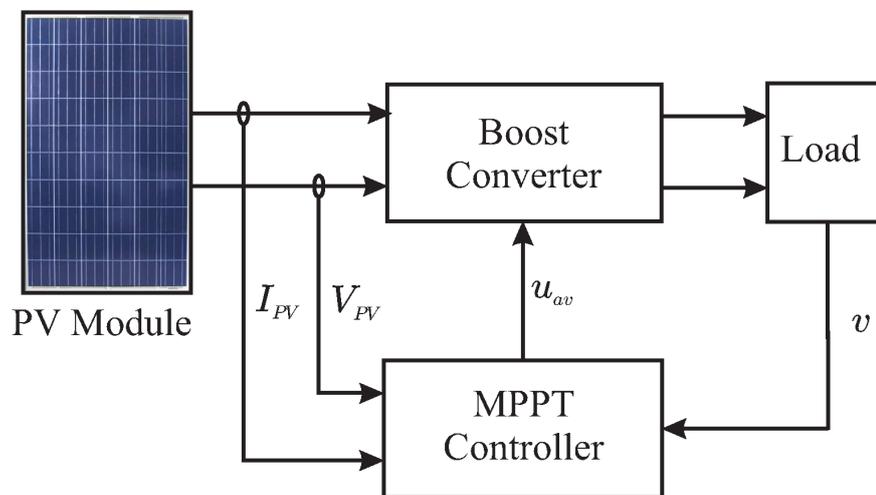


Figure 3.5: MPPT regulation for photovoltaic panels

When a solar panel is connected to the load, it is done through a DC/DC converter as shown in 3.5 that allows us to adapt the resistance at the output of the panel to match the equivalent resistance and thus, to be able to extract the maximum power.

This converter must be able to increase or decrease the voltage as the case may be. This must be commanded in such a way that the voltage at the panel output divided by the current gives the equivalent resistance calculated before since the power at the input of the converter and at the output must be the same if we consider it ideal.

In the case that the load ( $R$ ) is lower than the equivalent resistance, we will be in an operation point on the left of the maximum point and therefore we will need a voltage reduction converter (Buck-Boost Converter) since the voltage at the output of the converter will be lower than the one at the input. To make the equivalent resistance at the output of the panel be the same as the one we have calculated to obtain the maximum power, taking into account that  $V_2 = \alpha \cdot V_1$ , the inverse relationship with the current and taking also into account that  $P_1 = P_2$  we arrive to the next formula that will give us the command for the voltage reduction converter.

$$\alpha = \sqrt{\frac{R}{R_c}} \quad (3.3)$$

In the opposite case, where the  $R$  is higher than the equivalent resistance, it will be necessary a voltage booster, which with an operating ratio of  $U_2 = \frac{1}{1-\alpha}$  will have to operate with the  $\alpha$  presented in 3.4 to operate at maximum power.

$$\alpha = 1 - \sqrt{\frac{R_c}{R}} \quad (3.4)$$

## 3.4 Wind Power

### 3.4.1 Introduction

The Eolian system converts the energy provided by the wind speed into electrical current with the help of a generator. There exist mills with totally different shapes: vertical axis, horizontal axis, 2 blades, 3, 5... all with different characteristics. However, the most typical ones are those of 3-bladed horizontal axis with the following schema:

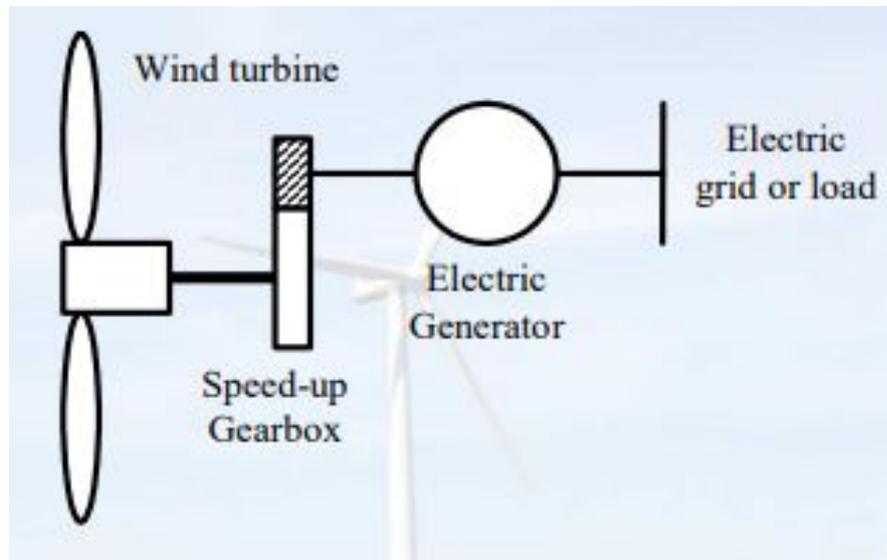


Figure 3.6: Schema of how Wind Power works

In order to build this kind of installation, the wind profile of the area must be very characteristic. Generally the most used as probability profile to represent the behaviour of the wind is the Weidbull one. This is done to know which wind

speeds are more frequent and if therefore it will be interesting to build this type of facility there.

### 3.4.2 Operation

The Wind farm, converts the kinetic energy of the wind given by the next formula:

$$P_w = \frac{1}{2} \cdot \rho \cdot \pi \cdot R^2 \cdot v^3 \quad (3.5)$$

Where  $\rho$  represents the density of the air [ $\text{Kg}/\text{m}^3$ ], the R means the radio of the blades m and v the speed of the wind [ $\text{m}/\text{s}$ ].

there is a parameter called  $C_p$  that states the relationship between the power of the wind and the mechanical power extracted from it.

$$C_p = \frac{P_{mec}}{P_{vent}} \quad (3.6)$$

This  $C_p$  depends at the same time of  $\alpha$  (blade pitch angle) and  $\lambda$ . This  $\lambda$  is called the "Tip speed ratio" (TSR) and it corresponds to the ratio between the linear speed of the blade tips and the actual wind speed coming onto the blade tip. It is also important to know that  $C_p$  is limited to a value fixed by  $\frac{16}{27}$ .

Therefore, we could express the  $P_{mec}$  as:

$$P_w = \frac{1}{2} \cdot \rho \cdot \pi \cdot R^2 \cdot v^3 \cdot C_p(\lambda, \alpha) \quad (3.7)$$

As it is shown in the figure 3.7, there is a minimal wind speed (Cut-in speed) to start extracting power and another point (Rated output speed) since the power starts to be maximal and a cut off speed from which we must stop the operation of the wind mill because it would exist risk of crash.

The objective is to maximize the  $P_{meca}$  extracted from the air. To do that, it is needed to maximize  $C_p$  through the maximization of the tip speed ratio and the blade pitch angle. Normally, the angle will be used to control the Eolian facility to extract the maximum possible power at any time. The TSR (Tip speed ratio) can be expressed with the following formula 3.8 where  $\Omega$  represents the angular speed

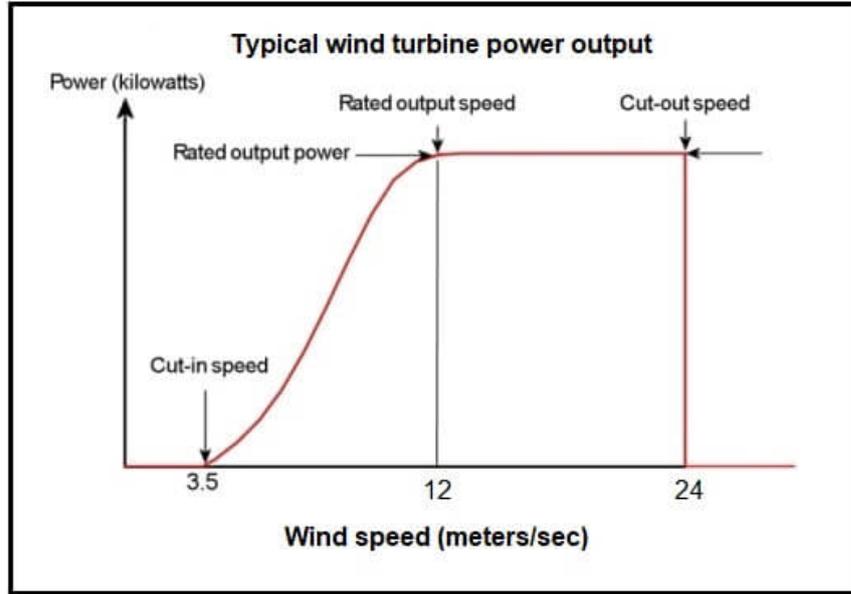


Figure 3.7: Diagram Power/wind speed

of the blades [rad/s],  $R$  is the radius [m] and  $v$  is the wind speed [m/s]. There exists a value of the TSR for which the CP and the power extracted is maximal.

$$\lambda = \frac{\Omega R}{v} \quad (3.8)$$

In the figure 3.8 it is shown how  $\alpha$  and  $\lambda$  affects to the value of the CP (in the image, the TSR is represented with  $\gamma$  instead of  $\lambda$ . However, in the rest of the work, the TSR will be represented with  $\lambda$ ).

### 3.4.3 Control

In order to extract the maximum power it is possible to adjust the blade pitch angle ( $\alpha$ ) and the rotation speed ( $\Omega$ ).

There are various strategies for adjusting these two parameters. One well known is the "Disturbance and Observation" one. It is basically based on a process that consists in varying the parameter to be adjusted, such as the rotation speed of the blades, in one of the directions, then the power extracted is calculated and compared with the previous one. If the power has increased, the algorithm

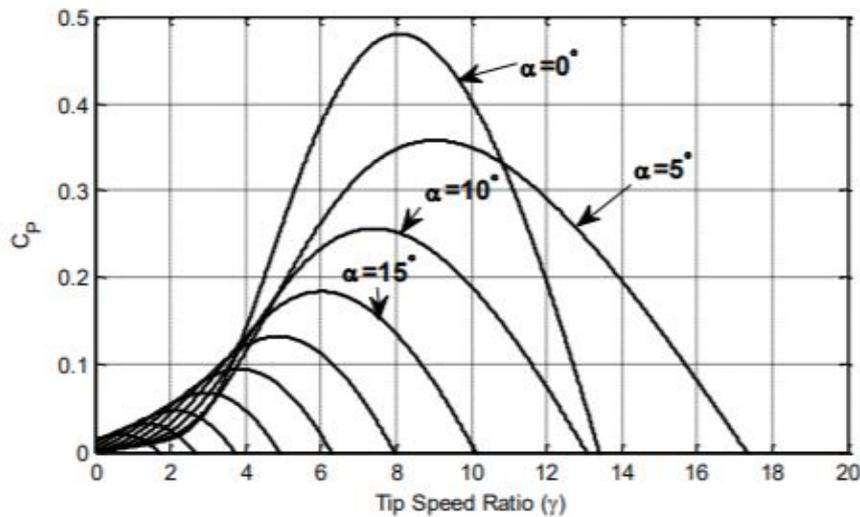


Figure 3.8:  $C_p$  in function of  $\lambda$  and  $\alpha$

will keep trying to increase it in the same direction, and if not it will go back. This process is repeated until the maximum value is reached.

The angle is easy to change since the blades are adjustable and the rotation speed in the case of wind mills is regulated by making adjustments to the torque resistance that the generator exerts. This is regulated with the current of the stator or the rotor (in the case of the synchronous generator which is the one that has been considered).

The energy produced is delivered in alternate form with variable frequency. It is therefore interesting to add an AC-DC converter that converts the energy produced into direct current without any frequency and then a DC-AC converter that works at the frequency of the network (50 Hz) for a good connection with the network.

## 3.5 Fuel Cell

### 3.5.1 Definition

The Fuel Cell is an electrochemical cell that converts the chemical energy of a fuel (being the Hydrogen the most often used) and an oxidant (often oxygen) in electrical energy thanks to two Redox reactions.

Every fuel cell has two electrodes called, respectively, the anode and cathode. The reactions that produce electricity take place at the electrodes. The reduction (gain of electrons) takes place in the cathode and the oxidation (electrons are liberated) in the anode. Between them, there is the electrolyte that will allow the ions to pass from one electrolyte to another but not the electrons that will have to pass by an external circuit (this is very important, if free electrons or other substances could travel through the electrolyte, they would disrupt the chemical reaction).

There is also another key element: the catalyst. Its function is to accelerate the reaction as they are reactions that generally take a lot of time. This catalyst is one of the parts with higher cost of the fuel cell as normally the materials used are quite expensive like the Platinum.

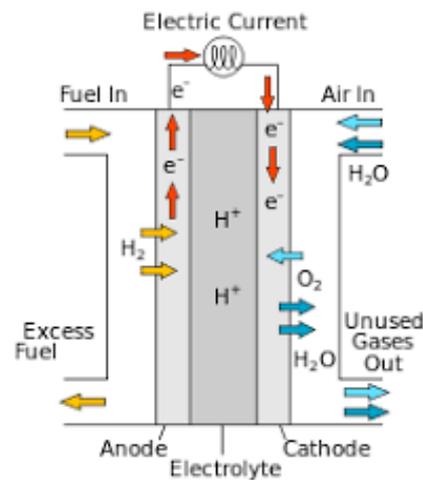


Figure 3.9: Scheme of a fuel cell

However, the output of this cells is a Direct current so if it was necessary to branch it to an alternative network it must be done through a converter DC/AC. It is also usual to add a DC/DC converter to regulate the tension and to have a better management of the power, as we can see in figure 3.10:

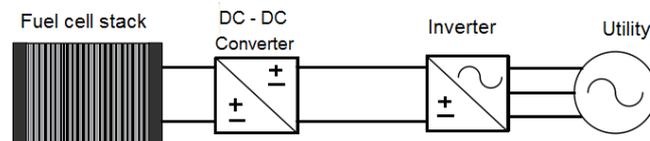


Figure 3.10: Connection of the fuel cell to the AC network

This process is based on a non combustion reaction and that is one of the advantages as this technology is not limited by the Carnot limit and the energy produced is very clean as the polluting emissions are very low. Fuel cells are not limited by the Carnot limit, this is why it is possible to reach very high performances with them if the heat dropped out by the cell is also used for other purposes (scale of 85-90%). Another advantage that can be found is that the fuel cells as well as the batteries are modular in nature, allowing a wide range of power output.

### 3.5.2 Types of Fuel Cells

There are many of types of fuel cells depending on the material that they use as electrolyte as well as the type of fuel that is being used. In the following, a brief introduction to each of the most important types is given.

**PEM (Polymer Electrolyte Membrane):** It uses as electrolyte a solid polymer and porous carbon electrolyte that contain platinum as catalyst. They need Hydrogen and oxygen, they work for low temperatures and they are light so they are very used in the transport field. Another advantage is that they can change quickly the production for satisfying the energy demand.

**DMFC (Direct-Methanol Fuel Cells):** It uses a polymer as electrolyte but in this case they use methanol in the anode so it is not necessary to use a reformer (The function of a reformer later will be explained later). They are used in electronic devices such as portables and battery chargers

**MCFC (Molten Carbonate Fuel Cells)** It uses salt of molten carbonate immobilized in a porous matrix as electrolyte. They are mostly used in centers of energy production (of a medium/high size) and they have a high efficiency. As the Temperature of working is about 600°C, it allows them to reform internally fuels like natural gas or bio gas.

**SOFC (Solid Oxide Fuel Cells)** It uses as electrolyte a ceramic component that is hard and porous. This kind of cells can work at very high temperatures (until 1000°C). Thanks to it, they are used in static systems as for example centers of energy production. This kind of cells are able to reform the bio gas and the gas natural and can be combined with motors for producing electricity with efficiencies near the 75%.

These are not the only type of Fuel Cells, they are the most important/used nowadays but there are many more as we can see in the following picture. This

image is a generic scheme of different types of Fuel Cells.

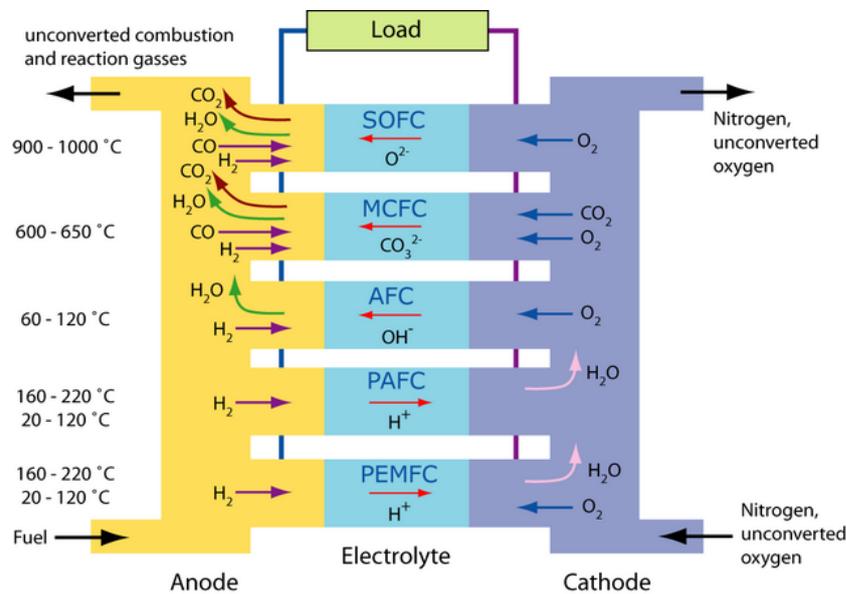


Figure 3.11: Generic fuel cell schema

### 3.5.3 Basic principle of a reformer

The hydrogen is difficult to manage and distribute. It would be interesting to be able to use a fuel easier to use/obtain in these fuel cells. Well, these reformers, take hydrocarbons and alcohols and convert them into hydrogen that will eventually be used in the fuel cell. This process is called steam reforming. Unfortunately, the generated hydrogen is not a 100% pure and other gases are also created, thus the efficiency of the process decreases considerably.

### 3.5.4 How does it work?

The cell principle is not based on direct combustion of the reactants but on controlled combustion. Two semi-reactions are carried out which can take place thanks to the presence of electronic (electrodes and electric circuit) and ionic (electrolytes) conductors.

To increase the speed of a reaction we can increase the concentration of the reagents, decrease the concentration of the products, increase the surface of the

electrodes, increase the temperature (because it will increase the vibration of the particles) and decrease the activation energy by catalysis (thanks to catalysts)

### Effect of the temperature in the speed of the reaction

The speed of the reaction is given by the Arrhenius law:

☞ **Loi d'Arrhenius :**

$$\text{Vitesse} \cong k \times [A]^m \times [B]^n$$

↑  
souvent !

*k* : constante de vitesse    *m* et *n* : ordres partiels de la réaction

Figure 3.12: Loi Arrheunius

where the Arrhenius constant *k* is given by:

☞ **Avancement de la réaction :**    **Constante d'Arrhénius**

$$k = A \times e^{-\frac{E_a}{RT}}$$

A : facteur de fréquence { collisions  
orientation

{ R : constante des gaz parfaits  
R = 8,3145 J.mol<sup>-1</sup>.K<sup>-1</sup>

Figure 3.13: Arrhenius constant

As it can be observed in 3.13, the temperature is present in the exponential part so it will be very important as a 2x change in the temperature would mean a reaction 3100 times faster.

The activation energy is another important factor in the equation that fix the speed. This factor can be modified with the use of catalysts that reduce this activation energy.

### 3.5.5 Most important equations

Electric work to release the electrons

$$W_e = \Delta G_{reac} = -nFE \quad (3.9)$$

We can define the variation of Gibbs energy as:

$$\Delta G_{reac} = \Delta G^0 + RT \ln(Q) \quad (3.10)$$

All the parameters must be in the units of the SI. in the case of energy parameters the unit is J and for temperature is K.

Q is the reaction quotient and as it happen in many cases the reagents are in gas state so it can calculated with the next formula (where  $v_j$  and  $v_i$  are representing the stoichiometric index):

$$Q = \prod \frac{\text{partial pressures of the products}^{v_i}}{\text{partial pressures of the products}^{v_j}} \quad (3.11)$$

#### Usage of Oxygen

Taking into account the stoichiometric relation of the raction, all these parameters can be calculated:

$$Charge = 4F \cdot \text{amount of } O_2 \quad (3.12)$$

so we can arrive to:

$$O_2usage = \frac{I}{4F} \text{moles} \cdot s^{-1} \quad (3.13)$$

As a fuell cell has n stacks of cells:

$$O_2usage = \frac{In}{4F} \text{moles} \cdot s^{-1} \quad (3.14)$$

The electrical power can be expressed as:

$$P_e = V_c \cdot I \cdot n \quad (3.15)$$

So, expressing the  $O_2$  usage in terms of the power

$$O_2usage = \frac{P_e}{4F \cdot V_c} \text{moles} \cdot s^{-1} \quad (3.16)$$

If  $V_c$  is not given, it can be calculated from the efficiency, and if that is not given, the figure of 0.65 V can be used for a good approximation.

Efficiency can be calculated with the following formula:

$$Efficiency = \frac{V_c}{1.48} \quad (3.17)$$

### Usage/Exit of Air

For calculating the usage of Air, the formulas of before will be recycled but taking into account the quantity of oxygen in the air

$$AirUsage = 3.57 \cdot 10^{-7} \cdot \lambda \cdot \frac{P_c}{V_c} Kg \cdot s^{-1} \quad (3.18)$$

The exit air flow rate can be calculated by:

$$\underline{Exit\ air\ flow\ rate = Air\ inlet\ flow\ rate - oxygen\ usage}$$

### Usage of Hydrogen

For calculating the usage of Hydrogen, it must be taken into account that for each mole of Hydrogen, it takes 2 electrons

$$Hydrogen\ Usage = \frac{In}{2F} moles \cdot s^{-1} = 1.05 \cdot 10^{-8} \cdot \frac{P_e}{V_c} Kg \cdot s^{-1} \quad (3.19)$$

### Water Production and Heating Rate

There are the same number of electrons for a mole of water than for the hydrogen:

$$Water\ production = \frac{P_e}{2F \cdot V_c} moles \cdot s^{-1} = 9.34 \cdot 10^{-8} \cdot \frac{P_e}{V_c} Kg \cdot s^{-1} \quad (3.20)$$

And the heating rate:

$$Heatingrate = nI \cdot (1.25 - V_c) \cdot W = P_e \left( \frac{1.25}{v_c} - 1 \right) W \quad (3.21)$$

## 3.6 Batteries

Now the operation of the batteries will be detailed, these components are key to this type of electrical structure (Micro-Grids).

The batteries are made up of a set of cells in which a redox reaction takes place. The battery transforms this chemical energy into electrical energy by circulating

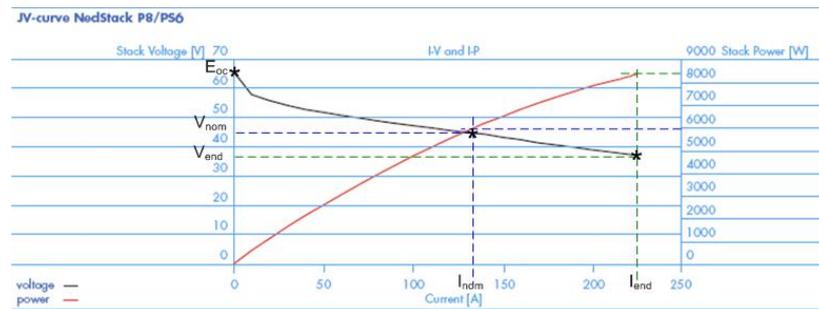


Figure 3.14: DataSheetFC6Kw

electrons in a process similar to that of the fuel cell. Nevertheless, in this case it is important the fact that the reaction is reversible, meaning that it will be possible to execute the inverse process. That is to say, from an electrical energy that we will provide to the battery, we will make that this one turns it into chemical energy, making as it has already been explained the inverse process (it will be possible to convert electrical energy in chemical and vice-versa).

There are two very important characteristics of the batteries. The first one is the voltage that is determined by the redox pair used. In second place, the load capacity, and the state of charge, which are expressed in Ah. These express the amount of current they can supply over the course of an hour. It is simple to calculate the energy stored in the battery by simply making the product of the voltage with the level of charge. The result will be given in Wh.

If we have two equal batteries, It is possible to increase the voltage of these by connecting them in series. However, the current passing through them will be the same. This is necessary in many occasions (connecting cells in series) to adapt the voltage of the battery to the application that you intend to give to the battery.

A very important characteristic of batteries is its very low resistance (of the order of  $m\Omega$ ) what permits the battery to supply very high currents.

In the image 3.15 is being showed the behavior of a lithium battery, the batteries vary slightly in voltage both in the process of charging and in the process of discharge, depending on the stage in which it is. This aspect is very important and must be taken into account when implementing a battery in the system.

The performance of batteries (ratio between the energy supplied to charge the battery and the energy delivered by the battery in the discharge process) is around the 80% depending on the materials used and so the reaction Redox that will take place.

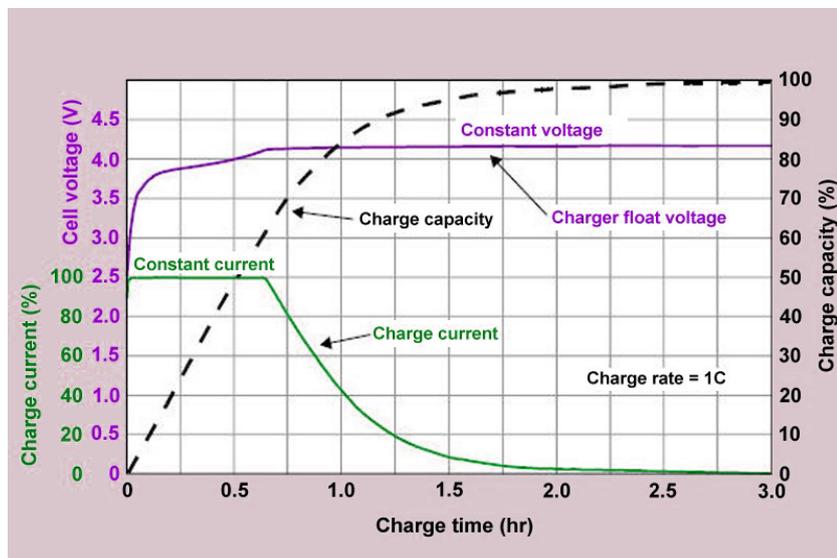


Figure 3.15: Curve voltage / Charge capacity

# 4. My Fuel Cell Simulink Model

## 4.1 Introduction

This model will reproduce the behaviour of a PEM fuel cell that are one of the most developed so far and that can reach powers of up to 1 MW. After analyzing the characteristics of the system, it was decided to model a 10 KW fuel cell with its respective controller in Simulink.

It has been also design a controller to control the operation of the fuel cell for a DC network but it will also be explained how to do it for an AC network. In order to simplify the problematic, this model will be designed in mono-phase but everything can be translated to a three-phase system.

## 4.2 Model

### 4.2.1 Matlab Block

For the model it has been used the block provided by Matlab in Simulink that represents a generic fuel cell in the detailed form. In this form it is possible to change almost everything as variable so it will be possible to observe all the outputs of the fuel cell. The equivalent circuit is the one that can be seen below:

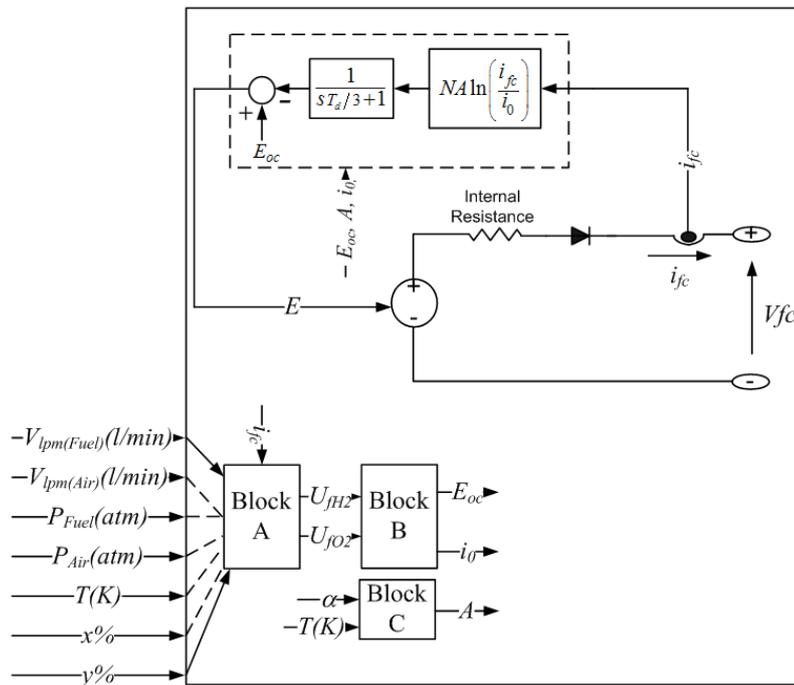


Figure 4.1: Simulink Generic fuel cell schema

The Matlab block requires a series of information in order to simulate the output of the stack. These features, which will allow the Matlab model to plot the V-I curve and the P-I curve are the following ones:

- Voltage at 0 and 1 A : Output voltage of the fuel cell when it supplies 0 and 1 A as output current
- Nominal operating point
- Maximum operating point
- Nominal stack efficiency
- Operating temperature
- Nominal supply pressure
- Nominal composition of the air, fuel...
- Number of cells

- Nominal air flow rate
- Fuel Cell response time

This data allows the block to reproduce the characteristic curves of the fuel cell that are normally given by the supplier in the data sheet. As it can be appreciated in the case of the 6KW model that Matlab uses as an example 4.2, the response is very similar to what the fuel cell would do in reality. That's why this block is going to be used to to reproduce the response of the cell.

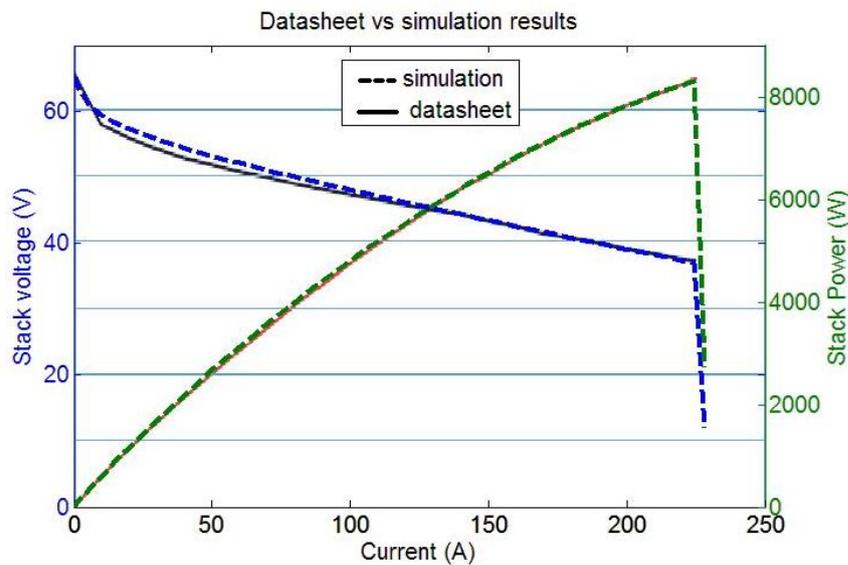


Figure 4.2: Fuel Cell Matlab Block Curve V-I and P-I

#### 4.2.2 Choice of the nominal power and introduction of the parameters to the Matlab Block

In the first moment, it was tried with a fuel cell of 6KW of type PEM, whose data sheet was easy to find in Matlab. However, as it can be checked in 3.14, its optimal operation point is around 45 V and it was very expensive and difficult to reach the 400 V of the network.

That's why the initial idea was changed to a fuel cell of 10 KW. After a lot of time of investigation looking for a data sheet for a PEM fuel cell of 10 KW, it was not possible to find a real one. So, finally, the parameters of a fuel cell

that would operate under normal conditions at 10KW were designed from the data sheet of a fuel cell of 6KW and another of 20KW. By studying very well the differences between both data-sheets and crossing information (interpolation and interpretation of parameters) and research, finally it was achieved to design a fuel cell whose optimal operating point was at 100 V output voltage and 100 A. That is to say, supplying a power of 10KW as it was required.

In 4.3 you can check the parameters that were fixed in order to successfully reproduce the behaviour of a fuel cell of 10 KW and in 4.4 the resultant characteristic curves of the fuel cell that explain how is going to respond the Matlab block.

Model detail Level:	Detailed
Voltage at 0A and 1A [V_0(V), V_1(V)]	[143,140]
Nominal operating point [Inom(A), Vnom(V)]	[100,100]
Maximum operating point [Iend(A), Vend(V)]	[240,50]
Number of cells	143
Nominal stack efficiency (%)	55
Operating temperature (Celsius)	65
Nominal Air flow rate (lpm)	2100
Nominal supply pressure [Fuel (bar), Air (bar)]	[1.5,1]
Nominal composition (%) [H2 O2 H2O(Air)]	[99.95,21,1]

Figure 4.3: DataSheet FC 10KW

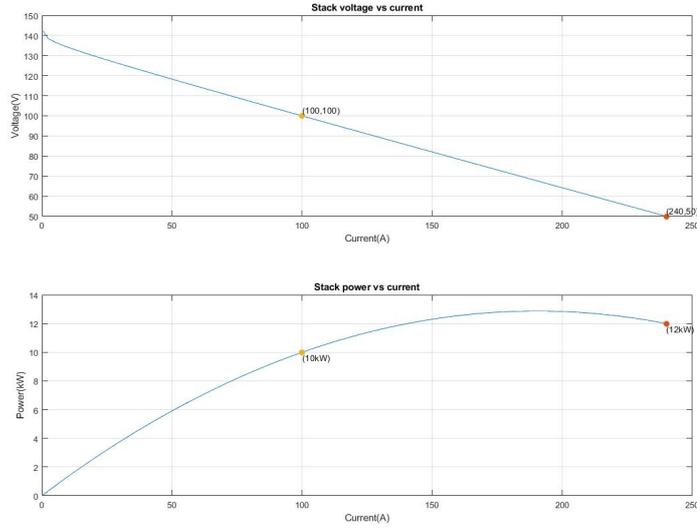


Figure 4.4: Characteristic curves V-I / P-I of the PEM FC 10KW

### 4.2.3 Fuel Regulation of the Fuel Cell

In order to regulate the fuel flow supplied to the fuel cell (and the behaviour of the fuel cell) it has been used a system that recuperates the output current and supplies the fuel consumption for this current, taking into account the nominal proportion. Fuel has been used in this case to control the fuel cell as it is the resource most difficult to obtain/produce comparing to the oxygen that will be supplied through the normal air. To sum up, the fuel cell model take its previous current value to regulate the input flows of the fuel cell.

$$V_{fuelcell} = \frac{60000 \cdot R \cdot T \cdot N \cdot i}{z \cdot F \cdot P_{fuel} \cdot U_{fH_2} \cdot x\%} \quad (4.1)$$

In 4.1 it is possible to check the formula used to regulate the input flow. Where  $R$  is the gases constant [8.3145 J/(mol K)],  $T$  is the temperature [K],  $N$  is the number of cells,  $i$  is the output current [A],  $z$  is the number of moving electrons,  $P_{fuel}$  is the absolute supply pressure of the fuel [in bars],  $U_{fH_2}$  rates of utilization of hydrogen,  $x$  is the percentage of Hydrogen in the fuel and  $V_{fuelcell}$  is the debit of fuel in [L/min].

This regulation system and the characteristics given to reach this curves of performance present this results in a simulation of 100s where the fuel cell supplies

power to an inductive charge.

### Model Used

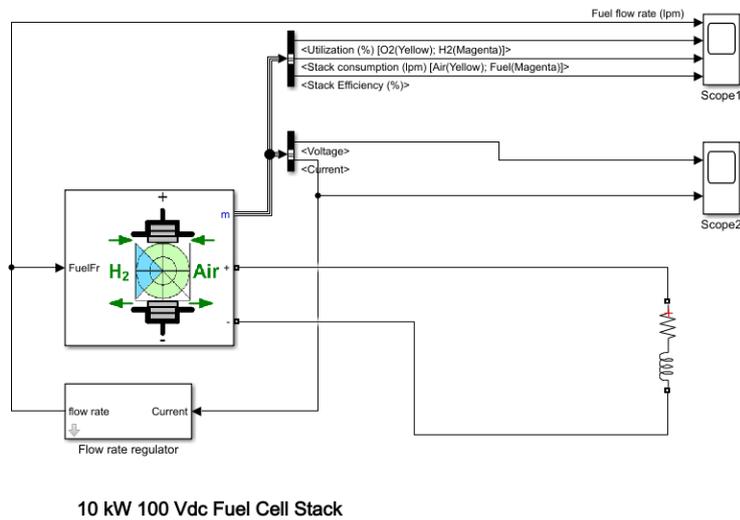


Figure 4.5: Simulink Model of the FC 10KW

### Results Obtained

The results obtained in 4.6 and in 4.7 are satisfactory. In these images, the current and the voltage goes to the optimal point. The performance of the stack is quite higher than 55 (value that was fixed as nominal performance stack) so the results were exactly what was attended.

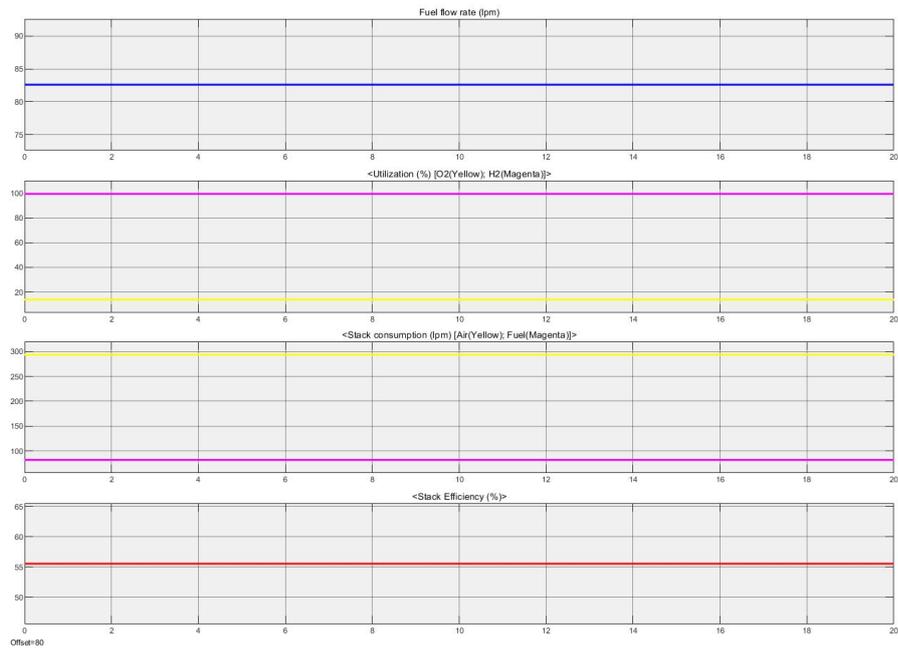


Figure 4.6: Results (Consumption) of the FC 10KW

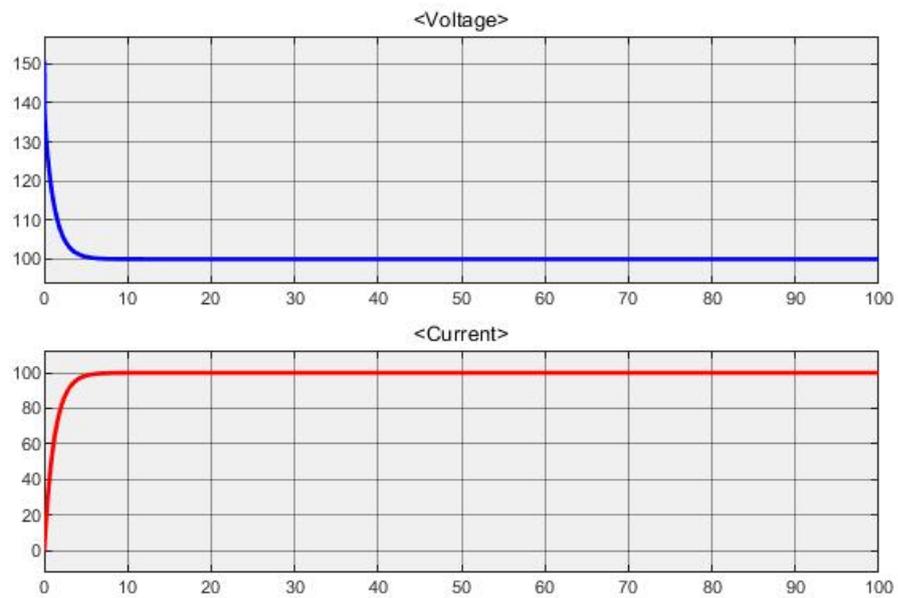


Figure 4.7: Results (Voltage-Current) of the FC 10KW

#### 4.2.4 Introduction to the controller design.

The objective is to reach a stable voltage output of 400V so a boost system (power electronics) will be needed to increase the output voltage. The problem is that if is directly implemented without a controller, the system is not stable and the current and the voltage of the fuel cell go to 0 due to the current changes that there are in the boost.

##### Boost system

A boost converter is a system capable of increasing the voltage that he receives as input. For doing this, the boost converter uses a transistor and a diode. The transistor is closed from 0 to  $D \cdot T$  and opened from  $D \cdot T$  to  $T$ . This  $D$  is called the "Duty cycle" (on other words, the proportion of time that the switch is ON) and it is what it is going to be used to control the output of the boost.

In a simplified way, it is estimated that:

$$V_{out} = V_{in} \frac{1}{1 - \alpha} \quad (4.2)$$

In the figure4.8 is easy to understand the change that it happens in the system when the time exceeds  $\alpha \cdot T$  and in 4.9 it is showed the system that that was carefully modeled in Simulink.

In this model, an inductive charge (coil) has been added in the beginning in order to try to keep more stable the input current and it is the same case for a capacitor that has been included at the output to keep more stable the output voltage. As the fuel cell is supplying 100 V as input voltage of the boost converter, this same situation is going to be reproduced to test the boost, fixing and input voltage of 100 V and fixing the Duty Cycle to 0.75 following the equation 4.2.

The values of the charges that were used are:

- $L = 5 \cdot 10^{-3}$  H
- $C = 82 \cdot 10^{-3}$  F
- $R_{charge} = 14 \Omega$ ;

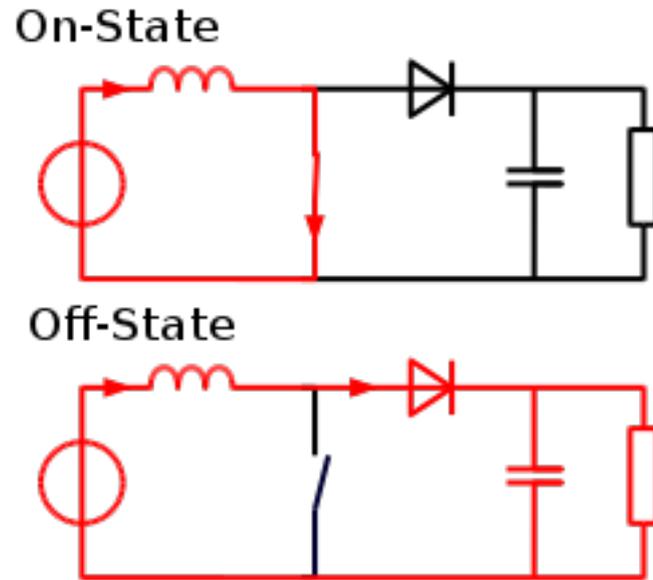


Figure 4.8: Boost Converter Modes

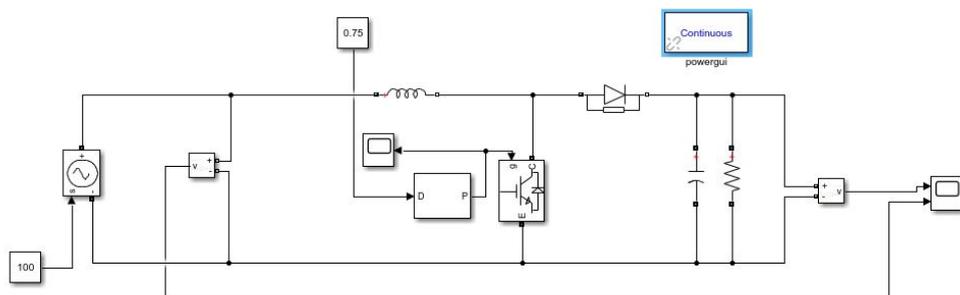


Figure 4.9: Simulink Schema of my Boost converter

### 4.2.5 Designing the controller

As Fuel Cell are complicated systems and its operating point depends on multiple aspects such as the resistance of the charge (as it changes the output current, changing at the same time the operating point and the fuel flow) it will be necessary to install a controller that will assure the output voltage to be **400 V**. This controller will take the difference between the output voltage and the reference one (400V) and will change the duty cycle in order to keep a stable output voltage of 400 V after some time that the system will spend to get stable.

In order to do that it is necessary to take a Bode diagram that lies the duty cycle and the difference of voltage for designing a State feedback controller that takes the output voltage and modify the duty cycle to assure the required voltage.

As the system is complex and Simulink can not return a bode directly (tried but it failed), A small-variation signal model of the boost is going to be used and subsequently the system will be linearized around the nearest equilibrium point to the desired operation point (output voltage=400V).

#### Small-Variation Model of the boost converter

In the On-model the steady state equations are:

$$\begin{pmatrix} \frac{di_L}{dt} \\ \frac{dV_c}{dt} \end{pmatrix} = \begin{pmatrix} -\frac{(r_l+rds)}{L} & 0 \\ 0 & -\frac{1}{C(r_c+R)} \end{pmatrix} \begin{pmatrix} i_L \\ V_c \end{pmatrix} + \begin{pmatrix} \frac{1}{L} \\ 0 \end{pmatrix} V_d$$

$$(V_o) = \begin{pmatrix} 0 & \frac{R}{r_c+R} \end{pmatrix} \begin{pmatrix} i_L \\ V_c \end{pmatrix} + (0) V_d$$

On the other hand for the OFF-Model:

$$\begin{pmatrix} \frac{di_L}{dt} \\ \frac{dV_c}{dt} \end{pmatrix} = \begin{pmatrix} -\frac{(r_L+r_F+\frac{r_cR}{r_c+R})}{L} & -\frac{R}{L(r_c+R)} \\ \frac{R}{C(r_c+R)} & -\frac{1}{C(r_c+R)} \end{pmatrix} \begin{pmatrix} i_L \\ V_c \end{pmatrix} + \begin{pmatrix} \frac{1}{L} \\ 0 \end{pmatrix} V_d$$

$$(V_o) = \begin{pmatrix} \frac{r_cR}{r_c+R} & \frac{R}{r_c+R} \end{pmatrix} \begin{pmatrix} i_L \\ V_c \end{pmatrix} + (0) V_d$$

Applying the steady-state averaging technique we obtain the following equations :

$$\begin{pmatrix} \frac{d\hat{i}_L}{dt} \\ \frac{d\hat{V}_c}{dt} \end{pmatrix} = \begin{pmatrix} -\frac{(r_l + D*r_{DS} + D'*(r_f + \frac{r_c*R}{R+r_c}))}{L} & -\frac{D*R}{L(r_c+R)} \\ \frac{D'R}{C(r_c+R)} & -\frac{1}{C(r_c+R)} \end{pmatrix} \begin{pmatrix} \hat{i}_L \\ \hat{V}_c \end{pmatrix} + \begin{pmatrix} \frac{1}{L} \\ 0 \end{pmatrix} \hat{V}_d + \begin{pmatrix} \frac{I_L*(r_f - r_{DS} + \frac{R*r_c}{R+r_c})}{L} + \frac{R*V_c}{L*(R+r_c)} \\ -\frac{R*I_L}{C*(R+r_c)} \end{pmatrix} d\hat{t}$$

$$(V_o) = \begin{pmatrix} \frac{r_c*R*D'}{r_c+R} & \frac{R}{r_c+R} \end{pmatrix} \begin{pmatrix} \hat{i}_L \\ \hat{V}_c \end{pmatrix} + (0) \hat{V}_d + \left(-\frac{R*r_c*I_L}{R+r_c}\right) d\hat{t}$$

being D the duty cycle and D'= 1-Duty cycle.

In this model, it has been neglected  $r_L$ ,  $r_c$ ,  $r_{ds}$  and  $r_f$ . That's why the final equations are much simpler:

$$dI = \frac{(V_d - D' \cdot V_c)}{L} \quad (4.3)$$

$$dV_c = \frac{D'}{C} \cdot I_L - \frac{1}{R \cdot C} \cdot V_c \quad (4.4)$$

In the next step, a block that reproduces the behaviour of these equations is implemented in Simulink:

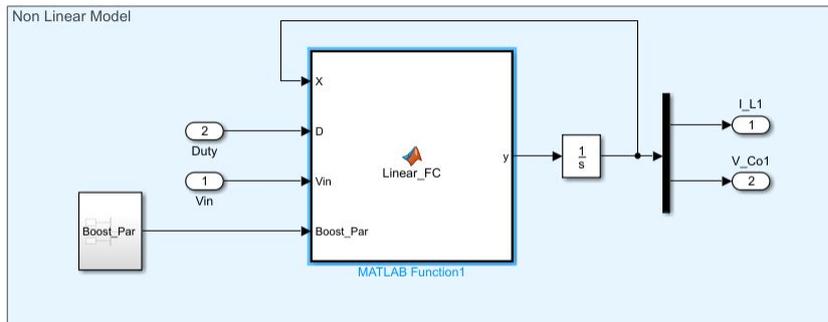


Figure 4.10: Simulink average boost model

Basically, this block receives the input voltage, the duty cycle, the value of L, C etc. and the equations presented in 4.3 4.4 and returns a differential of the variables x's (output voltage  $V_c$  and current passing through the coil  $i_L$ ). This dx is integrated and returned to the model for recalculating the new differential.

### Linearization of the boost model

For linearizing the model, is has been used the Matlab function trim whose specifications can be found in [21]. This function looks for the nearest equilibrium point to some initial conditions that you have specified. This function returns 4 matrix A, B, C, D that allows you to build a State-Space linearized system of the boost. In this case, the equilibrium was found in  $V_c = 400V$  and  $I_L = 115A$ , near to the optimal operation point of the fuel cell.

The same system is reproduced with the State-Space block provided by Simulink. In this model we supply the input voltage of the boost and the duty cycle in the form of small-signal variations and also the matrices given by the trim function in the step of before. Doing this it is possible now to build a Bode diagram that relies the difference between the voltage and a reference voltage (400V in our case) so a controller can be designed in function of it.

Two different models for the controllers have been tested:

### 4.2.6 Control PID

The first option that was chosen was a PID controller with high stability that would reduce to 0 the steady state error and would stabilize the fuel cell in some seconds.

The PID designed have the following structure:

$$P \cdot \left( 1 + I \cdot \frac{1}{s} + D \cdot \frac{N}{1 + N \cdot \frac{1}{s}} \right) \quad (4.5)$$

In order to obtain the values of P, I, D, N this characteristics of the system have been taken into account:

- Crossover frequency = 60 rad/s.
- Phase Margin desired= 75° (minimum).

- Gain Margin=-52.
- Phase= 183°.
- Phase Margin= Phase+180.

Using the following formulas it has been determined the parameters of the controller:

$$T = \frac{\text{tangent}(0.5 \cdot (\text{PhaseMargin}_{\text{desired}} - \text{PhaseMargin} + 90))}{\text{CrossoverFrequency}} \quad (4.6)$$

$$I = \frac{1}{2T}; \quad (4.7)$$

$$TD = \frac{T}{2}; \quad (4.8)$$

$$N = \frac{10}{TD}; \quad (4.9)$$

So the final values obtained for the controller are:

- $P = 0.76 \cdot 10^{-4}$ .
- I=4.75.
- D=0.05.
- N=190.

### **Boost Test**

The design of the boost system with the PID becomes:

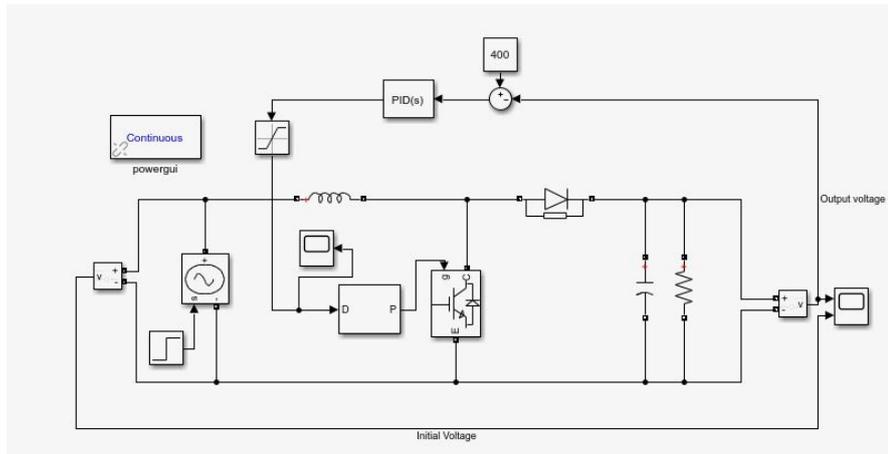


Figure 4.11: Boost circuit with the PID

First of all, it has been done a test with the boost system for an initial voltage of 100V that becomes 120 after 4 seconds. The result as can be checked in the following picture (where we can see the output voltage in the upside of the photo and the initial voltage in the downside)(4.12) is very satisfactory:

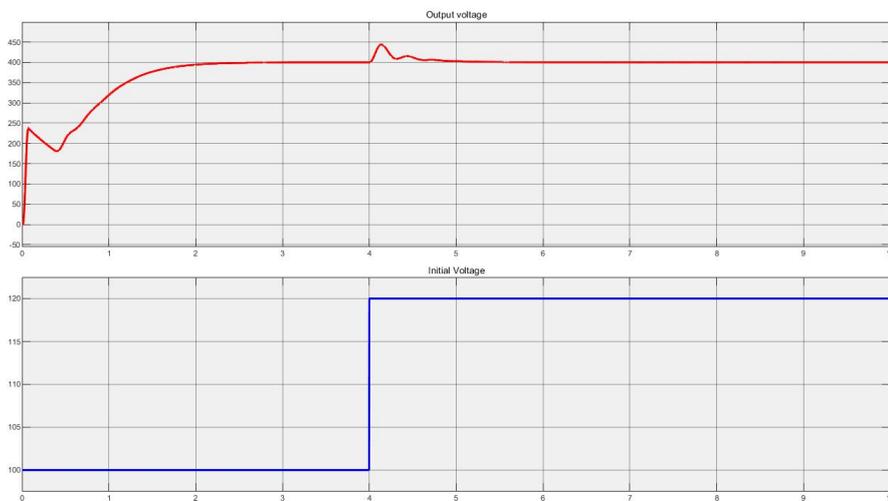


Figure 4.12: Response of the Boost to a change in the initial voltage

In the picture 4.13 the changes in the duty cycle during the simulation are observable. As it is shown, in the beginning, the duty cycle is constantly modified until the system gets stable. When the system is stable, the duty cycle is 0.75 as it was expected in the predictions. However, when it arrives the second 4, the system make a comparison between the output voltage and the reference one and

change the duty cycle to 0.7 (now as there are 120V of the entry, if the duty cycle were 0.75 yet, the output would be 480V) in order to keep the output voltage fixed at 400V.



Figure 4.13: Response of Duty Cycle of the Boost

As the result is correct, it has been implemented in the model with the fuel cell resulting in the next structure:

### Results with the PID

In 4.14 is possible to identify the fuel cell block, the boost system with the PID included, the fuel flow regulator and a serie of blocks in the entry of the fuel cell. One of this blocks is a a switch that changes to OFF when it arrives to him a signal superior than 0. A signal  $\geq 0$  is being sent with a time of arrival of 15s, modelling the decision of turning off the fuel cell after this 15 seconds.

A simulation of 20 seconds has been carried out and the following results that are visible in the figure 4.15 have been obtained. The upper voltage and current represent these at the fuel cell output and the lower two represent the voltage and current at the output of the boost converter.

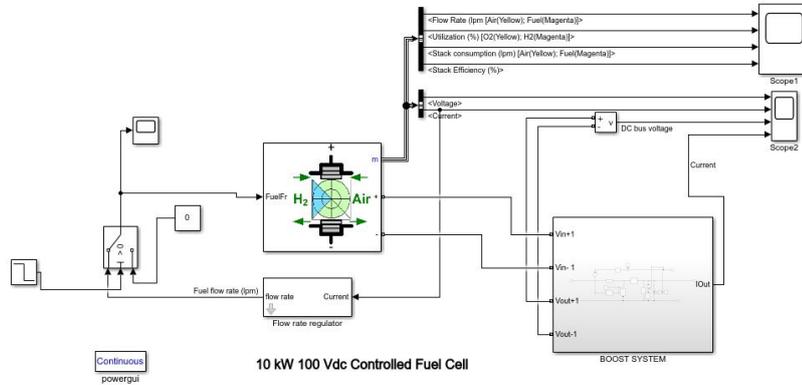


Figure 4.14: FuelCell Controlled (PID)

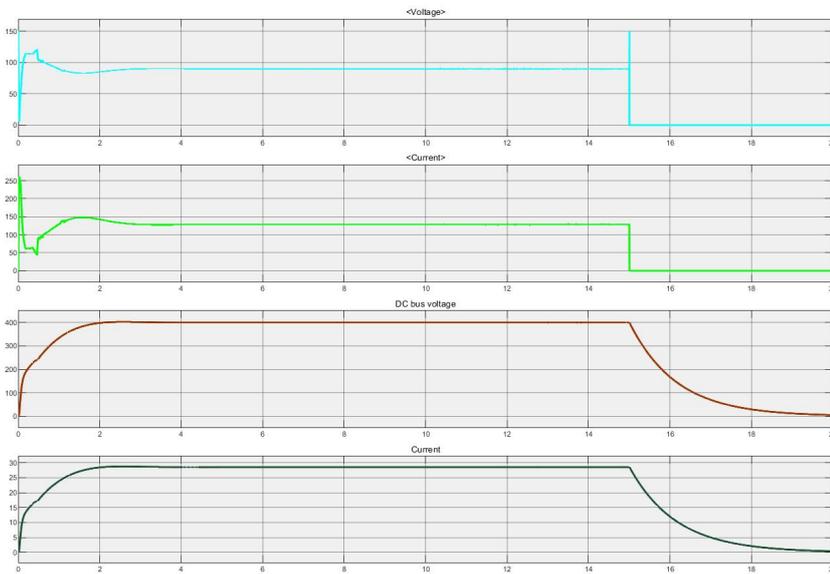


Figure 4.15: Results Fuel Cell Control

## Results Analysis

The upper voltage and current represent these at the fuel cell output and the lower two represent the voltage and current at the output of the boost converter. In the beginning the system takes 2 seconds to get stable what can be considered a good performance. Also it is possible to appreciate that there is no steady state error and when the decision of turning off the fuel cell arrives, the residual voltage is practically null after 5 seconds (15-20s in the test) so the response presents a good balance between stability, no steady state-error and rapidity. If the results are analyzed more carefully, it will be realized that the system has an output of 400V and a current that we could approximate by 28 A. So the fuel cell complete system is supplying 11.2KW, being a little bit at the right of the optimal point in the curve U-I [4.2].

### 4.2.7 Second Control

#### Introduction

A second type of controller has been tested and this time it consists on a phase lead + PI and the results will be compared with those of the PID.

#### Process

For this part the same method than before is followed. The only thing that is going to vary is the kind of the controller. That is to say, the only thing that changes with respect to the previous process, is the calculation of parameters of the controllers.

To calculate the values of the PI and the ones that I have to insert in the phase lead controller, I will use this new values. I have reduced the crossover frequency, looking for a good balance between rapidity, stability and no steady state error but that will make this model to be slower than the one of before.

In this case:

- Crossover frequency = 30 rad/s.
- Gain Margin=-51.

- Phase= 188°.
- Phase Margin= Phase+180.

and the equations that I have used were:

$$T = \frac{1}{\text{CrossoverFrequency} \cdot \sqrt{a}} \quad (4.10)$$

$$K = \left(10^{\frac{\text{Gain}}{20}}\right) \cdot \sqrt{a}; \quad (4.11)$$

$$Ki = 1 \quad (4.12)$$

$$Ti = \frac{10}{\text{CrossoverFrequency}}; \quad (4.13)$$

So the PI has this values now:

- Ki=1
- I=3 (I= $\frac{1}{Ti}$ )

and values of K and T that will be also used in the controller (K as a proportional multiplying everything and T as part of the phase lead part) of:

- K=0.0012
- T=0.0816
- $a = \frac{1}{6}$

The objective of the PI is to finish with the steady state error and the phase lead controller tries to increase the phase the 90° that are going to be lost in the crossover frequency due to the PI.

In order to correct this decrease in the phase. Two phase lead are going to be implemented with the parameter a=(1/6). One phase lead controller with this

parameter is able to increase  $45^\circ$  the phase margin in the crossover frequency. As there will be 2, it will be able to increase the phase margin in  $90^\circ$ , neutralizing the phase margin lost in the PI. It is possible to use also two phase lead of  $a=1/12$  or  $1/8$  which increase the phase margin by  $51^\circ$  and  $55^\circ$  respectively instead of  $45^\circ$  but the behaviour of the system is almost the same so it would not be interesting in term of cost. (It has been tried with just one phase lead with  $a=1/12$  but the system has not been stabilised)

So what has changed in the Simulink model is that 3 new blocks have appeared to substitute the previous PID. In other words, everything is the same than before but in the boost system, in the control part, PID has been substituted for this 3 new blocks:

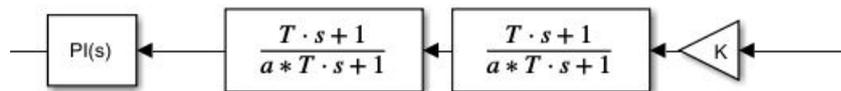


Figure 4.16: Schema of the PI + 2 Phase Lead control

## Results with the PI + 2 Phase Lead

Now in 4.17 can be regarded the response of the system with this type of control:

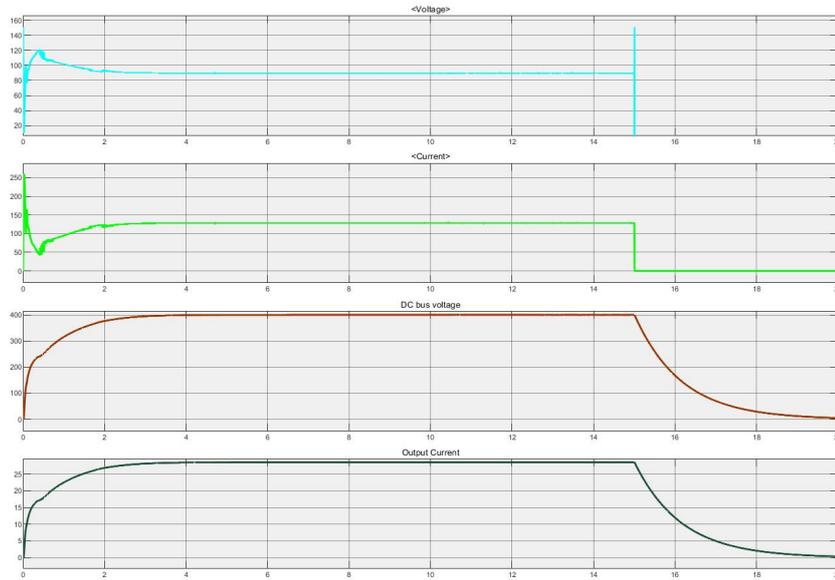
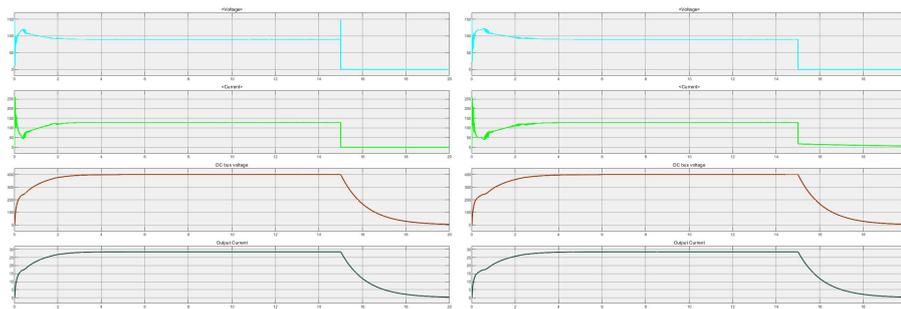


Figure 4.17: Response of the system with the PI + 2 Phase Lead

Two more images are added with the response of the system for an  $a=1/8$  and other one for an  $a=1/12$ .



(a) Results for  $a=1/8$

(b) Results for  $a=1/12$

Figure 4.18: Other experiments

## Results analysis

As it is possible to check with the images, the response of the system with  $a=1/8$  and  $a=1/12$  is practically the same so it would not be worth in terms of cost. As it was attended the speed of the first type of control is faster (higher value of cross-over frequency, lower time response) but this controller is very very good in terms of stability and no steady state error. In this kind of control we stability is being prioritized in front of the speed even if the first control the stability was already very good.

### 4.2.8 Commentaries about the results

Very similar results are obtained with both controllers. Both of them get stable very near to the optimal point (it can be attended as the fuel cell is supplying the power to a charge that is the same than the one that was taken into account in the linearization process. If the value of the resistance is changed, it changes the position in the curve of the fuel cell where we will be situated but it will not change the output voltage that will remain in 400V thanks to the controllers that have been implemented. It will be the output current, the one that will vary (at the output of the boost because at the output of the fuel cell, both voltage and current would change. However, the controller will design a new duty cycle to keep constant the output voltage of the system to 400V).

With both controllers the fixed objective is achieved. In order to choose one of them the prices of the components of both should be checked and also it must be analyzed if for the real application it is needed a bigger or smaller time of response, no- steady error etc. For example in the case where somebody would be interested in prioritize speed, between both of the possibilities, the PID should be chosen as it is observable that its response is faster. In this case it has been shown that the model can work with both of them so, as we are not taking into account any requirements of the type (the system must respond in x time), any of them could work and the cheapest one would be chosen.

REMARK: Both controllers can be optimized in order to reach a better performance in some characteristics if the requirements ask for it but in this chapter, a good balance/compromise between all the characteristics of the response is what has been searched.

### 4.2.9 Complement: Connection to an AC network

The local network can be based in a DC connection. In this case, the fuel cell will be connected with a boost that will raise the voltage until the one that is needed.

However, there exists the possibility that we are interested into connecting it to an AC grid/load. In this case there are two possibilities:

- BOOST+Inverter: with the boost configured to reach an specific voltage and the inverter to convert it into a sinusoidal signal (AC).
- To connect the fuel cell directly to an inverter and suddenly with a transformer that will match the voltage and will make the signal smoother as they are good against armonics.

In this work it is not detailed the modelling of the connection to the grid in the Simulink model but I will try to explain the process.

Firstly, it is necessary to connect the transformer with the desired relation at the inverter output.

In the AC network it is not just important to match the voltages, it is also important to match the phase. So if we are interested in supplying just an active power to the grid, we will try to deliver a current in phase with the voltage. To do that, we would need to build a reference current with this same phase than the voltage (To obtain the phase of the voltage we would use the PLL block in Simulink).

The grid is represented as an ideal sinusoidal source in Simulink and an inductive load is added between the inverter (between the transformer just at the output of the inverter) and the grid (which will take care of the harmonics). Then, the output current is measured and compared with a fixed reference current. We add a PI to the inverter that controls the difference between the currents and provides us with a voltage that when compared with the toothsignal gives us the PWM of command of our inverter.

REMARK: the development of Micro-Grids has brought about a new debate. This debate is about the appropriateness of continuous or alternative networks. Generally, we work in alternative in order to reduce the losses. However, in Micro-Grids, the production is very close to the consumption. In these cases more effective the continuous one. Unfortunately, some of the appliances we use in our

day to day life: chargers, washing machines etc. should be adapted to this type of installation as they have been made in order to work in alternative networks. This possibility opens up a new range of possibilities that will probably vary depending on the characteristics of the Micro-Grid as it is analysed in the article [22]

## 5. Algorithm of supervision

The Micro-Grids need, as it has been shown before, a control mechanism that allows to turn on the fuel cell when its use is necessary, to use the surplus energy of the solar panels and wind energy to produce hydrogen and even to recharge a battery that will feed the installation when the renewable sources are not able to supply the demand. In the graph 5.1 it is shown how a general supervision algorithm works.

In this algorithm that can be run in an average computer, the demand is checked every **15 minutes**. However in those 15 minutes, the algorithm calculates and recalculates with some loops the work regime and it is able to turn down the fuel cell for example if the demand has been satisfied in less than 20 seconds. 20 seconds is the maximum time that the algorithm is going to take to adapt the regime of work. The idea is that with a more powerful computer it would be possible to arrive to run the algorithm in a time very short and always managed by a supervisor to fix possible errors.

There are two ways to command the algorithm: with the power or with the energy.

If it is done just with the power, the algorithm calculates the power **demanded** in those 15 minutes and elaborates the configuration of the micro-grid to satisfy that demand. On the other hand, if it is done with the energy, it also will be possible to simulate how the battery is getting charged and can take changes in the structure, irradiation etc. into account. That's why an algorithm focused in the energy is going to be presented (ideally a power algorithm calculated in a period of time almost null would work better).

## 5.1 Energy algorithm

The algorithm receives the power demand and it calculates the energy that is going to have to supply in the next moment (in our case the information about the demand is given each 15 minutes so it is going to be considered constant during these 15 minutes). And by means of some functions and loops (that are recalculated in a maximum time of 20 seconds), as it will be shown in the following steps, the algorithm is capable of changing the configuration of the Micro-Grid throughout the time.

### 5.1.1 Matlab Model

In the figure 5.2 can be checked the whole Simulink system that has been done to carry out the following simulations

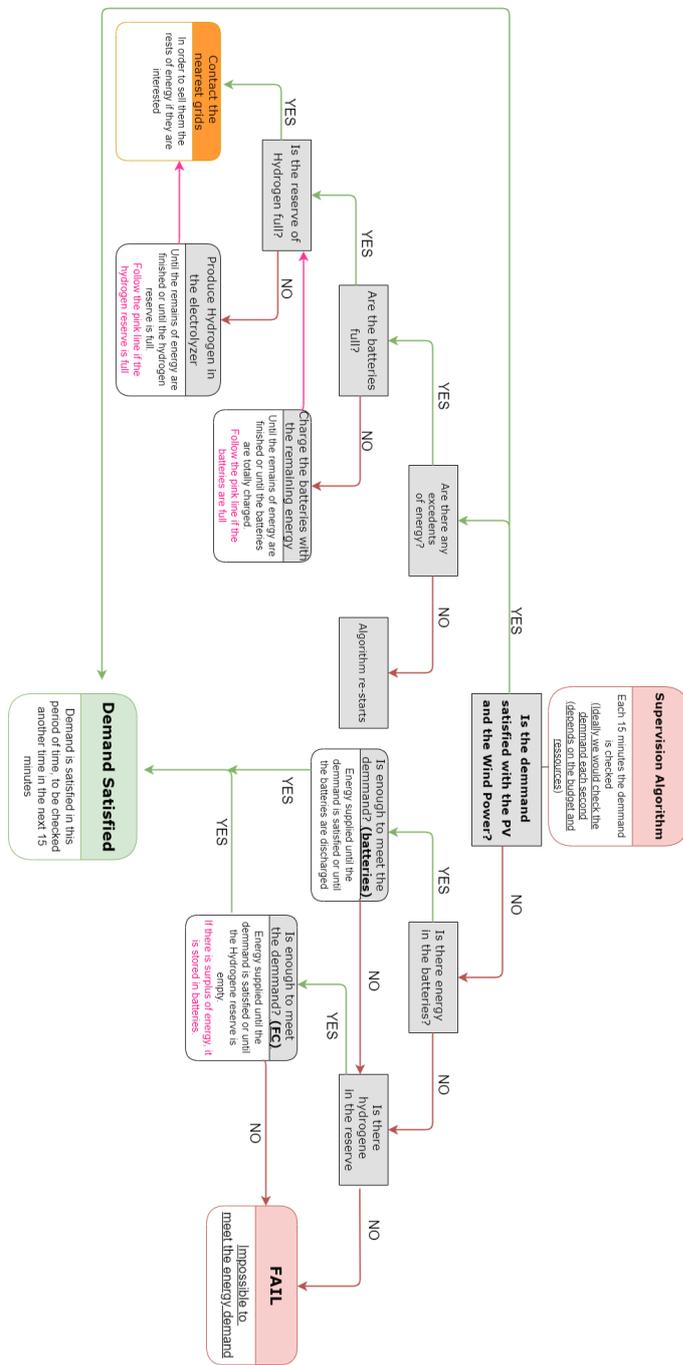


Figure 5.1: Flux diagram of the supervision algorithm

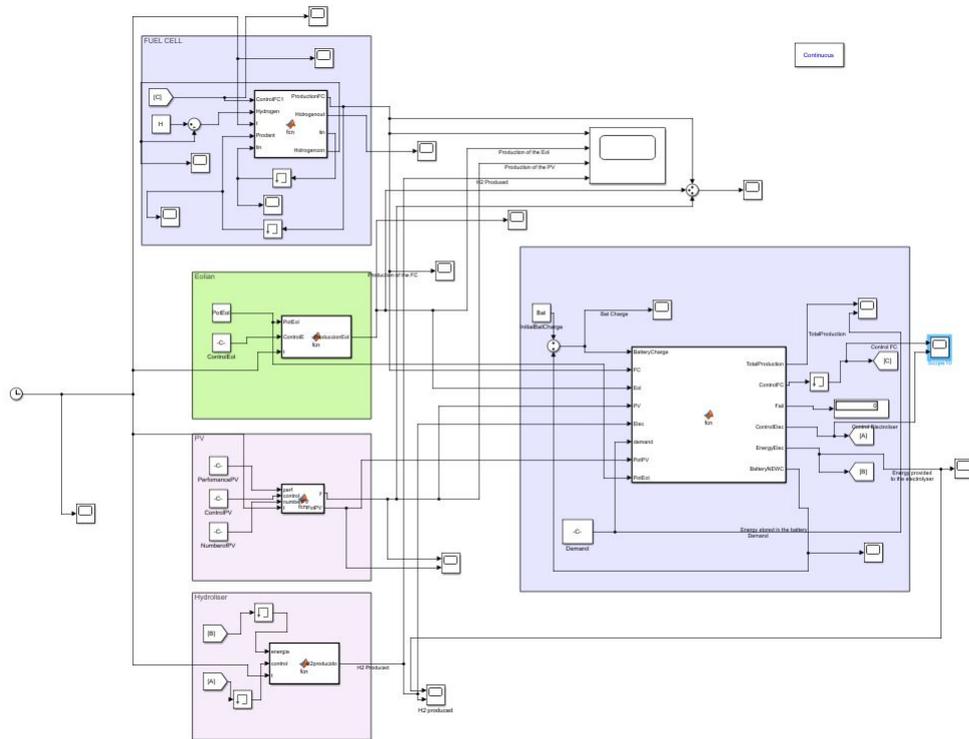


Figure 5.2: Simulink Model of the Micro-Grid with its respective supervision algorithm

### Fuel Cell Block

On the Simulink model that reproduce this behaviour, there is one block that shows the behaviour of the Fuel Cell. This block takes like input the hydrogen stored, a control parameter called "ControlFC" (that is equal to 1 if the supervisor/the algorithm decides that the FC must work or 0 it must not work), the nominal operation of the FC and the time to calculate the energy supplied as:

$$EnergyFC = \frac{NominalPowerFC \cdot timeIN}{3600} \quad (5.1)$$

This "EnergyFC" is calculated only if the hydrogen reserve is not empty and the control parameter is equal to 1.

The  $H_2$  consumed is also calculated, taking into account the average energy that produce an average fuel cell for a Kg of Hydrogen. 25 Kwh/Kg has been chosen as reference but it can be changed to be adapted to the level of production

of any fuel cell.

$$H_2Consumption = \frac{EnergyFC}{25000} \quad (5.2)$$

### Eolian Block

In this case the eolian model is taking like inputs: the time, a control parameter and a parameter that states the power that the Eolian is producing in that moment (we are going to suppose it stable and fixed for the 15 minutes but it is possible to include a variable signal and it will perfectly works). The way to calculate the energy produced is very simple. If the control parameter is equal to one, the energy produced in this period will be given as output. On the other hand, if the control parameter is equal to 0, the algorithm will understand that we have stopped the energy production of the wind farm. In this case the function time is a clock that starts to count so we can check the energy produced in every moment. We do not use in this case the time that is working the Eolian as it will works all the time if the control parameter is equal to 1. We can take into account the lack of wind decreasing the power of the power farm or just changing the control parameter to 0. We will also make the parameter null if we want to stop the production because the wind speed is too high.

$$H_2Consumption = \frac{EnergyFC}{25000} \quad (5.3)$$

### Solar Block

The solar block takes like inputs the number of photovoltaic panels that are available, its nominal performance and a control parameter that will be useful to regulate the stop and continuity of the operation in case of dangerous situations. The irradiation arriving to the panels is also modeled with the control coefficient a it will be explained. In this case the energy production by a solar panel is given by:

$$SolarEnergy = Control * 1000 * performance * numberOfPV * \frac{t}{3600} \quad (5.4)$$

So,  $1000 \text{ W/m}^2$  as the usual irradiation. However, we can take into account the lack of light just fixing a proportional number to the control parameter. If the irradiation is  $500 \text{ W/m}^2$ , a control parameter of 0.5 will adapt the model.

### **Electrolyser Block**

This block works in coordination with the supervision block. The electrolyser block takes as input the time, the energy and the control parameter. The last two are calculated with the supervision algorithm that sends the surplus of energy and turns on the electrolyser when this happens. So it works as a loop, the electrolyser receives an order to be turned on or down by the supervision algorithm and with the energy received, it produces  $H_2$  that is supplied to the Fuel Cell in the next 15 minutes. It has been considered an average consumption of 50KWh to produce a Kg of  $H_2$ . So it can be concludes that the whole operation electrolyser+Fuel Cell as a way of storing energy in form of  $H_2$  to re-produce energy when it is needed have an overall performance in our system of 50%. Anyway, those parameters can be corrected for a better adaptation to the system.

### **Supervision Block**

This block is in charge of turning on or off the rest of the blocks. It takes all the data that it receives from the energy production blocks and performs the steps shown in the diagram of the algorithm by using multiple loops and conditionals that regulate the response of the system to the different possibilities. This block returns a "fail" parameter that becomes 1 if the algorithm detects that it is going to be impossible to satisfy the demand. This parameter would make the supervisor to communicate immediately with the nearest network to buy extra energy. In case this is not possible or we are talking about a Micro-Grid isolated, the system would give a warning to the user communicating that the supply might stops and would ask to try to reduce the consumption. This block also returns a block that summarizes the total energy production and compares it to the demand. It also regulates the control parameter of the fuel cell and the electrolyser if the necessary conditions are met. Finally, it calculates the variations in the battery charge either because they are being charged or because they are being used to supply energy. The production blocks and the supervision one must work together and the exchange of information must be uninterrupted for a proper functioning.

**First Case: PV and the Eolian supply all the energy demand and batteries are full**

**Remark:** For this case we are going to state as inputs:

- NumPV=133 (number of solar photovoltaic panels)
- Performance=0.12 (performance of the PV)
- H=2 Kg of Hydrogen stored
- PotEol=7500 W (Average power of the eolian system)
- Bat= FULL (charge of the battery)
- Demand=1720 Wh

**How to choose the initial parameters.**

Basically the characteristics of the renewable sources have been introduced as inputs in the system and also a fixed a demand of 1720 Wh. In order to fix this value there are different strategies: to take the peak value of consumption is the last 15 minutes (more secure) or to take the last value of consumption of the last 15 minutes (risky as it would be possible that everything is turned down in that moment and the expectations would be smaller than the real consumption) or to take an average of the last 15 minutes real consumption giving some coefficients for the time intervals when energy is more required (very balanced option). For example, if the system register an average consumption of X Wh in the interval between 20:15-20:30, it can predict that the owners arrive home at 20:30. So, the system can preview that the consumption is going to increase so it is going to configure the system for  $1.5 \cdot \text{AverageRealDemand}$  in the last 15 minutes (we can also use the average of the hour or half an hour, it depends on the system and its capacity of change)

**Results**

So the simulation was executed for 900 seconds (15 minutes) and the following outputs have been received:

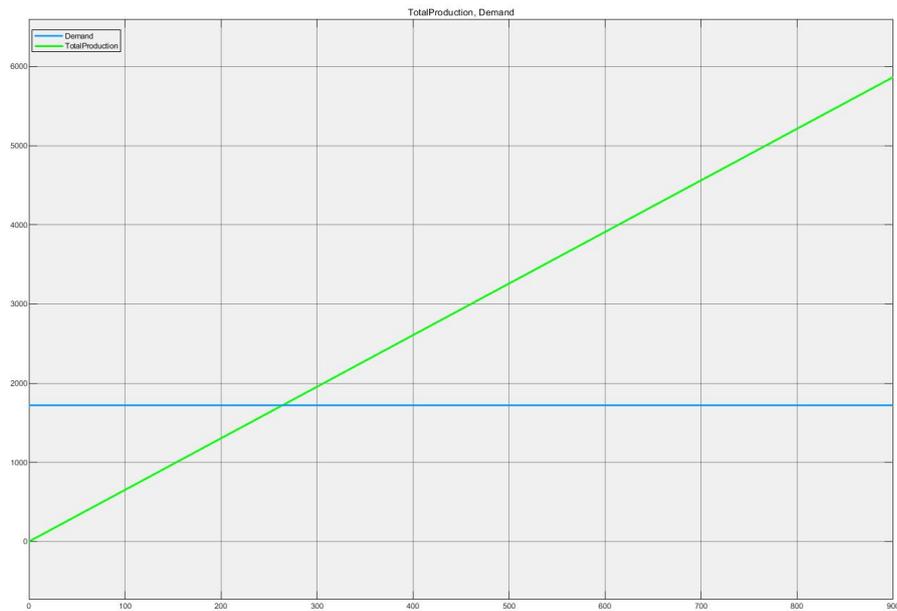


Figure 5.3: Total production (Green) and demand (Blue)

The green line is the total consumption and the blue one the barrier that fix the demand. So, in this first case, the whole energy that is going to be consumed in the following 15 minutes (900 second) is already produced in the second 260 more less.

Regarding the graph of the algorithm and clarifying that 2 Kg is not the maximum capacity of the hydrogen reserve, we are seeing that the rest of energy must have been supplied to the electrolyser in order to use this surplus of energy to produce  $H_2$  (as batteries are already charges) that will be used in the future to produce energy in the fuel cell.

As it has been seen before the production exceeds the demand of the whole period in 260 seconds (that means that the whole energy that is going to be needed is already produced in the second 260. (**Note:** In the real model this energy would be supplied with small batteries or systems to distribute the energy in a larger period of time).

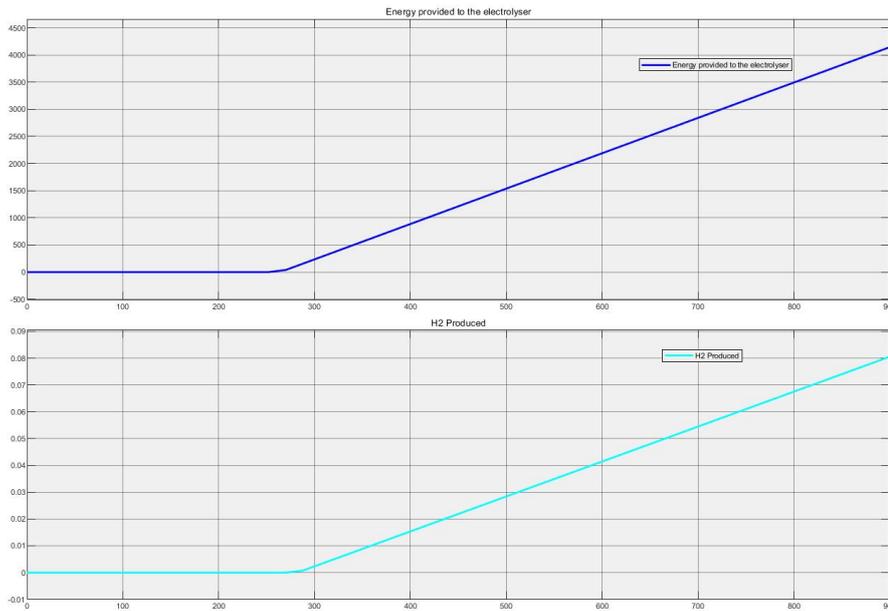


Figure 5.4: Energy supplied to the electrolyser (Dark Blue) and H<sub>2</sub> produced (Light blue)

The result of the electrolyser in the system is satisfactory as it can be checked in the results. Some energy is supplied to the electrolyser in the second 260 and some H<sub>2</sub> is produced.

At the end of the simulation we have produced 0.08 Kg of H<sub>2</sub>. Result that was attended as we had a surplus of energy of more less 4KWh being 50KWh the average energy that takes our electrolyser to produce a Kg (As it was said before, this value can be changed to be adapted to the electrolyser of the facility).

In the next figure you can appreciate that the control of the FC is always zero (turned down). On the other hand, it is possible to see how the control parameter of the electrolyser changes when we have a surplus of energy (it is not a direct change as the algorithm takes some time to do all the operations)

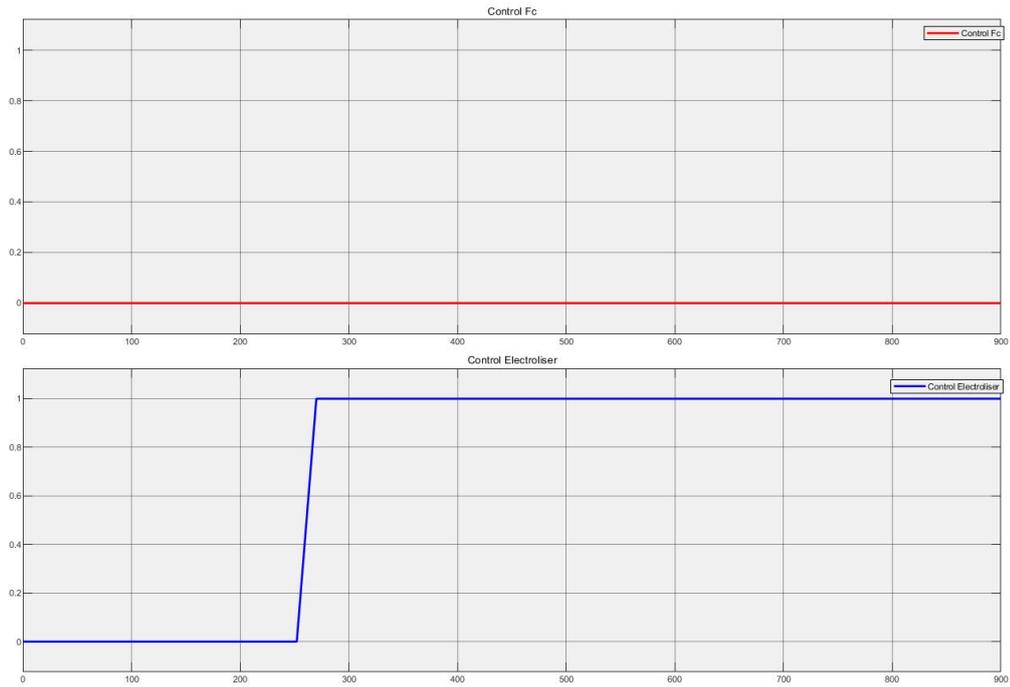


Figure 5.5: Control parameter value of the FC (Red) and the electrolyser (Blue)

And in the next picture 5.6 the production of each block can be found:

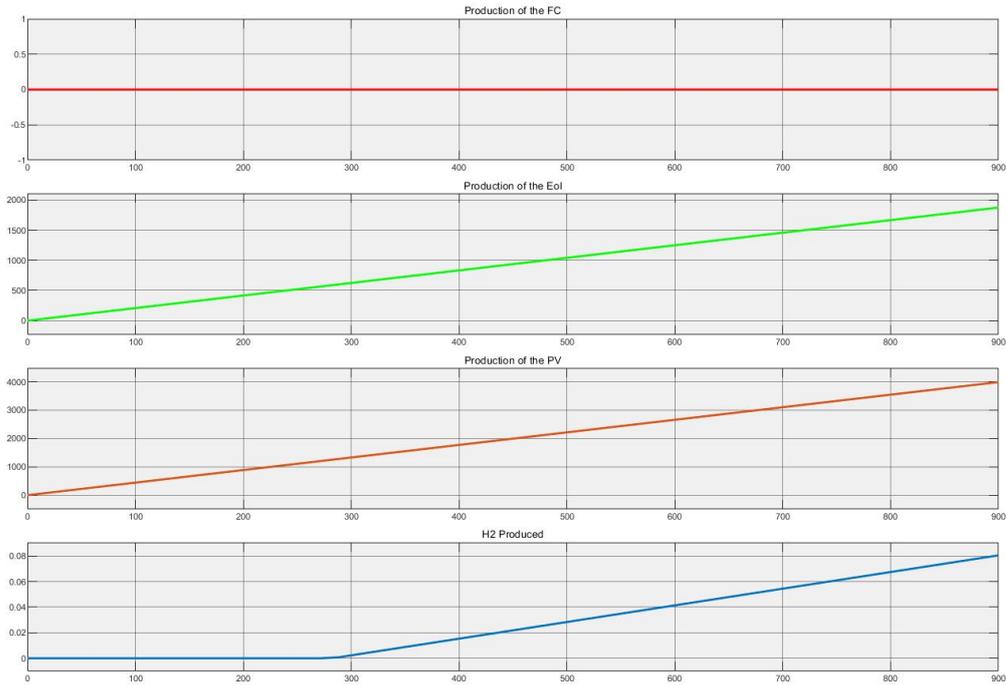


Figure 5.6: Plot of all the blocks production: FC (Red), Eolien (Green), PV (Orange) , H2 production of the electrolyser (Blue)

As it was expected the production of the Fuel Cell is null and the total production of the PV and the Eolian is near 5800 Wh that is clearly enough to satisfy the demand of 1760 Wh and to use the surplus of energy for producing 0.08 Kg of  $H_2$ .

### Second Case: PV and the Eolian system are not enough to supply all the energy demand

In this case it will be necessary to turn on the FC as we are going to see in the following case. The only changes with respect to the inputs of the last try are the demand and the battery charge (now they are empty).

In blank the changes of the input parameters (just the demand in this case)

### Input Parameters

- NumPV=133 (number of solar photovoltaic panels)
- Perfomance=0.12 (perfomance of the PV)
- H=2 Kg of Hydrogen stored
- PotEol=7500 W (Average power of the eolian system)
- **0 Wh** (charge of the battery)
- **Demand=6500Wh**

### Results:

This time, the results of the simulation are going to be presented in first time and after the results will be discusses as the general behaviour of the algorithm has already been explained.

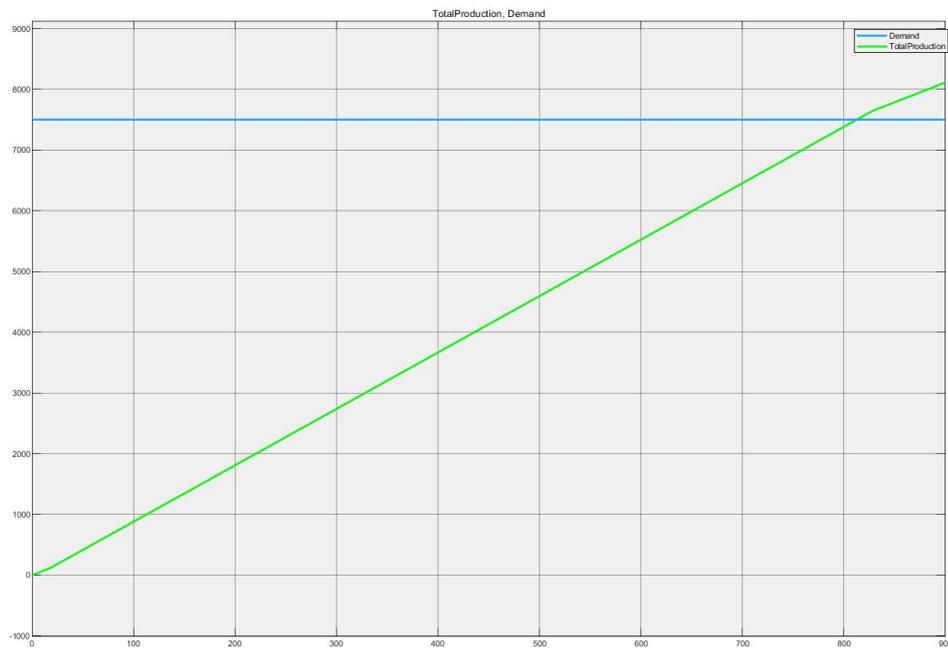


Figure 5.7: Plot of the total production and the demand of these 15 minutes (Second Case)

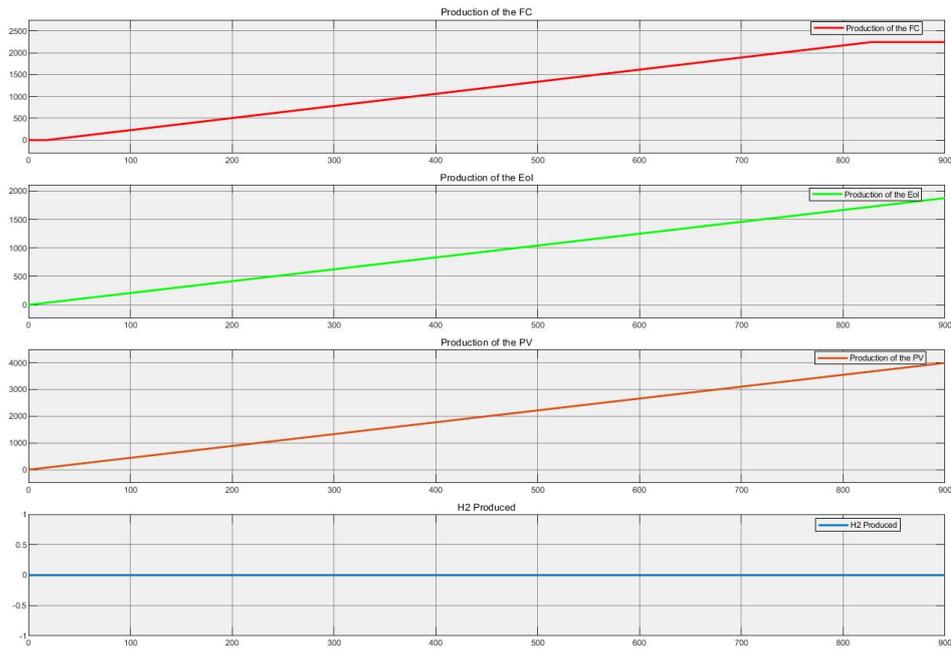


Figure 5.8: Plot of all the blocks production: FC (Red), Eolien (Green), PV (Orange) , H2 production of the electrolyser (Blue) (Second Case)

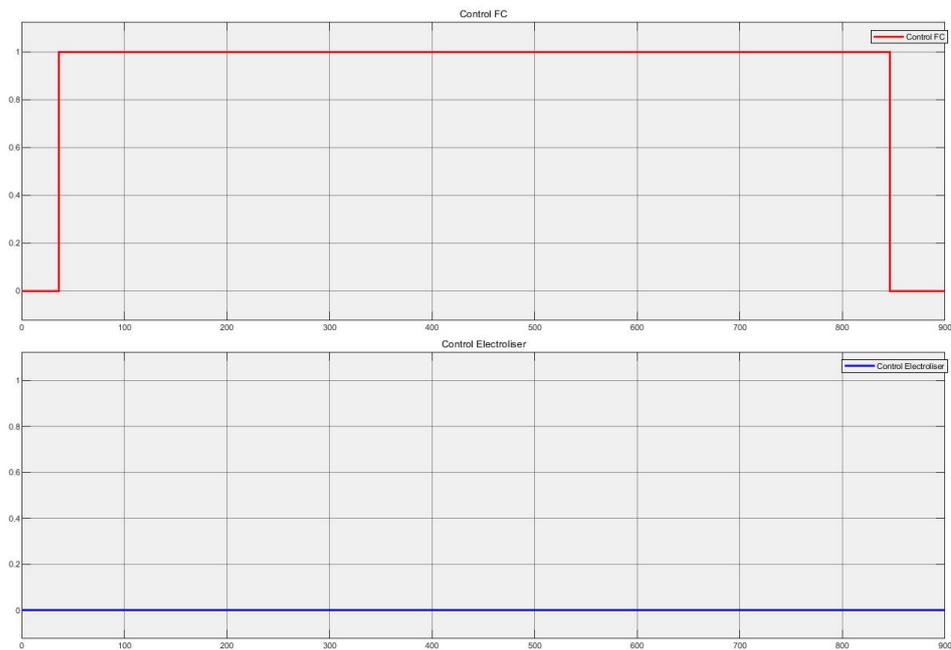


Figure 5.9: Control parameter value of the FC (Red) and the electrolyser (Blue) (Second Case)

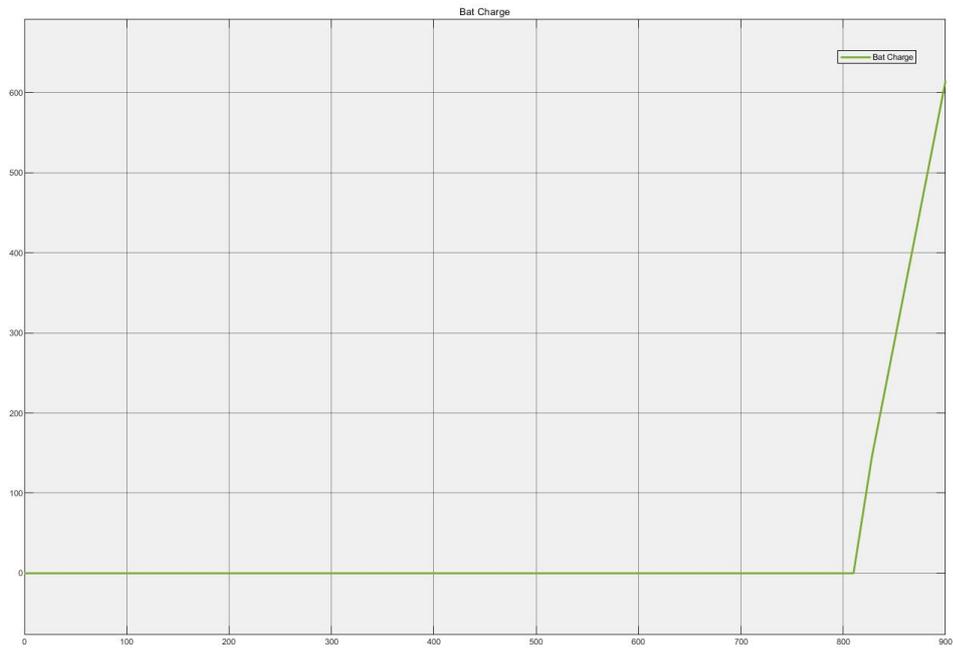


Figure 5.10: Battery Charge (Second Case)

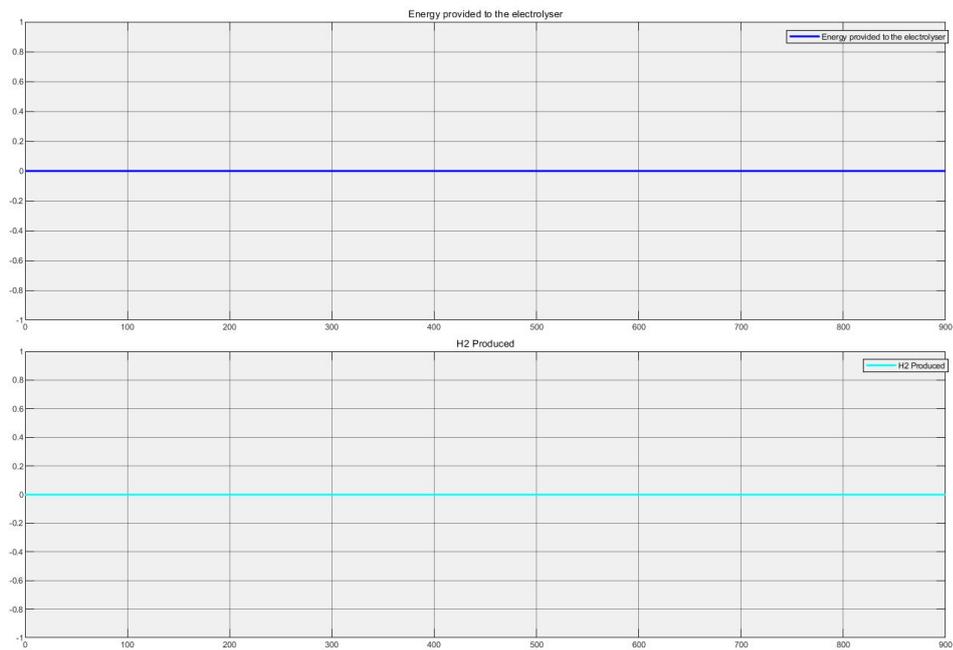


Figure 5.11: Energy supplied to the electrolyser (Dark Blue) and H2 produced (Light blue)(Second Case)

In this case, the algorithm calculates that it is not going to be possible to supply the electricity demanded in the following 15 minutes just with the PV and the Eolian system. It will try to check if it would be enough adding the batteries charge but in this case, they are empty. That will result in a change of the control parameter of the fuel cell that will change to 1. Thanks to the help provided by the fuel cell we will produce all the energy needed in those 15 minutes in the minute 13-14 as it is shown in B.5 (we will use the surplus of energy to store it in the batteries). Once the algorithm is sure that the energy is going to be provided, it can turn down the fuel cell.

The algorithm takes a little period of time as we can check in 5.9. That's because the algorithm has to be re-started and there is a loop between the block that states the control of the fuel cell and the one that calculates its production (to give it another time to the block that states if the control must be 1 or 0). This system conditions force us to use the "memory blocks". This block creates a type of delay between the different results creating steps of the calculated value in some sample periods. This memory blocks have initial conditions. The initial condition of the control parameter of the fuel cell is equal to 0.

If the resources were unlimited to execute the algorithm in a continuous way between the 15 minutes interval, the response of the algorithm would be faster as it happens when the fuel cell must be turned down. As I need this block that creates this small delay and taking into account that the initial value is 0, it takes some time to change to 1. To sum up, the algorithm takes the initial value that is 0, takes this value for a small interval of time and calculates that we need the fuel cell. It returns a parameter explaining that the fuel cell must be turned on and after a small delay, the order arrive to the fuel cell block. The control parameter is equal to 1 until  $t=850$  more less when the algorithm calculates that it is enough to supply the energy demanded and it orders the fuel to be turned down. As the algorithm is already running, the response is much quicker.

As there is a surplus of energy in the last seconds, we take advantage of the situation and we charge the batteries directly with this charge as it s shown in 5.10. In this program it has been supposed an ideal charge of the battery a performance of the 100% but that can be changed at any time with the specifications of the batteries.

As it was expected, the electrolyser has not received any energy so it has not produced any Hydrogen 5.11.

### **5.1.2 Other cases**

Other cases are presented in the appendix B in order to prove that the algorithm model works under all the circumstances. However, the results will not be discussed as the overall functioning of the model has already been explained.

# 6. Economical Analysis

## 6.1 Introduction

In the following pages, it will be given an approach of the cost of a Micro-Grid based only on solar technology and the fuel cell as sources of energy production. Also some comments on the profitability of each case and on aspects to take into account will be given. In this case, it will be considered the consumption of 4 domestic houses.

## 6.2 Consumption of a domestic home

The average domestic house consumes between 9-12 KWh on average per day in Spain. However, in Spain, the majority of houses have a consumption of gas for example for heating/cooling systems. This makes the consumption reach a value of 30 KWh per day between electricity consumption and heating systems.

A demand profile has been elaborated with the help of an excel sheet and with the average consumption of each electronic appliance you can find in a house. To do this, I have divided the 24 hours that a day has into 96 intervals of 15 minutes and I have selected which device is on at each moment. Doing it over the winter period (worst case scenario since it is necessary to turn on the heating which consumes a lot of energy) and trying to represent the consumption of a very demanding day, we reach a total consumption of 30.798 KWh. Reviewing the consumption of my own house and those of an average house in Spain (more than 15KWh for a single-family home in total electricity[23]) and being said that the heating system represents a 47% of the consumption in Spain [24], it can be concluded that the consumption profile elaborated would be the one of a "big" house and in a super demanding day. However, when designing this type of installation is

always essential to consider a worst case scenario and even include a safety factor for avoiding the risks of not being able to supply the necessary energy. So in the rest of the economic analysis it will be this consumption profile the one that will be used.

In this case, the heating system also will be electric (although its cost is much higher than using gas and it is possible to take advantage of the heat emission of the fuel cell) as it is difficult to quantify this contribution.

### 6.3 Analyzing the consumption profile

In the graph 6.1 you can see, the estimated consumption profile that has been elaborated for the analysis. Each line is the energy consumption in 15 minutes. As it is explained previously, it is a demanding winter day. Also it has been calculated the the peak power that the system may need to supply because in the case that it is not possible to supply it, there will be an electrical outage. This will be an important information to choose the number of solar panels, the nominal power of the fuel cell, the capacity of the batteries etc.

With this model, an average house uni-familiar in an exigent day of winter present the following consumptions per day:

- With an electrical heating system: **30,798 KWh**
- Without:**17,393 KWh**

To elaborate the estimation about the peak of power the **Simultaneity factor** has been used.

#### 6.3.1 What is the Simultaneity factor and how to calculate it?

The simultaneity factor tries to calculate the maximum power you may have on at the same time at home. To do this, it is necessary to add up the power of all the appliances that consume electricity in the house [25]. It is also interesting to use some coefficients that will take into account the probability that two or more appliances are on at the same time. For example, in the case of the washing

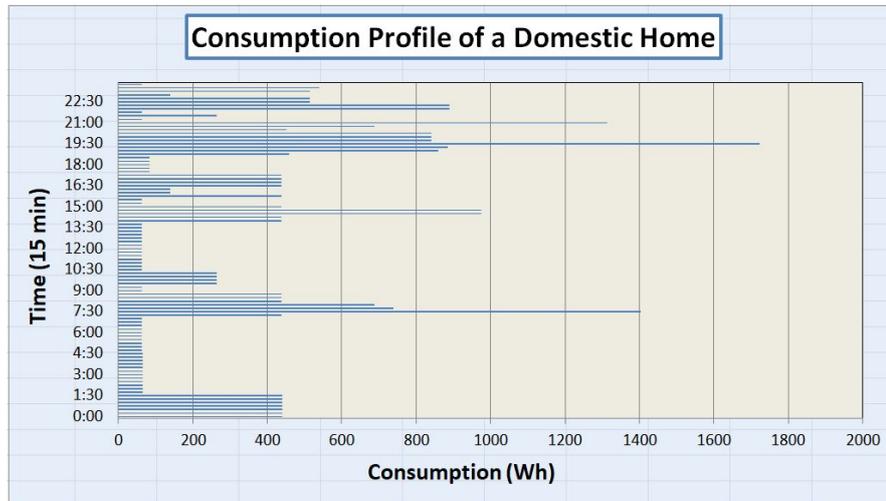


Figure 6.1: Consumption profile of a domestic house

machine and the dryer, as the normal situation is that you put the washing machine and later, when the washing machine has finished, things are put in the drier, their power consumption is going to be multiplied by 0.6 as it is not frequent that both are working at the same time. In this way, if each of the appliances has a power of 3000W, a total power between the two of  $0.6 \cdot 6000$  will be considered for the simultaneity factor.

In order not to risk a failure in the electricity supply, the power of our electricity generation systems should at least be similar to this simultaneity factor.

In the figure 6.2 you will be able to check the Simultaneity coefficient that has been given to any electric appliances in the model that is going to be analysed.

With this coefficient, the result given is a maximum power required by this uni familiar house of **18,41KW**. Besides, the profile of consumption allows to identify the hours where it is more likely to reach this power peak.

### 6.3.2 Analyzing the production of the solar panels

The value of  $1000 \text{ W/m}^2$  is normally accepted as the amount of radiation reaching the Earth from the sun. However this irradiation is not constant over time. There are cloudy days and even on a normal day the irradiation at 15:00 is not the same as at 05:00.

Object	Average Consumption (W)	Simultaneity coefficient
Fridge (200L)+Freezer	250	1
Electric Hob	2000	0,7
Electric Oven	2500	0,7
Micro-Wave	800	0,7
Coffee Maker	1200	0,6
Toaster	1000	0,7
Smoke Stractor	150	1
Mixer	200	0,7
Dishwasher	1500	0,7
Hot / Coolant Water Source	400	1
Washing Machine	3000	0,6
Dryer	3000	0,6
Clothes Iron	1000	0,7
Vaccum cleaner	800	1
Electric mower	1500	0,5
Water boiler	2000	1
Electric convector	1500	1
Boiler circulation pump	60	1
Hair Dryer	600	1
Shaving Machine	20	1
Mobile charger	5	1
TV plasma	300	1
Home Computer	80	1
Portable Computer	30	1
Printer	800	0,6
Scanner	600	0,6
Router Wifi	5	1
Fan	50	0
Air Conditioning	1200	0

Figure 6.2: Simultaneity Coefficient of each electrical device

That's why an elliptical profile of the solar irradiation is being considered as the one that is shown in the figure 6.3

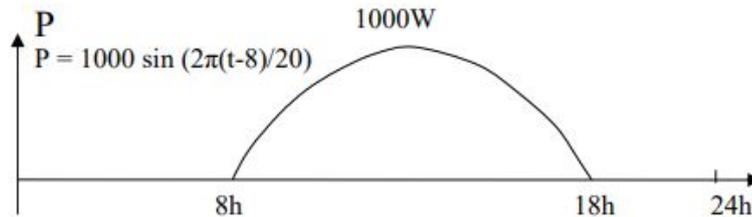


Figure 6.3: Solar illumination profile

It is possible to calculate the energy provided by  $1 \text{ m}^2$  of solar panel with this illumination profile. In this case, the energy will be calculated with the formula adapted to this solar illumination profile (6.1).

$$Energy = \eta \cdot \int_8^{18} 1000 \cdot \sin(2\pi(t - 8)/20) \quad (6.1)$$

Obtaining a result of:

Energy provided by the solar panels is:  $6366.2 \cdot \text{Number of Panels} \cdot \eta$

Each square meter of solar panel (with a performance of 19,7%) produce in a day (with the irradiation profile already detailed): 1254.14 Wh

### 6.3.3 Choice of the material needed

First of all, it is necessary to define the quantity of solar panels that are going to be bought. To calculate how many are necessary, it is required to choose an specific model to calculate the energy production over the day.

Nowadays, there exist a lot of solar panels suppliers with different performances and techniques used.

Another important difference between solar panels is the guarantee they offer and the assured performance at the end of 10 or 25 years. For this economic analysis, we will use a **"Panasonic" brand solar panel VBHN325SJ47**. It is one of the best panels on the market in 2019 according to the OCU with a

score of 94/100 and a considerable difference compared to other manufacturers who can offer the same performance at a lower price. The difference between these manufacturers and Panasonic is that for this product, Panasonic offers a 25 year warranty, a proper functioning is assured during this period of time. After consulting some web pages of solar panel suppliers, it has been found that from 50 solar panels, these have a cost of about 205 euros per panel of 1x1.67. On the Panasonic website, it is possible to find more information about this module [26]

As this Micro-Grid was designed for 4 uni-familiar domestic homes, the requirements will be 4 times those of just one uni-familiar domicile.

To assure the supply of electricity and to be sure that the installation will be able to provide as many electricity as needed, the micro-grid will be designed with a **security factor of 1.5 the demand estimated** So the production of energy must be at least  $1,5 \cdot \text{Electrical consumption}$ .

Now the quantity of solar panels (that have a performance of 19,7%) to be bought is going to be calculated with the total energy that is consumed multiplied by the security factor:

- With an electrical heating system: **123,192 KWh** (184,788 KWh with the security factor)
- Without: **69,572 KWh** (104,358 KWh with the security factor)
- Maximum Power Required : **73.64KW**

In order to produce this electrical energy, it will be necessary:

- With the heating system  $147.34 \text{ m}^2 = 90$  panels of 1x1,67 m
- Without 69,572 KWh (104,358 KWh with the security factor) =  $83,21 \text{ m}^2 = 50$  panels
- Taking into account the 90 panels whose maximum power is 197W. We will be able to reach a maximum power of 17,730 KW

With this 90 panels, the Micro-Grid will provide the total energy needed over a normal day but we may have some problems to provide the power necessary to make work all the devices in concrete moment of the day.

Analyzing the demand profile that was elaborated, it is possible to check that there are 3 moments specially dangerous: morning (7-8h), lunch time (14-15h) and dinner time (20-21h).

At lunch time we can expect to have high levels of production due to the irradiation expected for this time but in the others, we will need the batteries and the fuel cell to supply the power so it will be very important the choice of them.

Normally, the energy that is going to be supplied is produced so it will be the objective of the batteries to supply this power (also with the help of the fuel cell and the PV). The maximal consumption of a house is 18,41 KW. We have four different houses but it will be very difficult that the four houses were in a moment of maximal demand of energy at the same time. Normally, a battery of 48V and 1000Ah would be enough to supply this energy. It is possible to find the data-sheet of this product in [27]

For the solar installation, they are also necessary [28]:

- Solar Inverter: It transforms the DC current produced by the solar panel into AC current for use.
- Support Structure: In charge of orienting and protecting the panels
- Bi-directional counter: allows to elaborate a load curve of the house for an optimization of the self-consumption
- AC and DC protections: include all the necessary protections for the installation
- Legalization and bulletin: regularization of the installation
- Labour force and materials

Regarding the electrolyser and the fuel cell. The Micro-grid that is being used for the economic analysis will be composed of a 10 KW fuel cell and an electrolyser capable of producing a standard cubic meter of hydrogen in one hour.

In this way, between the battery and the fuel cell, we could supply more than the maximum expected power calculated thanks to the simultaneity factor for three houses (instead of 4 as increasing the power of the fuel cell increased a lot the cost of the installation and normally the 4 houses do not reach this point of maximum power at the same time) This maximum power capacity is already very

good taking into account their average consumption and the security factor that has been used).

### 6.3.4 Cost of the whole installation

In the table 6.4 the costs of the installation are going to be detailed by parts. The total cost of the installation depend a lot on the cost of the fuel cell and the electrolyser, whose technology is being developed quite fast with the help of some big companies that have bet for this kind of technology. Some of these companies are TESLA or NIKOLA, who pretend to build the Hydrogen network of the USA so the cost of the electrolyser and the fuel cell may will be reduced in the following years. Given this we arrive to a cost of the whole installation of 100 000€(rounding the final value).

Producto	Quantity	Unitary price	Total Price
Paneles Solares Panasonic VBHN325SJ47	90	205	18450
Inverter charger of 48V and 8000W	4	1778	7112
Support structure	45	80	3600
Bi-directional counter	1	220	220
AC and DC protections	1	350	350
Legalization and bulletin	1	300	300
Labour force and materials	1	800	800
BAE Stationary Battery 48V 1000Ah	1	10066	10066
Electrolizer (including Hydrogen reserve)	1	10000-15000	10000-15000
Fuel Cell (10KW)	1	45000	45000
<b>TOTAL PRICE</b>			<b>95898-100898</b>

Figure 6.4: Table with the costs of the installation

### 6.3.5 Cost Analysis

The solar installation has a warranty of 25 years while the electrolyzer-fuel cell systems have a warranty ranging from 5-10 years depending on the use and the manufacturer. That's why it will be necessary to take into account that maybe during the 25 years, there exist the possibility of having to change the hydrogen system.

To calculate the amount of money that is saved for not buying the energy from the general grid, it is important to know that the rates vary according to the time interval. In this analyses, it is going to be used the average value throughout the day, even though people normally consume more electricity during the day, since there is not so much difference between the lowest and highest price of the day (0.089-0.102 the KWh).

If the consumption is about 123.92KWh per day, this makes 3717.6 KWh per month and 44611.2 KWh per year. Taking the current average daily price of electricity (0.06 euros per KWh) this makes a consumption of 4282.68 euros of consumption saved in the first year.

The RPI (equivalent to the Spanish CPI) in recent years has presented an average increase in the cost of electricity of between 5% and 10%. That is why, being optimistic, an inflation rate of the 5% is going to be used for the price of electricity.

Analyzing the investment, all the expenses will count as costs in the first year, and the money saved over the years will be presented as a benefit of an inversion (always updated to current prices with a discount rate took from the banks loan rates)

When updating future prices to a current price, it has been taken into account the average interest rate for the month of April 2020 in Spain: 7.41 % as it will be the one that is going to be used to calculate the NPV (VAN in Spanish)

#### NPV result

Taking into account the discounted rate and the inflation of prices, a **net present value of 83123,44 €** is presented as the energy costs saved with this inversion (without taking into account the costs of the Micro-Grid).

It has to be compared with the cost of the whole installation that are presented

in the table 6.4 However, we may consider the replacement of the hydrogen system once in this 25 years what would increase the costs until 150000 - 160000 €.

For calculating the NPV, the cost of the KWh has been multiplied by the annual consumption and also by the inflation factor (as many times as years have passed) as shown in 6.2 and in order to bring this value saved (that i am going to take into account as benefit) and to update it to an actual value I am going to divide it for the discounted rate as many times as years have passed 6.3

$$EnergyCost = ActualCost \cdot (1 + PriceInflation)^{Numberofyears} \quad (6.2)$$

$$ActualValue = \frac{EnergyTotalYearCost}{(1 + DiscountedRate)^{Numberofyears}} \quad (6.3)$$

### 6.3. Analyzing the consumption profile

Consumption (KWh) (diary)	123,195
Consumption (KWh) (annual)	44350,2
Electrical Inflation rate	1,05
Discounted Rate	1,071
Electrical Price	0,096

Figure 6.5: Parameters used in the NPV calculation

Years	Price per Kwh	Benefits	Updated benefits	VAN
1	0,1008	4470,50016	4174,136471	83123,44313
2	0,10584	4694,025168	4092,290657	
3	0,111132	4928,726426	4012,049664	
4	0,1166886	5175,162748	3933,382024	
5	0,12252303	5433,920885	3856,256886	
6	0,128649182	5705,616929	3780,644006	
7	0,135081641	5990,897776	3706,513731	
8	0,141835723	6290,442665	3633,836991	
9	0,148927509	6604,964798	3562,585286	
10	0,156373884	6935,213038	3492,730672	
11	0,164192578	7281,97369	3424,245757	
12	0,172402207	7646,072374	3357,103683	
13	0,181022318	8028,375993	3291,278121	
14	0,190073434	8429,794792	3226,743256	
15	0,199577105	8851,284532	3163,47378	
16	0,20955596	9293,848759	3101,444883	
17	0,220033759	9758,541197	3040,632238	
18	0,231035446	10246,46826	2981,011998	
19	0,242587219	10758,79167	2922,560782	
20	0,25471658	11296,73125	2865,255669	
21	0,267452409	11861,56782	2809,074185	
22	0,280825029	12454,64621	2753,994299	
23	0,294866281	13077,37852	2699,994411	
24	0,309609595	13731,24744	2647,053344	
25	0,325090074	14417,80981	2595,150337	

Figure 6.6: NPV of the inversion

### 6.3.6 Analysis of the results and conclusions

The calculation of the NPV is detailed in the tables 6.5 6.6. As conclusion it can be considered that the general balance of this installation, in an isolated way, dedicated to a self-consumption would present an NPV-Cost= -12774.6 / -17774.6 euros so the inversion will present losses that would be increased in case of having to replace the electrolyser-fuel cell system. This inconvenience could lead to a negative balance of up to -70000 euros.

#### Houses with an existing grid

Firstly, it is going to be analyzed the appropriateness of this investment in cases where there is already a general grid from which to buy an energy supply.

Within this category, two different cases are considered:

#### Domestic houses

In this case, the clients are going to have money losses (since the NPV is lower than the initial investment) and they would only gain resilience and security, two not too important properties in a residential house where its inhabitants spend at most 50% of their time (since they have to go to work, study etc).

In this case, a Micro-Grid like the one detailed above would not be profitable on an economic level. In this case, it would be much more profitable to make a solar installation if there is the necessary space (since this way we would reduce the cost to 50% and the investment would become profitable). Moreover, being connected to a general network, the production does not have to be higher than the demand at all times, as it is possible to buy electricity from the general network. In addition, in this case, a Micro-Grid (based on a solar installation but without hydrogen) system can be programmed so that the purchase of this energy take place at the time when energy is cheaper and to store it in the batteries. This and the possibility of selling to the general network the overproduction of energy, make this Micro-Grid more interesting at present but not the one was designed for the economical analysis.

### **Special buildings**

On the other hand, there are buildings such as hospitals, police stations, fire stations etc. whose uninterrupted service is essential for the proper functioning of society. Some of these buildings, depending on their size and importance, could finance this operation despite the loss of money due to the extra security network resilience and reliability that this investment would bring. In addition it must be taken into account that the hydrogen technology expects to reduce its costs considerably which would mean a much lower cost when it will be necessary to replace the hydrogen network. Moreover, the possibility of buying energy from the network and storing it in batteries which can make the installation very profitable.

Therefore it can be summarized that some buildings, according to their function and structure may be interested in this installation due to the increase in security and operation of the network. In addition, there are measures that would allow these buildings in particular to optimize the installation to their needs and therefore reduce these economic losses.

### **Houses without an existing grid**

This case is a little more special. As it has been exposed, the 50 % of the people without access to electricity live in rural areas without access to a general grid. In this case, the installation is clearly profitable since it will allow the development of the area both technologically and economically. The possibility of using irrigation techniques that use electricity and also improve the quality of life justify this investment. In these cases it is not possible to calculate a NPV as there is no possibility of purchasing from a general network. Furthermore, in these cases there is no alternative for having access to electricity as bringing a general network to a remote point is almost unaffordable in this moment and clearly much higher than the cost of manufacturing this installation which also provides a quality electricity supply (which could even be converted into benefits thanks to the possibilities that electricity provides for an area where this supply did not exist before). In addition, with the passage of time the hydrogen technology will lower its price reducing the costs and other energy sources can be exploited, such as wind or hydro, that may be more adapted to the characteristics of each region what would make this installation even more profitable.

To sum up, since there is no other option, it is profitable because electricity is a necessary good for a community to develop economically and at the same time improve the quality of life of families. Not only it can be economically profitable

in this case, but it is also a great option to make electricity available to those who do not yet have access to it.

# 7. Conclusions extracted from the project

This project can be divided into 4 different parts that cover many aspects and problems of the current energy sector:

## 7.1 The research and understanding phase

Firstly, a phase of research and understanding of the current energy context and the situations in which a micro-grid could be very beneficial. In this phase a closer look at the energy market and the problems that engineers are encountering nowadays. It is also presented the main technology used by the renewable sources of energy that will be very important in the fight against the  $CO_2$  emissions. Also, in this phase Also in this phase, it is discovered the importance of the automatic and electronic systems, essential nowadays to obtain the best performance of this type of installations. In addition, the acquisition of knowledge about control is key in a moment when control systems are taking a superlative importance for the optimization of systems that make projects like this profitable. This results extremely important, there are many projects, many Micro-Grids that are profitable, in terms of economy and energy supply because of the optimization in the management of the grid. In the absence of an efficient control mechanism this kind of systems would not be able to supply the demanded power or would need more people responsible for carrying out that control manually, what would increase a lot the costs of the facility.

## 7.2 Control model of the Fuel Cell

This part has been the most important one of the project and by far the one that have required the longest time. This part has covered the study of the system, the study of the connection to the load and the adaptation of the output parameters to fit the requirements. Simulink is a software that allow its users to reproduce the behavior of the system (a fuel cell with the boost converter and the control system in this case). Thanks to the results given by the program, it is possible to modify the control system to obtain a response that meets the criteria that have been established. This way of anticipating the behavior of a system allows companies to reduce costs because once the control system is designed and the needed electronic system have been found in order to make the connection to the load, the minimum capacities of the pieces to order, its work regimes and the limit cases of the real system are guessed by the company.

Talking more specifically about the project, with the result obtained, it has been demonstrated that there is not just a single way for branching the fuel cell since it is possible to connect it to a continuous or alternate installation. Also, it is possible to receive different responses/behaviours from the fuel cell so the control system must be adapted to the requirements fixed by the environment of the project. There exist different ways of controlling the fuel cell and they can be adapted in each case for different functionalities and characteristics of the environment. For example: In the case that there is a low production coming from the photovoltaic or the wind system that is not able to cover the demand and it is necessary to turn on and off the fuel cell in multiple occasions for supplying the energy demanded. In that case it may be interesting to prioritize the speed against stability and non-steady error (always with a minimum requirement for the others). On the other hand, it is possible to find other situations where the most important thing is that the electricity supply is stable so that there is no risk of power outage (as could be the case in a hospital).

The model developed shows a system formed by a fuel cell and a boost converter (DC-DC) correctly controlled with the objective that at any moment the output voltage will be of 400V. This means that in case of having a physic fuel cell like the one described in the project, the system would make the same response with the PID or the PI +2 · Phase lead controller if the system were under the same circumstances (temperature etc.) described in the model

## 7.3 Supervision Algorithm

In this part the objective was to show the functioning of what could be a supervision algorithm. However, there are multiple options and the most important thing is that the system respond satisfactorily at every moment because one of the advantages of Micro-Grids is a supposedly greater reliability in the electricity supply. In addition, the more optimized this algorithm is, the better performance and better response will be received from the system, having a good impact on both functionality and costs.

It is also important to remark that as part of the design of a Micro-Grid it does not have a fixed configuration. Being one of the most used, the one described in the corresponding chapter, we can find different algorithms adapted to a specific profitability or need. For example, in the case of a Micro-Grid connected to a general network, it can be interesting to automatically buy energy to the general network whenever it is below a certain cost and the reserves are between fixed limits.

Another time, Simulink results a very interesting tool to test different algorithms and to quantify its performance in different environments, cases, installations and in order to fix concrete requirements.

## 7.4 Economical Analysis

The economical analyses that can be found in the annex A shows us the multitude of options when it comes to designing a micro-grid. The use of one font or another will depend on the characteristics of the environment.

On the one hand, the economic analysis of this type of installation in places where there is no electricity supply will aim to reduce costs as much as possible while the supply remains stable.

On the other hand, we find environments, such as a large city with an existing network where the installation that was necessary to bring electricity to a farm in Africa is not profitable and on the contrary it would be more interesting to renounce to some systems or to consider some of the possibilities that an existing grid can provide (for example with an installation of PV pannels and batteries to store energy from the grid when it is the cheapest)

But it is not just that, there are facilities who are may interested in paying a little bit more if that is going to increase the security of its energy supply.

To sum up, there exists a lot of possibilities when we are talking about micro-grid and two deep studies should be taken before building one: a technical one to check which technology is needed and an economic one in order to reduce costs and achieve the best quality/price ratio. Both studies must be go in a coordinate way as all the economic terms depend from the technology used and at the same time we need a technology that fit the requirements, including the economic ones.

# A.Appendix SDG

## A.1 Introduction

”The Sustainable Development Goals (SDGs) are a collection of 17 global goals designed to be a blueprint to achieve a better and more sustainable future for all” [29].



Figure A.1: Sustainable Development Goals (SDGs) by the United Nations

These SDGs have as objective a fair development of the world based in three main dimensions: The environment, the economy and the society.

As it was explained in the context, this project has as objective the understanding and modelling of a Micro-Grid, a type of facility that has a direct impact in the SDGs.

But it's not just about the environmental impact they can have to solve the  $CO_2$  emissions problems due to energy production. They are also trusted to provide universal access to electricity, a basic need for both health and economic development.

## A.2 Primary SDG identified in the project

### 7. Affordable and clean energy

The primary purpose of Microgrids for [30] is "to ensure local, reliable, and affordable energy security for urban and rural communities, while also providing solutions for commercial, industrial, and federal government consumers." so it is clear that this project follows this goal as it was the main objectives why Micro Grids were designed.

We live in a world where near 650 million people has not access to the electricity yet and it may be the key to solve this huge problem.

**The World Bank made recently an analysis where they assured that more-less the 50% people who has not access to electricity would be more cost effectively served via micro grids [31]**

### 9. Industry, innovation and infrastructures

"Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation" is the description of this objective. As it has been already explained, one of the advantages of Micro Grids is the resilience and that they are based on renewable sources of energy so they can be considered as sustainable and resilient infrastructures of energy production.

**41.5% of  $CO_2$  (Figure 1.1) emissions come from energy and electricity. This percentage would be reduced if the energy produced comes more from clean sources such as solar, hydrogen etc**

### 11. Sustainable cities and communities

"Make cities and human settlements inclusive, safe, resilient and sustainable" is the description of this objective. Micro Grids can have a direct impact in this goal as it encourages the development of



renewable energies that can be built near structures who are sensible to natural disasters in order to ensure the energy supply in cases where the general grid is out. If this objective is studied more in depth, it will be found that between the initiatives proposed by the United Nations, some of them very related with the development and growth of renewable energy sources and Micro-Grids.

Case Puerto Rico: It is a very good example of how Micro Grids can help to achieve this goal. In 2017 the Hurricane Maria caused massive outages in the country. Sonnen, a German start-up has worked in some projects to recover electricity in the region at that time. Among them we can find the construction of a solar micro-grid that has been called a “model for the resiliency created by [solar and storage] technologies.” The company with the help of other partners, built another Micro-Grid for a hospital in Utuado. These Micro-Grids contributed to Puerto Rico’s restoration of electricity, while also increasing resilience to future hurricanes.

**One of the recommendations of this SDG: ”Collaborate for increased resilience through the participation in Micro-Grids connected by well planned, increasingly webbed, and resilient utility transmission that allows access to remote renewable generation sources” [32]**

### **13.Climate Action**

”Take urgent action to combat climate change and its impacts” is the description of this objective. Basically, this SDG 13 has as a main objective to raise the awareness of the population and governments to reduce the emission of greenhouse gases in order to stop the increase of temperatures. As Micro grids take profit from sources of energy that do not imply the combustion of coal, the greenhouse emissions using this kind of technology are very very low. In the Micro-Grid presented in this project, is also used the technology of the fuel cell, a very clean energy whose reduction level of  $CO_2$  emissions is even bigger than the PV solar technology [33]



**”Microgrids offer the opportunity to deploy more zero-emission electricity sources, thereby reducing greenhouse gas emissions” [34]**

### A.3 SDG identified in a secondary way

There are others SDG that are not explicitly affected by the development of Micro Grids but that may result implicitly promoted by Micro-Grids. This is the case of:



Figure A.2: SDGs identified

This project is mainly focused on the environmental impact and access to energy and safety worldwide.

However, in less developed countries or areas without access to electricity, the development of Micro-Grids can lead to an economic and technological development in region. Like every construction process, it offers jobs to the population (A.2e). In addition, farmers and other workers will be able to implement new techniques such as irrigation systems, which require electricity. This will improve their health as they will have more food (A.2b) and less poverty (A.2a). Also, they will have more materials to sell. This growth will allow the inhabitants of the region to live in better conditions and in a healthier way thanks to the previous improvements. However, not only this, electricity would also allow the implementation of water purification systems (A.2d) that would continue to improve the health of the people (A.2c). Therefore it can be concluded that Micro-Grids can help to develop the economy of a region with a sustainable source of energy. Finally, these Micro-Grids will allow the population to produce only what they consume because the surplus can be stored. This is why Micro-Grids can clearly be considered a type of electrical installation that respects the (A.2e).

[6] is a very interesting article that talks about how Micro-grids can help to finish with poverty around the world and the impact of bringing electricity to an area/region where there was not before.

# B. Other cases of the supervision algorithm

## B.1 Case 3: The fuel cell and the batteries are necessary to supply the demand

The simulation is going to be carried out with the following inputs:

- NumPV=133 (number of solar photovoltaic panels)
- Performance=0.12 (performance of the PV)
- H=2 Kg of Hydrogen stored
- PotEol=7500 W (Average power of the eolian system)
- Bat= 2000 Wh (charge of the battery)
- Demand=8500 Wh

In this case the demand can be supplied thanks to the fuel cell and the battery that supply their energy until the battery is out and until the demand is satisfied.

As it is shown, the contribution of the batteries and the FC make possible the total supply of energy.

**Results obtained in the simulation:**

APPENDIX B. OTHER CASES OF THE SUPERVISION ALGORITHM

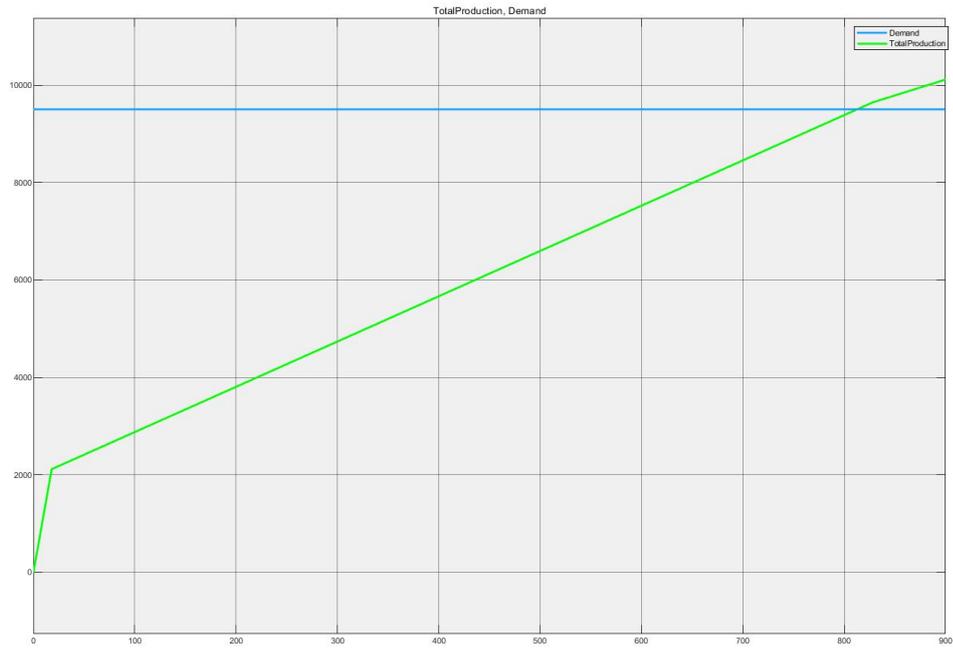


Figure B.1: Plot of the total production and the demand of these 15 minutes (Third Case)

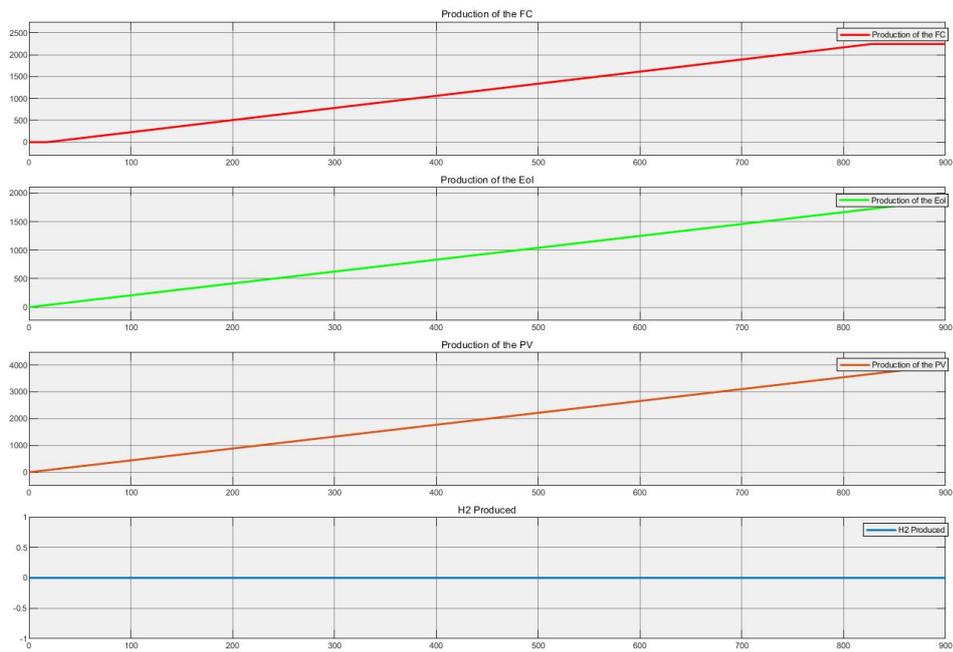


Figure B.2: Plot of all the blocks production: FC (Red), Eolien (Green), PV (Orange) , H2 production of the electrolyser (Blue) (Third Case)

*B.1. Case 3: The fuel cell and the batteries are necessary to supply the demand*

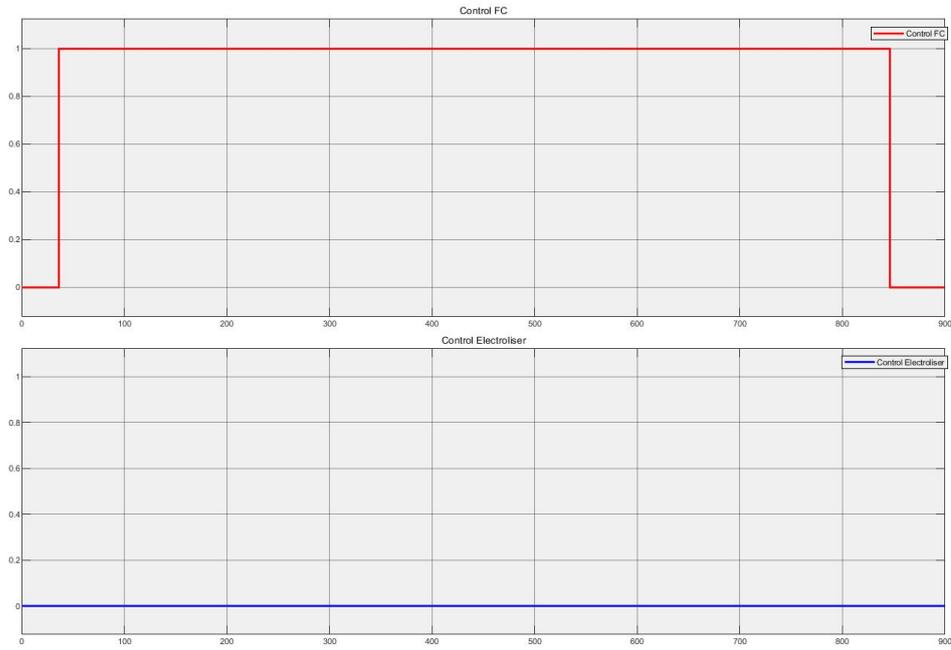


Figure B.3: Control parameter value of the FC (Red) and the electrolyser (Blue) (Second Case)

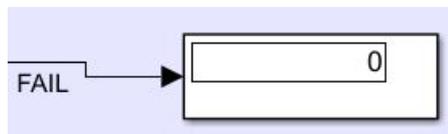


Figure B.4: Fail parameter that indicates that the demand has not been satisfied

## B.2 Case 4: The system tries to supply the demand but it does not achieve the goal (FAIL)

The simulation is going to be carried out with the following inputs:

- NumPV=133 (number of solar photovoltaic panels)
- Performance=0.12 (performance of the PV)
- H=2 Kg of Hydrogen stored
- PotEol=7500 W (Average power of the eolian system)
- Bat= 2000 Wh (charge of the battery)
- Demand=9500 Wh

With this increase of 1000 Wh, the system will not be able to supply the whole energy demanded and will return a parameter that is called "FAIL" with a 1 that indicates that the production is not enough to satisfy the energy consumed. In this cases if the Micro-Grid were connected to a general network, it would be possible to buy from the the lack of energy

**Results obtained in the simulation:**

B.2. Case 4: The system tries to supply the demand but it does not achieve the goal (FAIL)

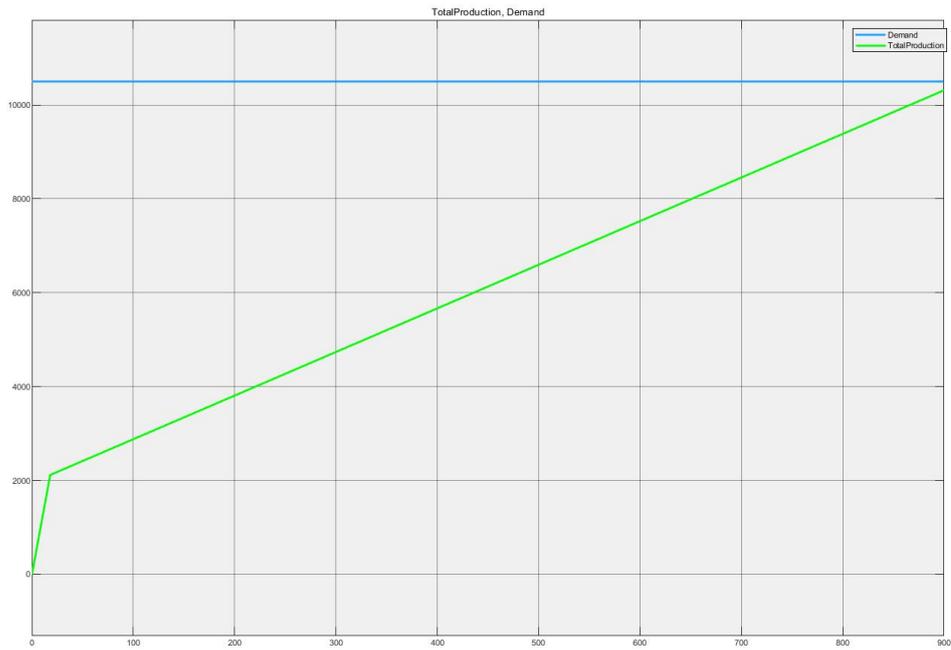


Figure B.5: Plot of the total production and the demand of these 15 minutes (Third Case)

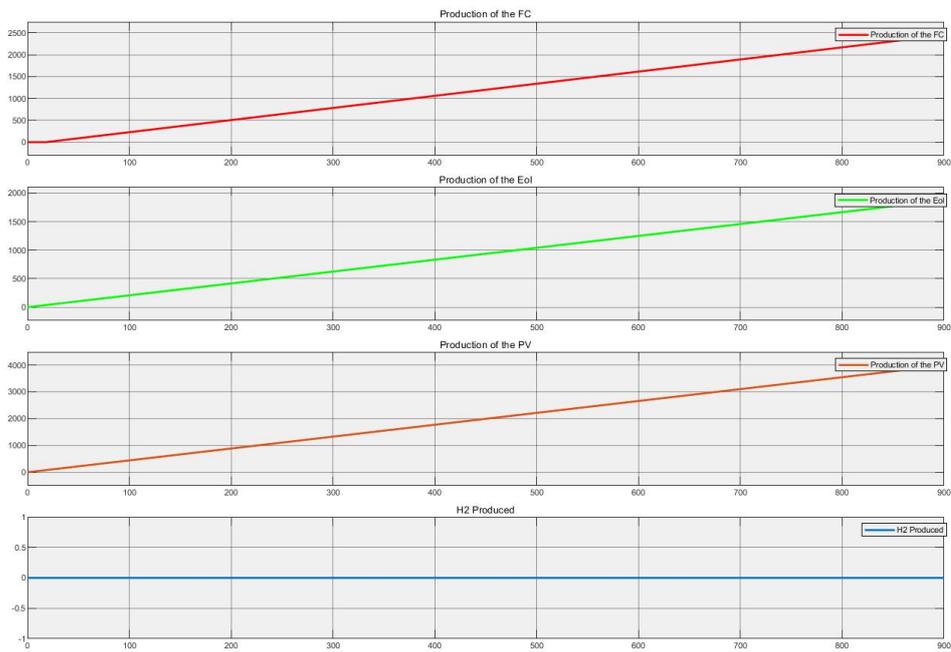


Figure B.6: Plot of all the blocks production: FC (Red), Eolien (Green), PV (Orange) , H2 production of the electrolyser (Blue) (Third Case)

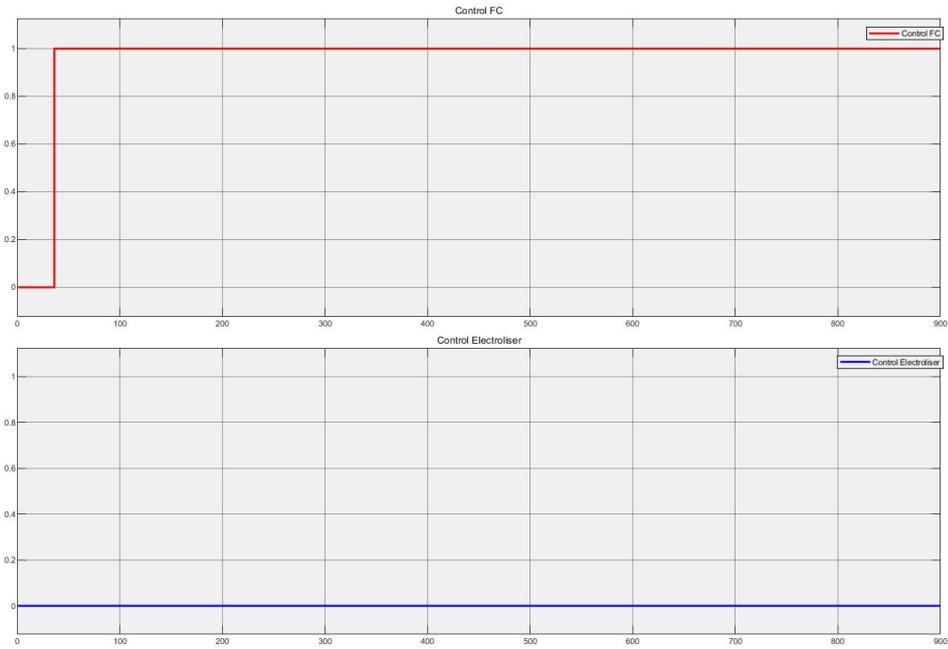


Figure B.7: Control parameter value of the FC (Red) and the electrolyser (Blue) (Second Case)

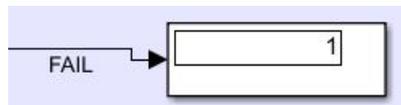


Figure B.8: Fail parameter that indicates that the demand has not been satisfied

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