

E.T.S. de Ingeniería Industrial,  
Informática y de Telecomunicación

# Distributed Energy Systems for Grid Application



Grado en Ingeniería Eléctrica y Electrónica

Trabajo Fin de Grado

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## ABSTRACT

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Renewable energy production such as solar PV systems or wind turbines are characterised by their intermittent nature. Therefore, a large-scale implementation of renewable energy production systems provoke difficulties and challenges for matching the supply with the demand. Using energy storage systems can help increasing the energy efficiency and improving at the same time the reliability and stability of the electricity network. In this way the current electricity network can be converted towards a plurality of interconnected micro-grids.

The purpose of this bachelor thesis is to study the potential of combining grid-connected energy storage systems (ESS) with renewable energy production. An extensive state of the art study related to renewable energies and energy storage technologies is done. With a study about the applications of ESS for the grid when a case of an ESS and renewable energy production systems are working together connected to the grid.

In addition a study of the different companies that commercialize with ESS will be done to choose the systems that fits better into the electricity network.

Last but not least, a sizing tool for distributed ESS will be designed. The system is going to be designed for a single family home using the application MATLAB® & SIMULINK®. It is going to be formed by a renewable energy generator and an energy storage system, also it is going to be connected to the grid.

## RESUMEN

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La producción de energía renovable, tales como los sistemas fotovoltaicos solares o turbinas de viento se caracterizan por su naturaleza intermitente. Por lo tanto, una implementación a gran escala de los sistemas de producción de energía renovable provoca dificultades y retos para la adecuación de la oferta a la demanda. El uso de sistemas de almacenamiento de energía puede ayudar a aumentar la eficiencia energética y mejorar al mismo tiempo la fiabilidad y la estabilidad de la red eléctrica. De esta manera la red eléctrica se puede convertir a una pluralidad de micro-redes interconectadas.

El propósito de este trabajo de fin de grado es estudiar el potencial de combinar los sistemas de almacenamiento de energía (SAE) conectados a la red con la producción de energía renovable. Se realiza un extenso estudio del estado del arte relacionado con las energías renovables y las tecnologías de almacenamiento de energía. Con un estudio acerca de las aplicaciones de los SAE para la red cuando se da el caso de que los SAE y los sistemas de producción de energía renovable están trabajando juntos conectados a la red.

Además, un estudio de las diferentes empresas que comercializan con ESS se va a llevar a cabo para elegir los sistemas que mejor se ajuste a la red eléctrica.

Por último, pero no menos importante, se diseña una herramienta de dimensionamiento para los SAE distribuidos. El sistema va a ser diseñado para una vivienda unifamiliar utilizando la aplicación de MATLAB® y SIMULINK®. Va a estar formado por un generador de energía renovable y un sistema de almacenamiento de energía, los cuales van a estar conectados a la red.

# CHAPTER 1: INTRODUCTION

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“Energy is essential to our society to ensure our quality of life and to underpin all other elements of our economy.” [1]

## 1.1 Renewable Electrical Energy Production

The term renewable energy is used to refer to energy that comes from a big wide of resources, it is produced when the renewable resources are presented and is inexhaustible. The sun is the origin of all the renewable energies, the heat of the sun provokes pressure differences in the earth's atmosphere which are transformed into the wind, arranges the water cycle, allows plants their life, etc.

Energy is an essential ingredient of socio-economic development and economic growth. Related to that way, renewable energy is used to produce electricity for all economic sectors and also it can help in reducing the dependency on fossil fuels. That is the reason why renewable energy technologies offer important benefits compared to those of conventional energy sources [2].

Renewable energy resources are not equally distributed all over the world. However, every region has some renewable energy resource that is more present than others. For example, Switzerland has reservoirs that are used to generate hydroelectric power; by against, Spain uses the sun and the wind to generate solar and wind power.

Something that every renewable energy has in common are the following advantages:

- Renewable energy does not emit carbon dioxide or other contaminant gases to the atmosphere;
- It is not exhaustible;
- It is not necessary to buy because is done by the earth;
- It does not generate waste that need a difficult treatment.

The use of renewable energy systems is the correct option, they do not generate big quantity of waste or pollutants that provoke environmental problems, furthermore they do not contribute to acid rain, urban smog, and health problems, and do not require environmental clean-up costs or waste disposal fees [1].

Below the most known and used renewable energy systems are described.

### 1.1.1 Solar Power

Solar power is the energy that comes from the sun, it is converted into thermal or electrical energy. Energy that comes from solar power is the cleanest and most abundant renewable energy source available in the world. The studies that modern technology does continuously can take advantage of this energy for a wide variety of applications, including: the generation of electricity, the supply of light or a comfortable interior environment, heating water for domestic, commercial, or industrial use.

There are many ways to benefit from solar energy: solar photovoltaics, solar heating & cooling, concentrating solar power and passive solar. The first three technologies receive the name of *active* solar systems, because they use mechanical or electrical devices for converting the sun's heat or light to another form of usable energy. *Passive* solar is used in buildings, which are designed and oriented to collect, store, and distribute the heat energy from sunlight to maintain the comfort of the occupants without the use of moving parts or electronics.

In addition, solar energy is a flexible energy technology due to solar power plants can be built as distributed generation (located at or near the point of use) or as a centralized generation-station.

#### 1.1.1.1 Solar PV Energy

Solar Photovoltaic (PV) energy consists in the direct conversion of sunlight into electricity without the interference of any heat engine. The solar panels are the producers of the electricity, they have a design simple and rugged with maintenance.

PV Solar cells, mechanical and electrical connections, mounting devices and means of regulating or converting the electrical output; all of them are the components that form the solar PV system in their totality **[3]**.

##### 1) PV Solar Cell

The solar cell is the basic element in photovoltaic generation. It is responsible of generating the electricity. It is the component of the solar panel that absorbs the sunlight due to the material with it has been made. One solar cell is not enough for producing the energy that is required for a solar PV system, but a plurality of solar cells can generate it.

Every solar cell has crystalline semiconductor material in its structure, the material most used in solar cells is Silicon. The process that this material do is absorbing photons that come from the sunlight and generates free electrons via the photovoltaic effect **[4]**.

Solar cells are made by semiconductor materials and allow the flow of electrons when they receive a quantity of radiation energy from the sun. Semiconductor materials of group IV of the periodic table, but mainly silicon (Si), is used for the production of solar cells.

Commonly, the current collection of the solar cell is done by two metallic contacts, one of them there is on the front of the panel, the side that is also impacted by the sunlight and the other one is on the back of the panel. The metallic contact of the front panel has to let free most of the front surface of the cell. The back panel can be covered by all the metallic contact because there is no requirement of free surface for sunlight impact on it. In addition, adding a thin layer of antireflective material at the front panel increases the absorbance of solar energy.

## 2) Photovoltaic Systems

The combination of a plurality of solar cells creates a solar panel. The combination of one or more solar panels together with all required mounting components and a means for transforming the electrical current (i.e. inverter) from the one or more solar panels into electrical power that matches that of the electrical network (voltage level and frequency), forms a PV system.

There are two types of photovoltaic systems. They are named depending where the produced energy is being used. The first type of system is named *off-grid photovoltaic systems*, it receives this name because its energy is used to power loads that are not connected to the main grid. The other type is called *grid-connected photovoltaic systems*, in this case all the energy is poured to the grid [4].

### 1.1.1.2 Solar Thermal Energy

Solar thermal energy is used to generate electricity in an indirect way. Solar energy is not employed to generate directly electricity like a solar PV system, however it is used to produce heat in a solar collector. This heat warms up a fluid that takes part in a classical thermodynamic cycle moving a turbine that generates electricity.

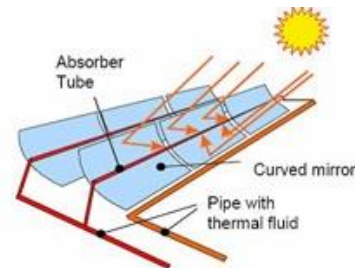
The places where this electricity is produced are called solar thermal power plants. They have a thermodynamic cycle, similar to that of conventional power plants, but the difference between both plants is that the conventional one uses fossil fuels (coal, gas ...) to heat the fluid whereas the solar thermal power plant one uses solar energy instead.

Obtaining electric power by thermal energy from the sunlight always follows the same process. Solar radiation is concentrated on a fluid (water, thermal oil, sodium, etc.) and transformed into thermal energy; fluid heated by passing through a heat exchanger produces steam that activates an alternator, in which electrical energy is obtained as in a conventional thermal power plant.

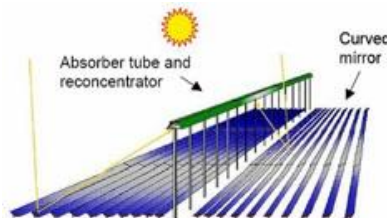
A solar thermal power plant consists of a collection system, a receiver system and a conversion system. Also, it comprises a field of heliostats or large directional mirrors that reflect the sunlight to the collector, where the fluid that moves the turbine is heated. Depending on how the sunlight is reflected, there are different types of solar thermal plants.

### 1) Parabolic Trough

The collectors of this type of solar thermal power plants, as it is shown in **Figure 1**, consist of a set of large curved mirrors that concentrate sunlight to a focal line. Inside the focal line there is a metallic absorption tube inlay an evacuated glass tube for avoiding losses where the fluid is circulating.



**Figure 1: Parabolic Through**



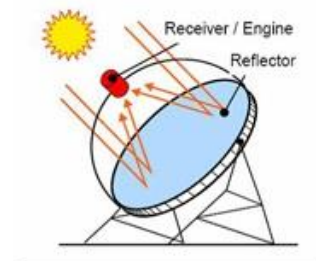
**Figure 2: Linear Fresnel**

### 2) Linear Fresnel

As **Figure 2** shows, this power plant is formed by a set of almost flat reflectors that concentrate solar radiation at high linear receivers invested. Inside these receivers flows the fluid that is heating. This technology is very similar to parabolic trough.

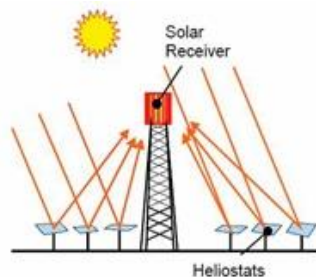
### 3) Dish/Engine

Reflectors of this type of solar thermal power plants consist of a large concave mirror, which concentrates sunlight on a receiver located at the focal point of a disk, as it is shown in **Figure 3**. The radiation of concentrated rays is absorbed in the receiver to heat a fluid.



**Figure 3: Dish/Engine**

Normally, this technology has a tracking system in two axes to take advantage of the maximum sunlight at every moment.



**Figure 4: Central Receiver**

### 4) Central Receiver

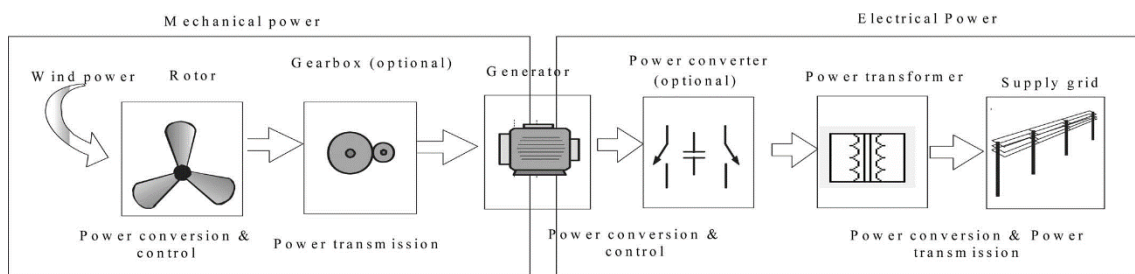
This type of solar thermal power plants has a hundred of big mirrors with tracking systems Sun's path in two axes that are installed surrounding a tower. In **Figure 4**, on the top of the tower it is situated the collector where reflected sunlight arrives [5].

## 1.1.2 Wind Power

Wind power is the energy that is obtained by the wind force, which is provoked by a differential heating of the earth's caused by the sun. Kinetic energy of the wind is converted to electrical energy by wind turbines. This wind turbine is connected by means of a gearbox with rotating blades, which are the responsible for the conversion of the wind's kinetic energy into mechanical (rotational) power.

Once the kinetic energy is converted into electrical energy, a further power conversion and transformation is necessary for grid connection.

The main components of a wind turbine system are shown in **Figure 5**, including a rotor, a gearbox, a generator, a power electronic system, and a transformer for grid connection. All of these components are necessary to obtain electrical energy from wind energy.



**Figure 5: Components of a wind turbine system**

Rotational blades turns with the wind at low speed, the generator produces electrical power at high speed, so it is necessary to increase the rotational speed of the blades. The gearbox is responsible for increasing the rotational speed.

Nowadays is easy to control the speed operation of wind turbines. The increase of using power electronic has developed a method to extract the maximum power from a wind turbine and provide to grid a constant voltage and frequency that are required [6].

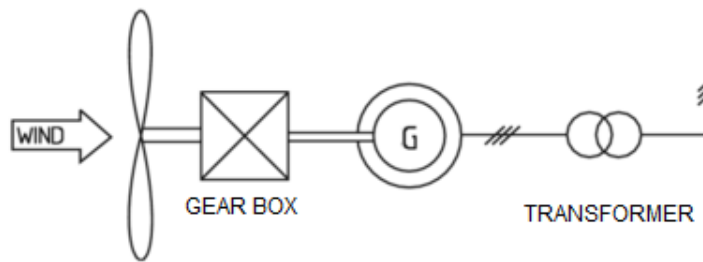
The two most common types of electrical machines used in wind turbines are induction generators and synchronous generators.

### 1.1.2.1 Types of grid coupling

Depending on the type of electrical machine (generator) used to convert the wind energy and grid connection, different types of grid coupling exist for wind turbine systems:

### 1) Direct Grid Coupling

Consists of a squirrel cage induction generator connected to the grid through a transformer, as it is shown in **Figure 6**. The system has a simple technology that is used in the first windmills, but the squirrel cage induction generator has problems to start moving and it consumes reactive power. The operational speed can be variable and if wind speed is slow, the system does not reach synchronous speed.



**Figure 6: Scheme of a Direct Grid Coupling**

### 2) Grid coupling via converter

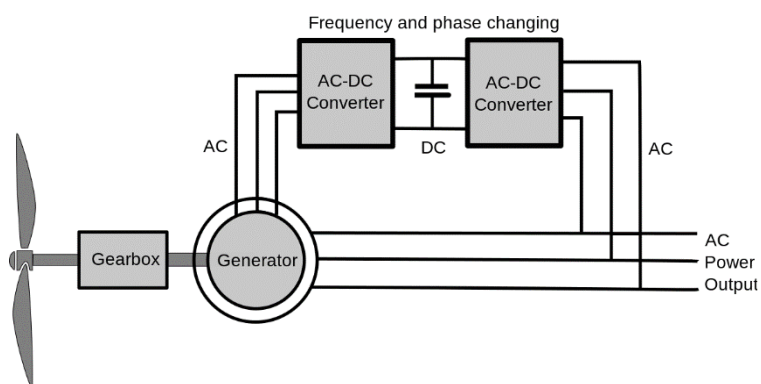
A squirrel cage induction generator is used to turn at synchronous speed, but it is not possible that the generator always turns at that speed. It often turns at a variable speed, that it means variable frequency. So, after the grid connection it is necessary to convert the electrical power. For this a converter is used.

### 3) Grid coupling via dc converter

This type of system produces electrical energy with a synchronous generator. The rotor can be excited by electrical excitation or permanent magnets. A synchronous generator always turns at the same (synchronous) speed, due to this limitation, the system cannot be connected directly to the grid because the wind makes it to work with variable speed which means variable frequency. For this reason it is necessary to use a power converter that changes the frequency of the generated voltage to the frequency (and voltage) of the grid.

### 4) Double fed asynchronous generator

This system has a wound rotor asynchronous generator. **Figure 7** shows that the stator is connected directly to the grid and the rotor is fed by a converter that controls the generator. This type of system can work with variable speed favouring an increase of the kinetic energy's use and a reduction of machine's fatigue. It is used for a doubly-fed



**Figure 7: Scheme of a Double Fed Asynchronous Generator**



generator for wind turbine up to few tens of megawatts that has two back to back connected IGBT inverters [7].

### 1.1.3 Hydroelectric power

Hydroelectric power must be one of the oldest methods of producing electrical power. It is considered as a renewable energy source, due to the fact that the water flow is renewed by following the natural hydro cycle.

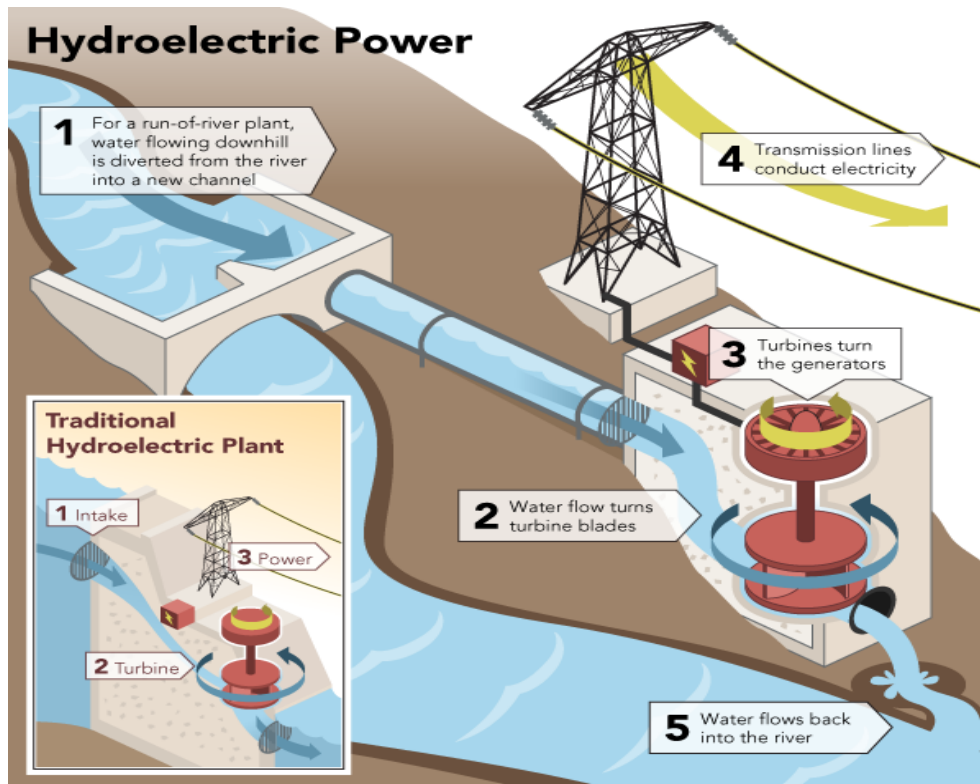


Figure 8: Hydroelectric Power Plant with a small canal / a reservoir

Hydroelectric power plants take advantage of the rivers' gravitational potential energy and they convert it into electrical energy by use of hydraulic turbines that are mechanically connected to the axis of an electrical generator.

There are different types of hydroelectric power plants, but the most common plants use a dam on a river to store water in a reservoir. Also there exist the pumped storage plant and the micro-hydroelectric power plant.

As it is said, the most common and traditional plant uses a reservoir to accumulate water. Water released from the reservoir flows through a turbine that moves a generator to produce electrical power. Also there is a variation of this type of power plant, where it is not necessary to accumulate water. The power plant use a small canal/pipe to channel the river water through a turbine. In **Figure 8** both types of power plants is shown and explained.

A pumped storage plant is other type of hydroelectric power plant that can store power. During the day the plant produces electricity that is sent to the grid, but at night, when the electricity is cheap, turbines are used to pump water from the lower to the upper reservoir.

The last type of hydroelectric power plant is a small or micro-hydroelectric power system that can produce enough electricity for a home, farm, or ranch [8].

### 1.1.4 Marine power

Marine power is the energy produced by waves, tidal currents, salinity and temperature differences. Energy is stored in the oceans as kinetic and thermal energy that is transformed by different devices to generate electrical energy. The systems, that use energy from waves, ocean currents and tides, are the most common to produce electricity [9].

Tides are produced by sun and moon's gravitational forces. A system that take advantage of tides energy is a dam or barrier tide that works equal to a hydroelectric power plant. The energy provoked by the ocean currents is transformed by inverters and horizontal and vertical turbines which are situated inside the path that follows the ocean's water movement. Finally, the waves' energy can also be used to generate electricity, the systems that transform this energy are Oscillating Water Column (OWC), floating and overflow devices, Archimedes Wave Swing (AWS); all of these devices take advantage of the waves' spread and circular movements [10].

### 1.1.5 Biomass power

Biomass is considered an organic matter originated in a biological process that can be used like power source. These resources are grouped in an agricultural and forest way. Also, organic matter of residual water is considered biomass.

Creation of biomass is done by solar energy that carries out the photosynthesis process, where plants transform carbon dioxide and water into organic matter with high energy content. In this way, biomass stores solar energy in the form of carbon, after

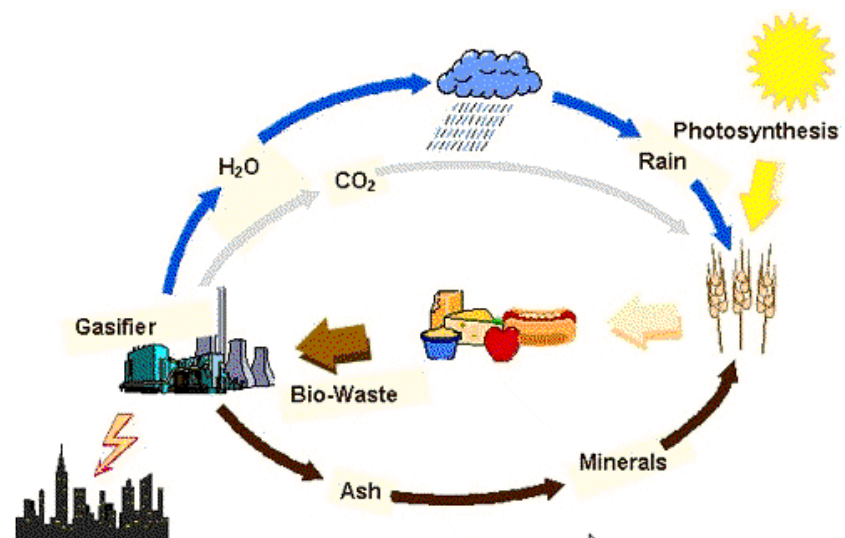


Figure 9: Biomass Cycle

which, when biomass is burned, the energy is transformed again, into heat, that can be used to produce electrical energy [11]. During the burning process of the biomass, carbon dioxide is being released.

Like is shown in **Figure 9**, the process where biomass is created and being used to generate electricity is considered as a closed cycle. This means that all the carbon dioxide that is being utilised for producing materials and food products, is returned into the atmosphere when the biomass is burned for generating electricity. Herewith the cycle of carbon is being closed.

### 1.1.6 Geothermal power

Geothermal power is power coming from the thermal energy that is accumulated under the earth's surface. It can be used by humans in a technical and economic way. The temperature of the geothermal resource is increasing with increasing depth. Of course, larger depth involves higher costs and sometimes is economically not viable.

Depending on the temperature of the geothermal resource, there are different types of applications like the ones shown in the **Table 1**.

Geothermal Resources	Temperature (°C)	Applications
Very low Temperature	$T < 30$	Air conditioning pump geothermal
Low Temperature	$30 < T < 100$	Direct thermal use in industrial and air conditioning processes
Mean Temperature	$100 < T < 150$	Binary cycle power generation and heat use in industrial processes and air conditioning
High Temperature	$T > 150$	Power generation

**Table 1:** Possibilities of using geothermal power

## 1.2 Why energy storage systems for grid application

Access to energy is the substance of modern society facilitating the light, heat, industry, transportation, agriculture, and medicine we rely on every day. One of the useful form of energy is the electricity because it is functional for many technology platforms, powering everything from cell phones to cars. However, conventional electricity generation and consumption can have significant environmental impacts, such as the emissions of greenhouse gasses and other airborne pollutants, the production of solid wastes, and the ecological impacts of withdrawal and consumption of huge quantities of water [12].

The current electric grid is an inefficient system, all the electricity that is produced by the different types of generators, then important amounts of it are wasted by the

grid system. That occurs because the amount of energy requires by the consumers is not equal to the amount of energy produced from generation sources **[13]**.

The electricity is an energy that delivers power only at the time it is generated, the current electric grid is a system in which supply, transmission, distribution, and demand are interdependent, that is why changes to any one part of the system necessarily affect the rest of the system, and the magnitude of impact increases with the scale of change **[12]**.

To maintain the power network stability, the load balance has mainly been managed through fossil fuel power plants. But as it has been discussed above, conventional electricity generation has environmental impacts that it is necessary to reduce **[14]**. So, it is occurring a greater respect for the environment due to the use of renewable energy has grown.

However, most renewable energy sources have a fluctuating and intermittent nature that is caused by the variations of power flow and it can significantly affect the stability and operation of the electrical grid. This situation created by renewable energies can bring severe problems that affects the microgrid security, such as system frequency oscillations and violations of power lines **[15]**.

As it is said, the penetration of renewable energies renders the power system vulnerable to instability, deteriorated reliability, and compromised power quality. But an appropriate Energy Storage System (ESS) can mitigate the impact of intermittency, assist the power system ride through peak power demands, and allow the transmission and distribution networks **[16]**.

In the past, ESS were more expensive than today, so it was more economical to build additional generation systems instead of opt for an energy storage. However, nowadays the price of ESS has fallen and the life cycle has increased what have made them more viable. The studies and technology related to this field have helped a lot **[13]**.

The incorporation of ESS for grid applications carries a big quantity of opportunities and challenges that must be studied in depth prior to full implementation. The ESS use on the grid have to obey with the law that governs the country where they are going to be installed. But also they must be integrated and operated in a safe and reliable manner **[17]**.

As it is known, it is necessary that an electrical power grid adapts energy production to energy consumption, knowing that both of which vary drastically over time. A combination between ESS and the current electric grid has some advantages that are explained below:

- It facilitates the use and integration of renewable energies because the ESS give to the grid more fast-start and fast-ramping resources to make up for generation shortfalls when renewable resources are not producing **[17]**;
- Additional energy storage inside the grid would allow many more plants to run closer to full capacity and reduce energy losses during electricity transmission, what it makes an efficient and constant production **[13]**;

- Due to the lack of energy storage devices within the grid system, energy must be immediately delivered to and used by the consumer; but with the aid of ESS energy can be stored and used later [13];
- It improves the grid reliability and power quality, avoiding voltage stability problems that can lead in system failures and preventing a potential system collapse [17];
- Decreased transmission losses and reduced transmission congestion [17];
- It generates an equilibrium in the electricity price, this balance benefits customers' prices due to the cost of the storage and demand management is included in pricing so there is less variance in power rates;
- Finally, this combination prepares the grid for emergency situations that can occur and vital needs can be met reliably, even when there is not power on the grid.

The use of EES for grid application have multiple attractive value functions to power network operation and load balancing, such as: helping in meeting peak electrical load demands, providing time varying energy management, alleviating the intermittence of renewable source power generation, improving power quality/reliability, meeting remote and vehicle load needs, supporting the realization of smart grids, helping with the management of distributed/standby power generation, reducing electrical energy import during peak demand periods **[14]**.

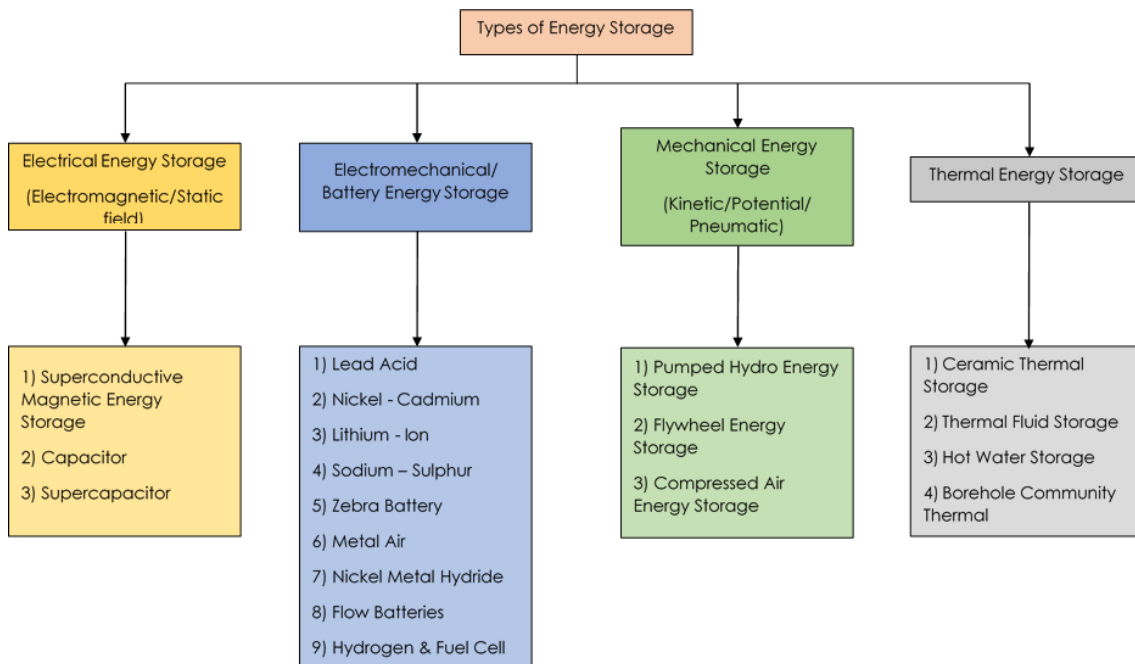
In brief, the incorporation of the ESS for grid application is a good choice due to it will favour the improvement of the power grid operation with all the developments that have been discussed above using the ESS.

# CHAPTER 2: ENERGY STORAGE SYSTEMS

## 2.1 Energy Storage Technologies

Energy Storage Systems (ESS) allow power to be taken from a source, stored and then released back into the system (e.g. the electricity grid) as and when required. Most ESS include four main components, a device called storage medium that stores the energy until it is required, a charging system that allows energy flow from the external system into the storage medium, a discharging system that is used to release stored energy back into the external system, and a control unit that governs the operation of the storage system.

In the following paragraphs, an overview about electrical energy storage technologies and alternative energy storage technologies will be given, as it is shown in **Figure 10**.



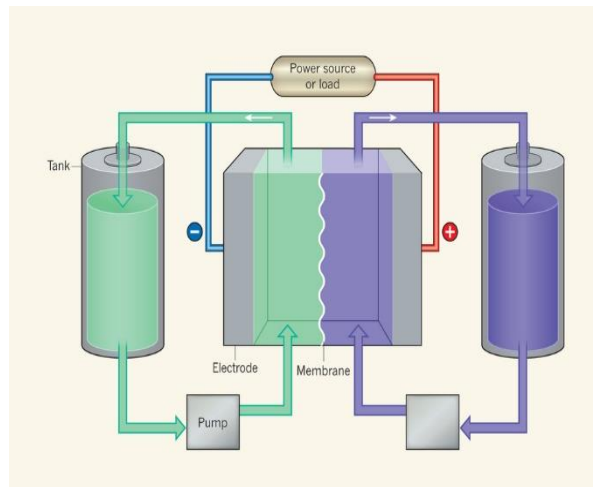
**Figure 10: Types of Energy Storage**

### 2.1.1 Overview of electrical energy storage technologies

This section is going to refer to the following types of electrical energy storage technologies: flow battery energy storage, superconducting magnetic energy storage, capacitor energy storage, supercapacitor energy storage, and battery energy storage systems.

### 2.1.1.1 Flow battery Energy Storage (FBES)

FBES works by converting chemical energy into electrical energy. It uses two aqueous electrolytic solutions contained in separate tanks, as it is shown in **Figure 11**. A normal operation consists on a reversible electrochemical redox reaction where electricity is generated. This reaction occurs when each of the aqueous solutions are pumped through an electrochemical cell, where there is a proton exchange membrane which permits the circulation of ions, generating an electric current [18], as it is shown in **Figure 11**.



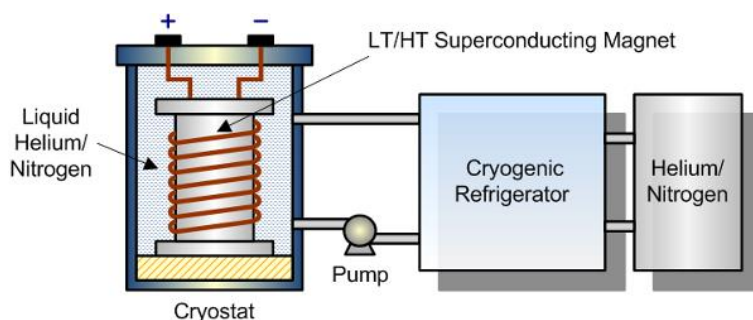
**Figure 11:** Two solutions of electroactive materials (green and purple) are stored in external tanks and pumped into an electrochemical cell.

FBES has a young technology, and three main types of commercially developed flow battery exist; Vanadium Redox Battery (VRB), Polysulphide Bromide Battery (PSB) and Zinc Bromine Battery (ZnBr).

FBES systems have both a long lifespan and low maintenance requirement, making the technology suitable for long term energy storage [19]. The FBs are used for applications with a power range varying from approximately 10 kW to more than 10 MW [18].

### 2.1.1.2 Superconducting Magnetic Energy Storage (SMES)

SMES consists of three main components; a superconducting magnetic coil; a power conditioning system; and a cryogenic refrigeration unit. It stores energy in the form of electromagnetic energy which is induced by the direct current flowing through the superconductive coil which is cooled down below the critical superconducting temperature using either liquid helium or liquid nitrogen, all these components are shown in **Figure 12**.



**Figure 12:** Illustration of an SMES system

Energy that is stored in the SMES can be discharged from the system almost instantly as required. In addition, if power is needed in the grid, the direct current is converted back to AC electricity via an inverter [20].

### 2.1.1.3 Capacitor Energy Storage

Capacitors are formed by two metallic plates separated by a layer of insulating material known as a dielectric. The charging process consists of the storage of energy by the electric charge of the metallic plates and hereby forming an electrostatic field in the dielectric, as it is shown in **Figure 13**. The size of plates, plate separation and the material used for the dielectric affect the quantity of energy which can be stored. In **(1)** it is shown the parameters that are involved in the quantity of energy stored ( $Q$ ).

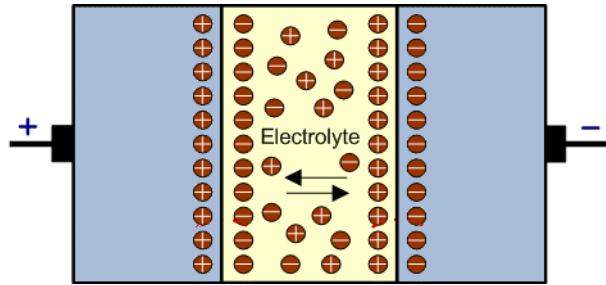


Figure 13: Schematic view of a capacitor

$$Q = \epsilon_r \frac{A}{4\pi d} V \quad (1)$$

Where:

- $\epsilon_r$  = dielectric's relative permittivity
- $A$  = size of plates
- $d$  = plate separation
- $V$  = voltage applied

One of the advantages of capacitors is being able to tolerate thousands of charge/discharge cycles without material degradation occurring. Also, they are effective in short term applications (e. g. bridging or voltage stabilisation); but they are not suitable for long term energy storage **[19]**.

### 2.1.1.4 Supercapacitor Energy Storage

Supercapacitors are similar to regular capacitors but with significantly larger capacitance, they have a high power density. They are formed by two conducting electrodes, a porous membrane separator and an electrolyte; like the capacitors. They are also known as Electrochemical Double Layer Capacitors (EDLCs).

Supercapacitors can support a high number of charge/discharge cycles without degradation, making them suitable for high power applications in a short period of time.

Compared to rechargeable batteries, the most important advantage of EDLCs is that they possess a relatively low internal resistance and can store and deliver energy at higher power rating **[20]**.



### 2.1.1.5 Battery Energy Storage Systems (BESSs)

Battery energy storage systems store electrical energy in the form of chemical energy. They use electrochemical reactions to convert electrical energy into chemical energy when charging and vice versa when discharging.

Despite the fact that the BESSs represent the first electrical energy storage system introduced, they are (depending on the type) still the most cost-efficient technology available today on the market due to advantages including; low cost, negligible maintenance requirement, and low self-discharge rates [20].

There are mainly six types of battery storage technologies at the moment: Lead-Acid batteries, NiCd/NiMH batteries, Li-Ion batteries, Sodium-Sulphur batteries and Sodium-Nickel-Chloride batteries. Each of them are going to be explained below.

#### 1) Lead–Acid Battery:

The lead–acid battery is the oldest type of rechargeable battery. It consists of a positive electrode and a negative electrode, submersed into an acid electrolyte.

The charging process takes place when the electrons migrate from the positive to the negative electrode. In this state, the negative plate is made of elemental lead, while the positive plate is made of lead dioxide (PbO<sub>2</sub>). While in the discharging process, the electrons migrate from the negative to the positive electrode.

The lead–acid batteries can be used for applications that do not exceed the power of 10 MW [18].

#### 2) NiCd/NiMH Batteries

NiCd batteries have been the second type of rechargeable batteries introduced. They use a cadmium negative electrode, a nickel (III) oxide–hydroxide positive electrode.

They have been replaced by NiMH due to their complex recycling procedures and because of health and environmental issues of Cadmium. NiMH batteries are similar to NiCd, but they have the disadvantage of a high self-discharge rate and the hydrogen formation can lead to cell rupture.

It is a battery use for applications with a power range varying from 1kW to approximately 1MW [18].

#### 3) Li-Ion Batteries

Li-ion batteries are electrochemical systems where the electrolyte permits the ion circulation but not the electron conduction. The basic principle of operation consists

on the migration of the positive Li ions from the negative plate to the positive during discharging and in reversed direction during charging.

This type of batteries possesses a low discharge rate. The main disadvantage is that the internal resistance can heat, thus causing failure of the battery.

These batteries are used for applications where the maximum power used is 1 MW [18].

#### 4) Sodium–Sulphur Battery

Sodium-Sulphur batteries consist of a sodium negative electrode, which in course of the discharge is oxidized at the surface, thus forming positive sodium ions which migrate through the beta-alumina solid electrolyte and, finally reduced, generating sodium pentasulfide.

Unfortunately, these batteries contain many hazardous elements such as the metallic sodium which ignites when in contact with water. They operate in a temperature range between 300-350°C and they are suitable for applications with a power range varying approximately from 0.8 kW up to more than 10 MW [18].

#### 5) Sodium–Nickel–Chloride (NaNiCl<sub>2</sub>) Batteries:

As for Sodium–Sulphur battery, the electrolyte of the Sodium–Nickel–Chloride batteries permits ion transport but no electron conduction and their operating temperature is between 270-350°C.

Nickelchloride (NiCl<sub>2</sub>) and sodium are obtained during the charging process, by the conversion of salt (NaCl) and nickel (Ni). During discharge, the reactions are reversed. The negative electrode is sodium, while the positive electrode is NiCl<sub>2</sub> in the charged state and Ni in the discharged state. This battery is used in applications where the maximum power can reach 10MW [18].

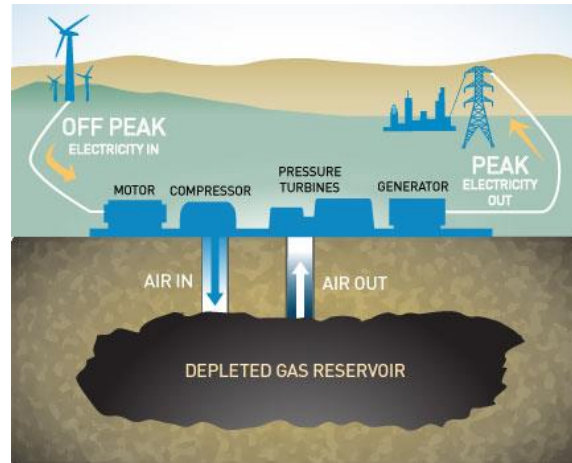
## 2.1.2 Overview of alternative energy storage technologies

This section, otherwise, will explain energy storage technologies that produce electrical energy by means of energy conversion from forms such as kinetic or potential energy. The technologies that are going to be described are: Compressed Air Energy Storage (CAES), Pumped Hydroelectric Storage (PHS) and Flywheel Energy Storage (FES).

### 2.1.2.1 Compressed Air Energy Storage (CAES)

Compressed Air Energy Storage is an energy storage technology that uses electrically powered compressors to force air into underground voids (such as caverns) at a very high pressure. It is a process which is often undertaken during times of low demand or during 'off-peak' electricity periods, as it is shown in **Figure 14** [19].

When the energy demand increases, the compressed air, released and mixed with fuel, is heated and expanded through a gas turbogenerator in order to produce electricity.

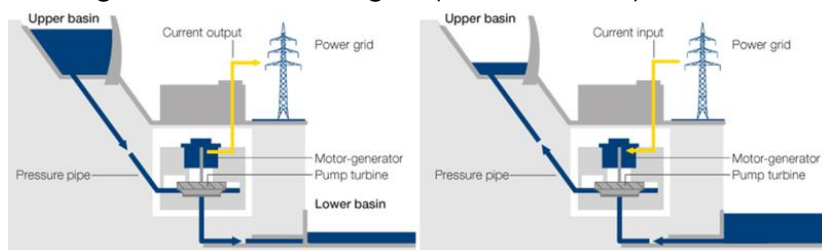


**Figure 14: Scheme how a CAES works**

The round trip efficiency for CAES is around 85% and is severely dependent on geographical conditions, which greatly restricts the utilization of this technology. Currently, there are only two systems in the world: one in Huntorf, Germany, of 290 MW built in 1978 and one in Alabama, USA, of 360 MW, built in 1991 [18].

### 2.1.2.2 Pumped Hydroelectric Storage (PHS)

Pumped hydroelectric storage systems transform electrical energy into potential energy by pumping water from a reservoir with a lower elevation to a reservoir/basin at a higher elevation during off peak electricity hours. A turbine/generator is used to



**Figure 15: Difference between the generation of electricity (turbine operation) and storage of electricity (pump operation)**

convert the water flowing from the higher level reservoir/basin into electricity during peak demand periods [19], as it shown in **Figure 15**.

The round trip efficiency is approximately 70 – 85%. The main drawback of pumped hydroelectric storage is the special requirement concerning geographical conditions, because the quantity of energy that can be stored is dependent on the size of the upper storage reservoir and the difference in height between the upper and lower reservoirs [20].

### 2.1.2.3 Flywheel Energy Storage (FES)

Flywheel energy storage is a system where the energy is stored in the form of rotating kinetic energy. This system consists of three components: the flywheel, the rotor bearings and the power interface; the flywheel rotates on two magnetic bearings (to reduce friction) that are connected to a generator allowing electrical energy to be produced, as **Figure 16** shows. The container where the flywheel rotates is filled with low friction gases such as vacuum or helium to improve the performance of the rotor [18].

The discharge process begins when an electrical generator is connected to the flywheel. Conversely, when a torque is applied to the flywheel, the system is charged. High speed FES provides long periods of storage (over periods of many minutes to several hours) but low power capacity. Low speed FES is the opposite [19].

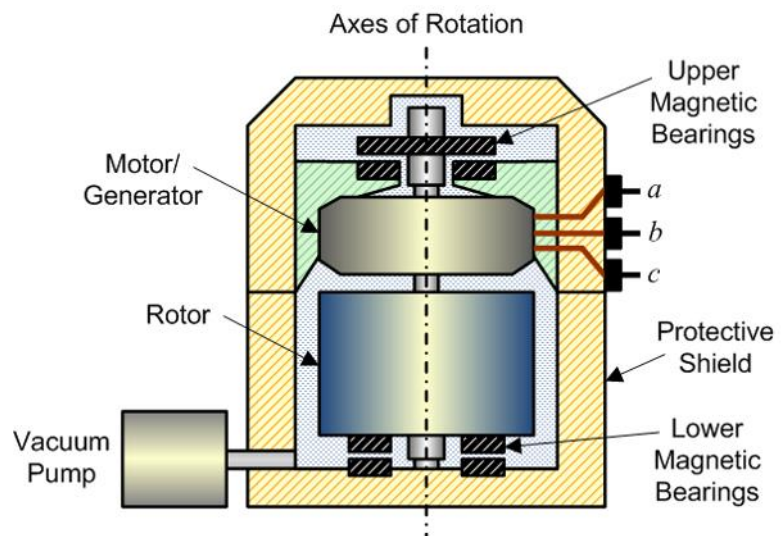


Figure 16: Structure of a conventional flywheel energy storage

The round trip efficiency is between 80% and 85%. This storage system is appropriate for power applications such as frequency regulation thanks to its characteristics of the high charge/discharge rates and the long lifetime [20].

## 2.2 ESS for grid Applications

Nowadays, with increased performance and fallings prices of production costs, one of the main areas where ESS can make an impact is large-scale energy content. Specifically, energy storage on the MW scale can be used by large consumers and utilities alike to reduce energy costs by taking advantage of various applications that have manifested themselves in the new smart grid.

ESS are increasing their impact on the utility grid as a solution to stability problems. The main advantage of a storage plant is to contribute to the quality of the grid by maintaining the power more constant.

The main role of the ESS is to increase the renewable energy systems penetration, to level load curve, to contribute to the frequency control, to upgrade the transmission line capability, to mitigate the voltage fluctuations, and to increase the power quality and reliability.

All these applications, in which ESS can take part, are going to be discussed below.

## 2.2.1 Electric Energy Arbitrage

Electric energy arbitrage is an application used for energy storage by large scale energy users such as a large consumer (e.g. factories, hospitals, etc.). In power systems, arbitrage is used when describing the buy and sell of electric energy. When for instance there is excess in production, electric energy can be bought at a lower price and can sold again when the price is high.

An energy storage system (ESS) can be used to keep (store) the electric energy that has been bought; and stored it till is the appropriate time to sell it.

The idea of the application of arbitrage is rather simple, but carrying out the implementation can be difficult. This it means, it is necessary to create an algorithm that takes care of the pricing structure that changes on a regular basis (e.g. every hour as the price of the next hour coming one hour ahead). But the algorithm should also take into account the energy efficiency, depth of discharge and lifetime of the ESS chosen. Only knowing the hour's price one hour ahead, it is impossible to generate a good algorithm, to solve it is necessary to dispose of a price predictor that gives information of a whole day [21].

Electric energy arbitrage is an application that allows to generate profit by charging the ESS with cheap electricity (e.g. when the demand is low) and selling it when the demand is high at a higher price. In addition, it could also influence the demand side, for example by using higher peak prices to induce a reduction in peak demand [22].

## 2.2.2 Electric Supply Capacity

When there is an increase in the load, a limited generation supply or a peak electricity demand; it is necessary to deliver more power to the load. To support the increased load an extra generation of electricity is needed.

To provide additional electricity generation, there are two possibilities: increase the infrastructure and the generator capacity or install an ESS. The first option is not the best choice, because it is necessary to expand the grid infrastructure and the associated cost is very high. Thus, the option of installing an ESS is better, because it avoids to expand the infrastructure. Furthermore, the extra energy generation can be supplied by releasing energy during the increased load, this released energy is being stored during off-peak periods [16].

Using the electric supply capacity as an application for ESS, extra generation may not be needed or could at least be deferred for some period of time. Further, the need of conventional peaking power plant is going to be reduced [21].

### 2.2.3 Electric Service Reliability

The reliability of the electrical grid is one of the most important points to take into account, because of its impact on the daily life. For customers, it is essential to have electricity in the industry, offices and homes. Power outage results in negative consequences and in some cases can be even dangerous. For this reason it is important to have a continuous electric power supply.

So, it is possible to use an ESS as an application to improve the reliability of the electricity grid. ESS can have different functions, depending on the activity that it is going to perform on the grid. The functions that ESS can provide are: full-time back-up in the case of an outage, back-up to allow for an orderly shutdown, or back-up to allow for other back-up generation to come online **[16], [21]**.

### 2.2.4 Load Following

The increase and decrease of some generation output sources are involved in the load following service because of the availability that this service has for competition in a liberalised electricity market. With this service it is possible to follow the load profile of the power system.

Instead of using conventional generation technologies, an ESS is a good candidate for substitution. The system has a fast response to control signals, is good at various output power levels and can follow loads in both directions (charge and discharge). At the end, ESS operate instantaneously, allowing conventional generation technologies to work in a (more) constant output power regime **[15], [21]**.

### 2.2.5 Voltage Regulation

Voltage regulation is based on maintaining the network voltage at its nominal value. It is an important service because voltage values have to be kept between the limits determined by national standards.

During the electric power transportation, the reactive power is transmitted by the lines. This power generates congestion and produces higher power losses, which provokes a voltage value variation **[21]**.

ESS is also an option that can be used for voltage regulation caused by reactive power. The ESS work very closely together with the generators, thus, when there is a large demand of real and reactive power, the ESS share real power with generators and so the generators transmit the needed reactive power **[16]**.

## 2.2.6 Increasing Renewable Energy Source Penetration

The intermittent nature of renewable resources, above all the fast growing of wind and solar power, provokes voltage and frequency fluctuations on the grid. That situation creates an inconvenience in the replacement of fossil-fuelled generation by renewable sources, because renewable sources have to be supported by other conventional power plants [16].

Due to the intermittent production of renewable energy, it is not possible that renewable energy systems supply energy constantly like conventional power plants. For this reason, it is necessary to propose a suitable ESS that offers a large storage capacity in which it is possible to store the energy produced when the renewable resource is abundant and use it later, when there are a shortage of resources. Thereby, the renewable systems supply energy constantly [22].

## 2.2.7 Primary Frequency Regulation

The grid frequency has to be in a permanent and stable value. Synchronous generators contribute to the frequency stability, but the increased use of variable speed wind turbines and large PV power plants connected to the grid do not contribute to this function.

To solve this inconvenience, ESSs can be used for the technical application that consists of transient and permanent grid frequency stability support. The application that ESSs perform is based on the emulation of the generators' inertia and is characterized by short response times allowing to mitigate the grid-frequency deviations [22].

## 2.3 Study of the Energy Storage Companies that exists nowadays

Contemporary society is strongly dependent on fossil fuels; it is necessary to change the way of the generation and accessibility energy. Renewable energy is the solution, but it requires energy storage systems to keep that energy that is not going to be used immediately.

As it is known, conventional resources are limited and the grid is overburdened. For this reason, energy sector is currently been transformed from the classical thermal and nuclear energy production into more green and renewable energy production. Wind and solar are renewable energy sources that are a critical part of the solution, but they are intermittent and limited to times when the wind is blowing and the sun is shining. This is why large amounts of intermittent energy simply can't be

accommodated our current energy grid. In addition, energy industry has made many efforts for more efficient production and consumption of energy.

Renewable energy production and energy efficiency are the energy trend, from energy mass production to consumption, for smart and eco-friendly use of energy. Where energy storage devices are at the centre of trend.

Energy storage systems provide a variety of values for both energy consumers and producers. They complement the intermittency of renewable energy produced by wind or solar power generation system. Also, they stabilize the output of renewable energy by charging and discharging irregular and intermittent power which is generated from wind and solar system.

In addition, energy storage systems can reduce the investment costs for upgrading transmission and distribution network. But also, optimize energy and reduce the energy bill of consumers. That is, when the demand is high and offer is low, power companies will charge a higher price for electricity, but when rates are low, batteries can store excess electricity and powers your home when rates are high.

In the case that a consumer has a rooftop solar array, it produces energy when most people are not at home. That energy that is produced and not used (locally) is saved by the energy storage system for consumption when consumers really need it, like in the evening and in the morning at home, or during the day for small businesses. So that home or commercial owners can cut peak demand and in this way electricity cost and provides emergency energy power during power outage.

Energy storage system will allow consumers to reach a level of autonomy never achieved and provides multiple additional benefits, like reduce the electricity bill; tax benefits in most countries; carbon dioxide emissions are reduced.

Nowadays there are a lot of companies that dedicate their investigations and resources to the design, development and production of energy storage systems that give to the consumer these benefits that have been commented.

In the following paragraphs, it is explained some of the different companies that have technology related to the energy storage system at consumers' homes. These companies are: Tesla, Orison, Samsung, Panasonic and Leclanché.

## 2.3.1 Companies

### 2.3.1.1 TESLA

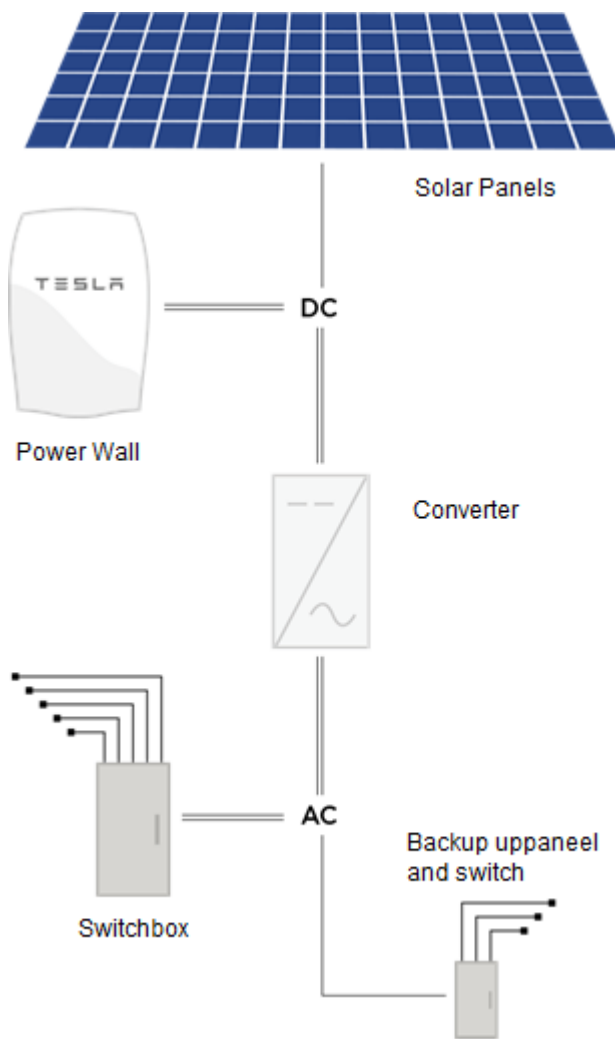
Tesla has recently designed a new energy storage system that is called Power Wall – Battery for Home. It is a home battery that is automated, compact, easy to install and requires no maintenance; it uses electricity to charge the battery from solar panels or during off-peak hours from the main grid.



The consumers get the most from their solar panels; they use electricity from solar energy at night and can be completely independent of the grid for a short period. The electricity generated by solar panels during the day is stored by the Power Wall and they have it available after dark.

The Power Wall comprises a lithium-ion battery that is based on the Tesla's automotive industry. All the technology that battery uses is provided by this industry.

The correct use of Power Wall is done by the addition of other components that help the battery to work properly. **Figure 17** shows a typical system consists of solar panels, an inverter that converts electricity from DC to AC, a meter to measure the ability of the battery, a switchbox and a secondary circuit that supplies the main items of equipment.



Solar panels, an inverter that converts electricity from DC to AC, a meter to measure the ability of the battery, a switchbox and a secondary circuit that supplies the main items of equipment.

Each component has its functions in the system. Solar panels convert sunlight into electricity; Power Wall is charged by the electricity that comes from solar panels or the grid; inverter converts direct current from solar panels into alternating current that is used at home; the meter measures the production of solar energy and energy consumption at home; the switchbox controls the inverter, and when there is no sun it switches the inverter to charge the battery; and the secondary circuit that provides electricity to all critical devices. The backup panel and switch or secondary circuit is necessary to provide emergency power when all critical devices and electrical outlets are connected.

**Figure 17: Components required in a typical Power Wall System**

The Power Wall system has a capacity of energy storage of 6.4kWh, which is enough to provide electricity during the evening hours [23].

### 2.1.1.1 ORISON

Orison is a home battery system that takes control of the consumer's energy. It charges itself when the rates are low, so the consumer can use the energy stored when the rates are high.

The energy storage system has a simply installation. Once the consumer has decided where to place the system, he may plug it and Orison's home battery starts working.

Orison's home battery system uses solar panels to charge itself, but if the consumer does not have solar panels, the system can use any power source including the grid power. The system gives the consumer power over the energy like never before, it stores energy automatically when the rates are low and uses that energy when rates are high to power consumer's house.

Each energy storage system is linked via the Orison Cloud. This is a network that uses data related to utility rates, peak demand charges, weather and consumer's usage profile to determine the optimal operation of the system.

Orison's home battery system can be used by any energy consumer, it is used to reduce the energy bill and to minimize the effects of increased charges for electricity during peak demand [24], [25].

### 2.1.1.2 SAMSUNG

Samsung has designed a new Energy Storage System for homes. It is considered an "All-in-One" solution because three functions are assembled in one. That means, a photovoltaic inverter, a battery inverter and lithium-ion battery are grouped in one system. It has a compact design that helps it to fit in any place of the consumer's home.

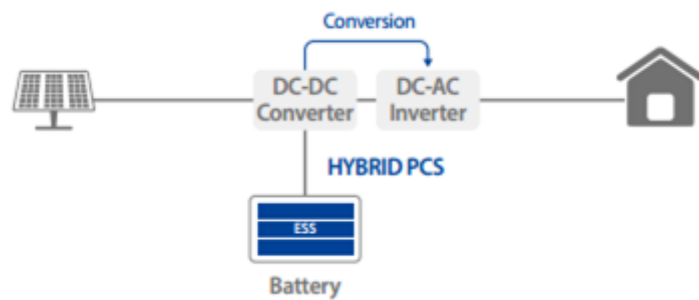


Figure 18: Conversion System

Electricity from solar panels has to be converted by the DC-DC converter and then through the DC-AC inverter before use for home applications, as it is shown in **Figure 18**.

Samsung's Energy Storage System is made with lithium-ion cells applied in cutting edge IT devices and automotives. It also uses a web monitoring that checks the amount of solar energy generated, the battery usage and the battery's status. It can offer the consumer an error detection in advance, thus it is connected to a local service.

There are three different types of Samsung's Energy Storage System, called AIO3, AIO5 and AIO8; which principal difference between them is the energy that they can store, they can store 3.6 kWh, 5.5 kWh and 8 kWh respectively. Also, AIO3 and AIO5 series have single-phase inverter with an AC output power of 4.6kVA, both of them are shown in **Figure 19**; but AIO8 has three-phase inverter with an output power of 8kVA [26], [27].



Figure 19: Samsung ESS AIO3 & AIO5

### 2.1.1.3 PANASONIC

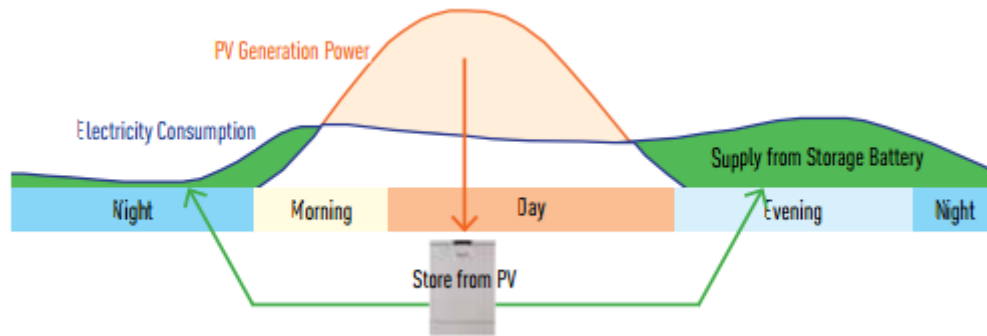
Panasonic has created a residential energy storage system, shows in **Figure 20**, which allows consumers reducing demand during peak times and favouring saving. The company has a good experience related to lithium ion batteries, the technology on which the system is based.

Panasonic's residential storage system has benefits for every field, in other words, it provides added value to distributors, retailers, consumers and society. It gives value to distributors to save costs related to capital investment for network upgrades; to retailers to reduce the demand during peak times; to consumers to reduce energy costs and to society to invest in renewable energies.



Figure 20: Panasonic Residential Storage System L.J-SK84A

The technology that Panasonic uses in their energy storage systems, is based on a compact lithium-ion battery, which is designed to be installed with an existing residential photovoltaic system. So, the storage system has to work in conjunction with the solar system, that it means, it stores the excess of energy generated by the solar panels during the day and supplies this energy at home when rates are high. **Figure 21** shows how the Panasonic's residential storage system stores and supplies energy during the all day.



**Figure 21: Storage and supply energy during a day by a Panasonic's ESS**

The storage system has the possibility of programming a predefined charge-discharge time mode in which the consumer can plan and determine the time at which the system stores or provides the energy.

The system has 8kWh usable capacity and a single-phase inverter with an output power of 2kAV [28].

### 2.1.1.4 LECLANCHÉ

Leclanché is a company that offers different types of energy storage systems.



**Figure 22: TiBox™ Energy Storage System**

These systems are characterized to have an easy installation and be compatible with the main inverter solutions on the market. The system used like a home energy storage system, shown in **Figure 22**, is called TiBox™ which has a technology based on lithium-ion titanate.

Like other energy storage systems, TiBox™ removes consumer's dependence on electricity owners, reduces bill's prices and gives consumer a control of their energy. It stores excess energy from solar panels for later use and also drops energy when solar system supply is not enough.

As it is said, TiBox™ is designed based on lithium-ion (NCO Titanate) energy storage technology, and in [29], it is also built with a ceramic separator that reduces the possibility of thermal failure.

It has 15,000 charging and discharging cycles and a storage capacity of 95%. In addition, it can be charged in one hour [30].

### 2.3.2 Summary

Throughout this chapter five different types of home energy storage systems have been described that can be combined with photovoltaic systems or other

renewable sources and that can supply energy to consumers, favouring bill's reduction and independence from the grid.

Below this paragraph, there is the **Table 2** that shows the most important characteristics of each system explained previously. Thereby, it is possible to compare each system and decide which is better for the application that is going to be used.

Battery	Technology	Thrift	Energy (kWh)	Power (kW)	Output Voltage Battery Pack	Operating Temperature	Weight (kg)	Dimensions
Tesla Power Wall	Lithium-ionic with liquid cooling	92,5% efficiency DC	6,4	3,3	350-450V	-20°C to 50°C	97	1302x862x183mm
Orison Tower	Lithium-ion	90%	2,2	2	110-240V (single phase)		18,1	863,3x228,6mm
Orison Panel	Lithium-ion	90%	2,2	2	110-240V (single phase)		17,2	558,8x711,2x63,5mm
Samsung AIO Series 5	Lithium-ion	95%	5,5	2	230V, 50Hz (single phase)	-10°C to 40°C	V 95	1000x267x680mm
Samsung AIO Series 8	Lithium-ion	96-97%	8	3	230V, 50Hz (3 phase)	-10°C to 40°C	95	1070x260x880mm
Panasonic Lj-SK84A	Lithium-ion	>93%	8	2	230V, 50Hz (single phase)	-10°C to 40°C	159	1380x966x279mm
Leclanché TiBox	Lithium-ion (NCO Titanate)	>90%	3,2	3,2	50,6V	0° to 40°C	120	731x515x312mm

Table 2: Characteristics of each ESS [23]–[28], [30]

## 2.3.3 Advantages and limitations of the technology used at the energy storage systems

### 2.3.3.1 *Lithium Ion Battery*

The lithium ion battery is considered as one of the best power battery system having the development potential. It can keep the power for long time, has a high energy density energy and does not produce pollution during its use of charges and discharges. But now, the challenge that prevents the use of this battery is its safety, although if it works between certain ranges it does not create problems.

The energy density of the lithium ion battery is higher than the energy density of hybrid energy storage (a system that benefits from gathering two or more energy storage technologies with supplementary operating characteristics) and of super capacitors; and the power density of lithium ion battery is less than the power density of the hybrid energy storage [31].

The popularity of the lithium ion battery is due to the advantages offered over other secondary (or rechargeable) batteries:

- High energy density - potential for yet higher capacities;
- Low maintenance;
- Specialty cells can provide very high current to applications (power tools);
- Do not suffer from battery memory effect;
- Environmental benefits: rechargeable and reduced toxic landfill;
- Less heavy than other rechargeable batteries for a given capacity.

Not everything related with lithium ion batteries are advantages, also they have some limitations in their applications, such as:

- Requires protection circuit to maintain voltage and current within safe limits.
- Poor cycle life, particularly in high current applications
- Expensive manufacturing, costs about 40% higher than nickel-cadmium.
- Rising internal resistance with cycling and age
- Safety concerns if overheated or overcharged [32].

### 2.1.1.1 *Lithium Titanate*

The lithium Titanate battery is considered a battery that has a rapid charged, that's why the higher surface area per gram, which contains the battery, allows the electrons to enter and exit the anode faster, favouring a quick recharge of the battery.

It is able to store and deliver current peaks that are between 30 and 100 times that of ordinary lithium batteries. Other points that this type of battery does better are long lifespan, less risk of auto-combustion, good operation in low temperatures, and rapid charging.

Batteries that used this type of technology have safety advantages because they do not have carbon in their manufacturing, with the lack of carbon they avoid thermal runaway or overheating which is the main cause of fires in lithium-ion batteries. This type of batteries also have good performances at low temperatures due to the advanced nanotechnology consisting of lithium-titanate nanocrystals and their increased surface area.

In other words, lithium Titanate batteries are characterized for having the following advantages:

- Wide operating temperature range, between -30°C and 50°C;
- Long cycle life, 3000-7000 cycles;
- High security;
- Fast charge ;
- Green and eco-friendly, that it means, the production and use of this technology causes a minimal harm upon the environment.

The disadvantage with this type of technology is that lithium Titanate batteries have a lower inherent voltage (2.4V/cell), which leads to a lower energy density than conventional lithium-ion battery technologies **[33]**.



## CHAPTER 3: SIZING TOOL FOR DISTRIBUTED ESS

Once a study of the different types of renewable energies that exists (focused on solar and wind energy) is done, the wide variety of energy storage technologies are known and exists a study of the energy storage products of the most important companies, it is possible to design a system that generates and stores energy.

The system is going to be designed for a single family home using the application MATLAB® & SIMULINK®. It is going to be formed by a renewable energy generator and an energy storage system, also it is going to be connected to the grid.

Initially, the system has to be able to supply all the energy required by the single family home, without help of the grid. That's why the choice of the energy generator and energy storage system has to be correct to supply the energy required for one day by the house.

A solar PV panel, which is placed on the roof of the house, is going to be used as energy generator. Then a battery pack is used as an energy storage system that is situated in the garage. Both of them, the solar PV panel and the battery pack, are connected to the grid via a converter that transforms Direct Current (DC) into Alternating Current (AC).

There is a DC bus where every current has to pass through it. The solar PV panel, the battery pack and the grid are connected to this bus via their own converters.

The solar PV panel uses a unidirectional Boost converter to increase the voltage value to the required rate need in the DC bus. However, the converter used by the energy pack is a bidirectional Boost converter, due to there are a process of charge and a process of discharge of the battery what it means that the current have to go in both senses. And, as it is said, the grid is connected to the DC bus via a bidirectional DC/AC converter.

On the **Figure 23** it is shown a scheme of the system explained above, where the arrows indicate the direction of the current.

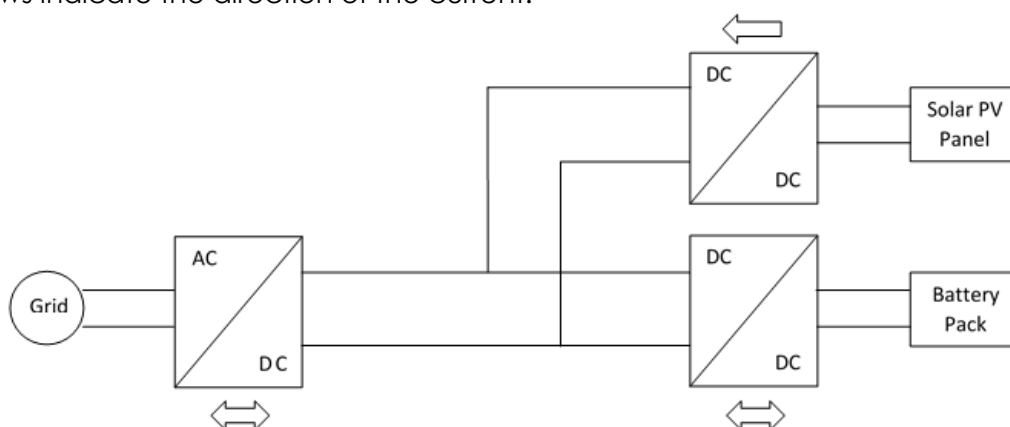


Figure 23: Scheme of the System

Once the system has been explained and how it works, it is time to describe the design of each converter and how is going to be their control. After each converter has been described and the steps to design their controllers have been explained, it can continue with the calculation of the parameters of the controllers. For so, make the design of converters in MATLAB® & SIMULINK® and start with the simulations.

### 3.1 Theoretical design of converters

#### 3.1.1 AC/DC converter

The AC/DC converter designed, also called as inverter, consists on an H-bridge that should inject into the grid a controlled current ( $i_{grid}$ ) in phase with the grid voltage. As it is shown in **Figure 24**, the inverter is formed by two switching cells that create the H-bridge, an inductance and a capacitor. Each element will be calculated previously.

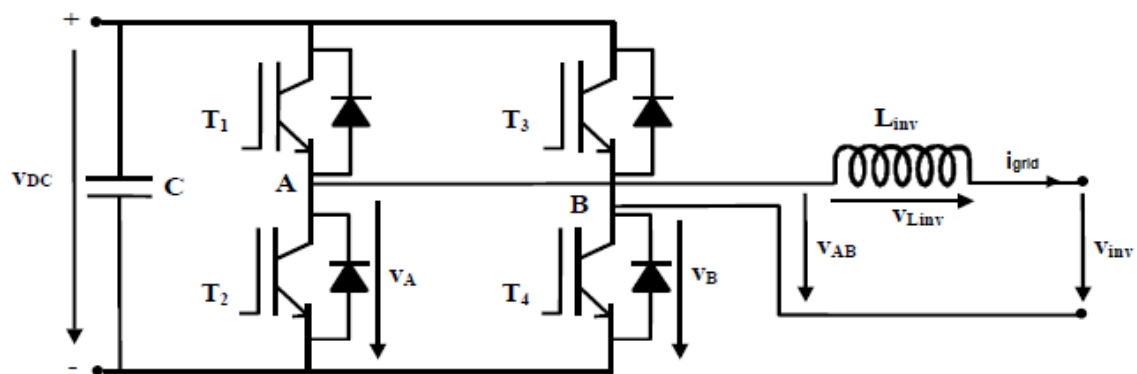


Figure 24: Inverter Modelling

It is proposed a cascade control structure, as it shown in **Figure 25**, in which the inner current loop controls the power fed into the grid to follow the slogan provided by the voltage control loop ( $i_{grid,ref}$ ). This control is performed by acting on the duty cycle of semiconductors and ultimately on the voltage applied by the inverter ( $V_{inv}$ ). The voltage loop is responsible for maintaining the bus voltage equal to the reference by a balance of powers. Extracting power bus is performed by the current control loop.

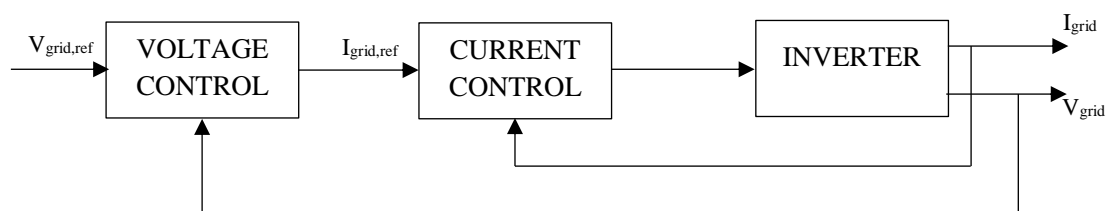


Figure 25: Inverter control scheme

### 3.1.1.1 Design inner current loop

The first step is to start with the design of the inner loop current, whose simplified diagram shown in **Figure 26**. The controller used is proportional-integral type (PI). Its output is the control voltage, which is compared with a triangular signal (PWM switching). The loop controls the current through the output inductor ( $L_{inv}$ ).

The process for the design of the control loop consists on the choice of the control structure, in the modelling of the system elements and the establishment of specifications and controller design. As it is said above, it is proposed a cascade control structure; next step is the modelling of the system elements.

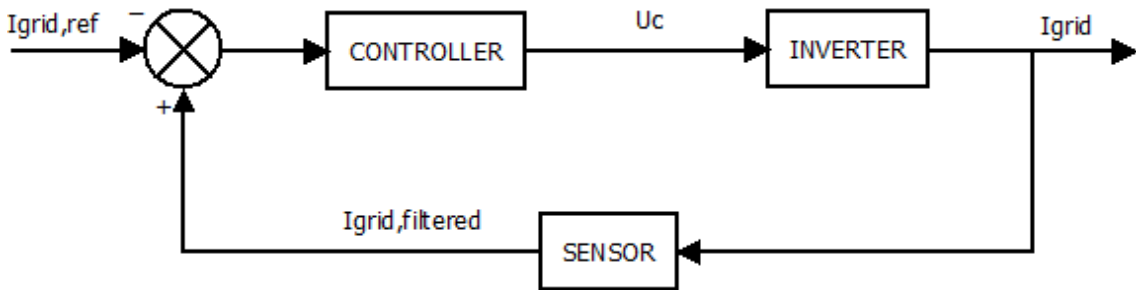


Figure 26: Simplified diagram of the inner current loop

First of all, the modelling of the inverter is created. From **Figure 24**, the following equations are obtained that are used to generate the model of the plant.

$$v_{AB} = d \cdot v_{DC} \quad (2)$$

$$v_{AB} = v_{inv} + v_{L_{inv}} \quad (3)$$

$$v_{L_{inv}} = L_{inv} \frac{di_{grid}}{dt} \quad (4)$$

The combination of equations (2), (3), (4), the following equation is obtained, with which the plant model is generated.

$$I_{grid}(s) = \frac{1}{L_{inv}s} [V_{DC} \cdot d(s) - V_{inv}(s)] \quad (5)$$

From equation (5) it is obtained the block diagram of the inverter, as it is shown in **Figure 27**.

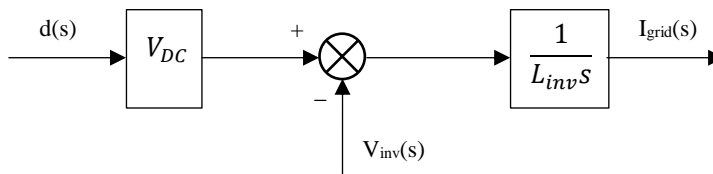


Figure 27: Block diagram of the inverter (current)

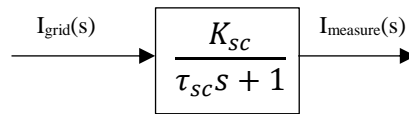
The next model to generate is the current sensor and conditioning of the measure, which is expressed by equation (6).

$$\frac{I_{measure}}{I_{grid}} = \frac{K_{sc}}{\tau_{sc}s + 1} \quad (6)$$

Where:

- $K_{sc}$ : sensor gain
- $\tau_{sc}$ : filter time constant measurement

From equation (6) it is obtained the block diagram of the current sensor and conditioning of the measure, as it is shown in **Figure 28**.



**Figure 28: Block diagram of current sensor**

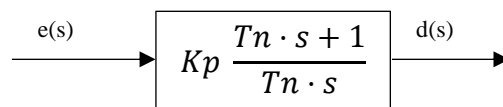
The last model to generate is the proportional-integral controller, which is expressed by equation (7).

$$u_c(t) = Kp \cdot e(t) + Ki \int e(t)dt = Kp \left[ e(t) + \frac{1}{Tn} \int e(t)dt \right] \quad (7)$$

Equation (7) express in frequency domain is obtained as equation (8):

$$d(s) = Kp \frac{Tn \cdot s + 1}{Tn \cdot s} e(s) \quad (8)$$

From equation (8) it is obtained the block diagram of the proportional-integral controller, as it is shown in **Figure 29**.



**Figure 29: Block diagram of the PI controller**

Once every block diagram is obtained, it is possible to create the block diagram of the inner loop current, shown in **Figure 30**.

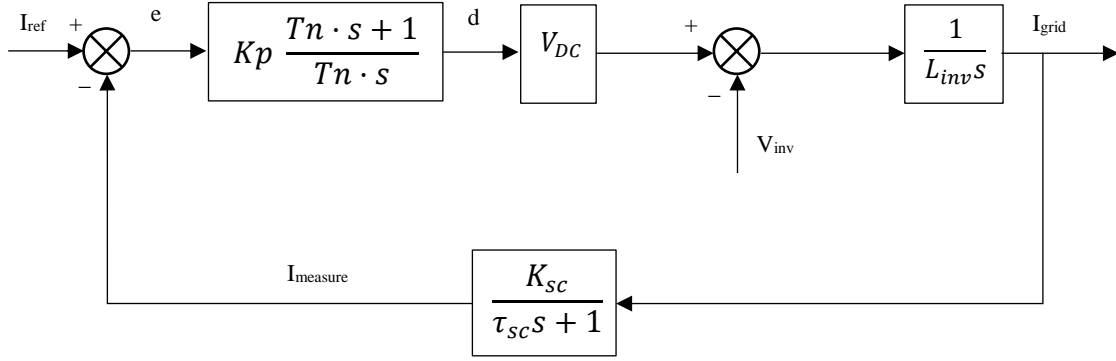


Figure 30: Complete system of internal loop current

From **Figure 30**, it is possible to obtain the transfer function open loop (9). Equation (9) is going to be used for calculate the parameters of the PI controller.

$$TF_c(s) = Kp \frac{Tn \cdot s + 1}{Tn \cdot s} \cdot V_{DC} \cdot \frac{1}{L_{inv}s} \cdot \frac{K_{sc}}{\tau_{sc}s + 1} \quad (9)$$

The establishment of specifications and controller design on the overall system are related to cut-off frequency ( $\omega_{cc}$ ) and Phase Margin (PM). The cut-off frequency ( $\omega_{cc}$ ) has to be the maximum possible, wise over a decade frequency reference (it will be limited by the current pole filter). The Phase Margin (PM) is used to ensure stability, the phase margin is usually taken between  $45^\circ$  and  $60^\circ$ .

Once the values of the cut-off frequency and phase margin have been elected, the constants of the PI controller can be calculated.  $Tn$  is obtained from the  $TF_c(s)$  phase to the cut-off frequency and  $Kp$  gain is calculated from the condition of unity gain  $TF_c(s)$  to the cut-off frequency.

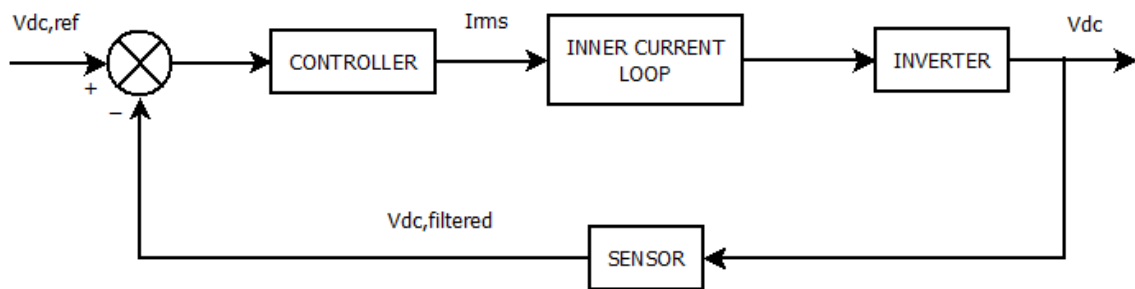
$$\begin{aligned} \varphi[TF_c(j\omega_{cc})] &= -180 + PM \rightarrow PM = \arctg(Tn \cdot \omega_{cc}) - \arctg(\tau_{sc} \cdot \omega_{cc}) \\ Tn &= \frac{\text{tg}(PM + \arctg(\tau_{sc} \cdot \omega_{cc}))}{\omega_{cc}} \end{aligned} \quad (10)$$

$$\begin{aligned} |TF_c(j\omega_{cc})| = 1 &\rightarrow \frac{Kp V_{DC} K_{sc}}{Tn L_{inv} \omega_{cc}^2} \sqrt{\frac{Tn^2 \omega_{cc}^2 + 1}{\tau_{sc}^2 \omega_{cc}^2 + 1}} = 1 \\ Kp &= \frac{Tn L_{inv} \omega_{cc}^2}{V_{DC} K_{sc}} \sqrt{\frac{\tau_{sc}^2 \omega_{cc}^2 + 1}{Tn^2 \omega_{cc}^2 + 1}} \end{aligned} \quad (11)$$

This design is a good compromise between speed and stability.

### 3.1.1.2 Design voltage loop

Once the design of the inner loop current is finished and works correctly, it is time to continue with the design of the voltage loop whose simplified diagram shown in **Figure 31**. The controller used is proportional-integral type (PI). Its output is the rms value of the current through the inductance, which is used as the current reference in the inner current loop. The loop controls the voltage across the capacitor DC bus ( $V_{DC}$ ).



**Figure 31:** Simplified diagram of the voltage loop

The process for the design of the control loop follows a similar process used in the design of the current loop. First of all, the choice of the control structure, then the modelling of the system elements and finally, the establishment of specifications and controller design.

First of all, the modelling of the inverter is created. From **Figure 24**, the following equations are obtained that are used to generate the model of the plant.

$$P_{AC} = P_{DC} \rightarrow V_{ef} \cdot I_{ef} = V_{DC} \cdot I_{DC} \rightarrow I_{DC} = \frac{V_{ef} \cdot I_{ef}}{V_{DC}} \quad (12)$$

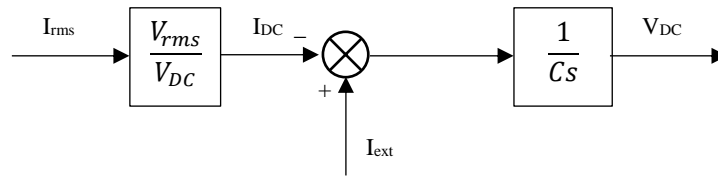
$$i_c = i_{ext} - i_{DC} \quad (13)$$

$$i_c = C \frac{d v_{DC}}{dt} \quad (14)$$

The combination of equations (12), (13), (14), the following equation is obtained, with which the plant model is generated.

$$V_{DC}(s) = \frac{1}{CS} [I_{ext}(s) - I_{DC}(s)] \quad (15)$$

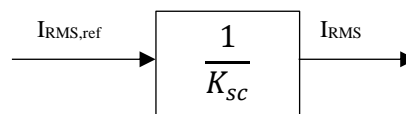
From equation (15) it is obtained the block diagram of the inverter, as it is shown in **Figure 32**.



**Figure 32: Block diagram of the inverter (voltage)**

This model does not represent the exact behaviour of the inverter, as it has made an assessment of average power to obtain the equations. But nevertheless, since the cut-off frequency of this loop is very slow (usually about few hertz), the approximation is valid. In turn, the model has an external disturbance: the  $I_{ext}$  current that comes from the elevator.

The current control loop should be modelled by its transfer function in closed loop. However, since the current loop is much faster than the loop voltage (usually more than ten times), can be modelled simply as a block of constant gain. That is, for any variation in the loop voltage, the current loop is considered to react almost instantaneously. Loop gain is the inverse of the gain of the current sensor. In short, the block diagram of this loop is shown in **Figure 33**.



**Figure 33: Model current control loop**

Referring to sensor voltage, the filtering of the measured voltage has no effect on the loop, since the cut-off frequency is much smaller compared with the current filter. The cut-off frequency is too small due to the frequency voltage ripple bus ( $V_{DC}$ ), the ripple frequency is 100Hz, and so the cut-off frequency has to be smaller. In **Figure 34** is shown the model of the voltage filter that it is obtained from equation (16).

$$\frac{V_{measure}}{V_{DC}} = \frac{K_{sv}}{\tau_{sv}s + 1} \quad (16)$$

Where:

- $K_{sv}$ : sensor gain
- $\tau_{sv}$ : filter time constant measurement

From equation (16) it is obtained the block diagram of the current sensor and conditioning of the measure, as it is shown in **Figure 34**.

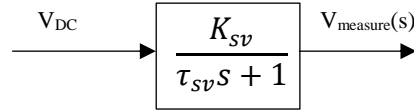


Figure 34: Block diagram of voltage sensor

The controller is, like in the loop current, a Proportional-Integral Controller, as it is shown in **Figure 29**.

Once every block diagram is obtained, it is possible to create the block diagram of the voltage loop, shown in **Figure 35**.

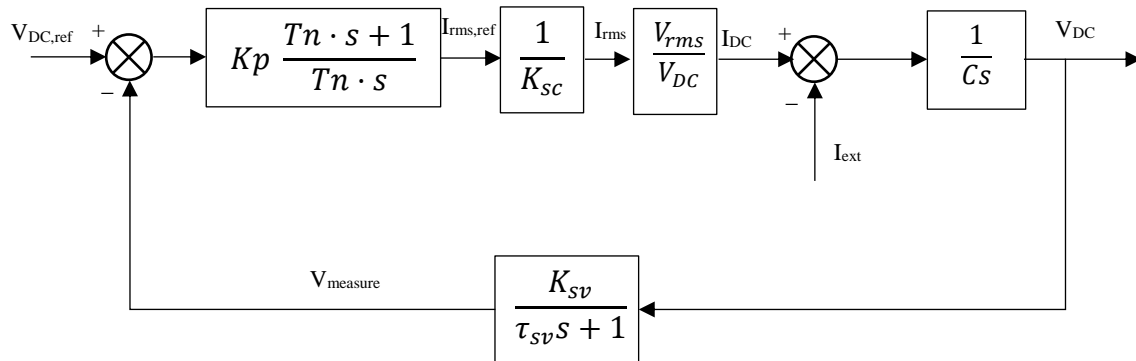


Figure 35: Complete system of voltage loop

From **Figure 35**, it is possible to obtain the transfer function open loop (17). Equation (17) is going to be used for calculate the parameters of the PI controller.

$$TF_v(s) = Kp \frac{Tn \cdot s + 1}{Tn \cdot s} \cdot \frac{1}{K_{Sc}} \cdot \frac{V_{rms}}{V_{DC}} \cdot \frac{1}{Cs} \cdot \frac{K_{Sv}}{\tau_{Sv}s + 1} \quad (17)$$

The establishment of specifications and controller design on the overall system are related to cut-off frequency ( $\omega_{cv}$ ) and Phase Margin (PM). The cut-off frequency ( $\omega_{cv}$ ) of the loop should control a DC voltage, so the cut-off frequency does not have to be high. It is advisable that this frequency is located, to least a decade below the cut-off frequency of the current loop, so that the cascade control structure does not destabilized. The value of this cut-off frequency usually represents few hertz. Referring to phase Margin (PM), the voltage loop uses a rough plant, due to balance middle powers being performed. Therefore, a phase margin is advised close to  $60^\circ$ , to ensure system stability. However, if the cut-off frequency is low, they can be lower phase margins.

Once the values of the cut-off frequency and phase margin have been elected, the constants of the PI controller can be calculated.  $Tn$  is obtained from the  $TF_v(s)$  phase to the cut-off frequency and  $Kp$  gain is calculated from the condition of unity gain  $TF_v(s)$  to the cut-off frequency.



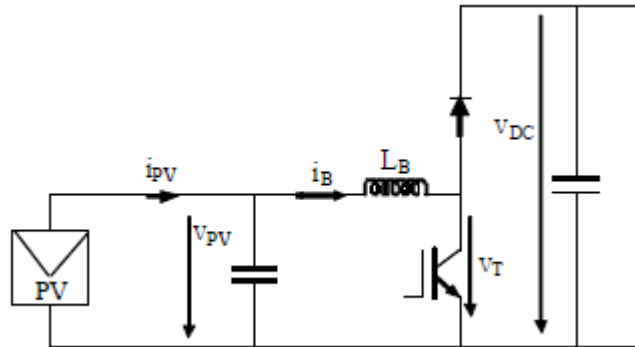
$$\begin{aligned} \varphi[TF_v(j\omega_{cv})] &= -180 + PM \rightarrow PM = \arctg(T_n \cdot \omega_{cv}) - \arctg(\tau_{sv} \cdot \omega_{cv}) \\ T_n &= \frac{\text{tg}(PM + \arctg(\tau_{sv} \cdot \omega_{cv}))}{\omega_{cv}} \end{aligned} \quad (18)$$

$$\begin{aligned} |TF_v(j\omega_{cv})| = 1 &\rightarrow \frac{K_p V_{rms} K_{sv}}{T_n K_{sc} V_{DC} C \omega_{cv}^2} \sqrt{\frac{T_n^2 \omega_{cv}^2 + 1}{\tau_{sv}^2 \omega_{cv}^2 + 1}} = 1 \\ K_p &= \frac{T_n K_{sc} V_{DC} C \omega_{cv}^2}{V_{rms} K_{sv}} \sqrt{\frac{\tau_{sv}^2 \omega_{cv}^2 + 1}{T_n^2 \omega_{cv}^2 + 1}} \end{aligned} \quad (19)$$

This design is a good compromise between speed and stability.

### 3.1.2 DC/DC converter for PV solar panel

The DC/DC converter designed is a unidirectional boost converter that increase the voltage generated by the PV solar panel to the required rate need in the DC bus. The converter is formed by an inductor, a capacitor, a diode and a switch; as it is shown in **Figure 36**.



**Figure 36: Modelling Solar panel Boost converter**

The Boost converter should control the voltage of the solar panel ( $V_{PV}$ ). To do this, a cascade control structure is designed with an inner loop that controls the current through the inductance ( $i_B$ ) and an external loop that do likewise with the solar panel voltage; as it is shown in **Figure 37**. Recall that the output voltage ( $V_{DC}$ ) is the inverter's input and is controlled by the bridge itself.

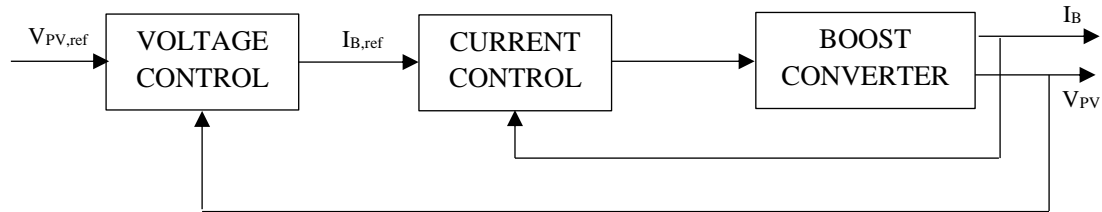


Figure 37: PV Boost control scheme

### 3.1.2.1 Design inner current loop

The first step is to start with the design of the inner loop current, whose simplified diagram shown in **Figure 38**. The controller used is proportional-integral type (PI). Its output is the control voltage, which is compared with a triangular signal between 0 and 1 (PWM switching). The loop controls the current through the inductance ( $L_B$ ).

The process for the design of the control loop consists on the choice of the control structure, in the modelling of the system elements and the establishment of specifications and controller design. As it is said above, it is proposed a cascade control structure; next step is the modelling of the system elements.

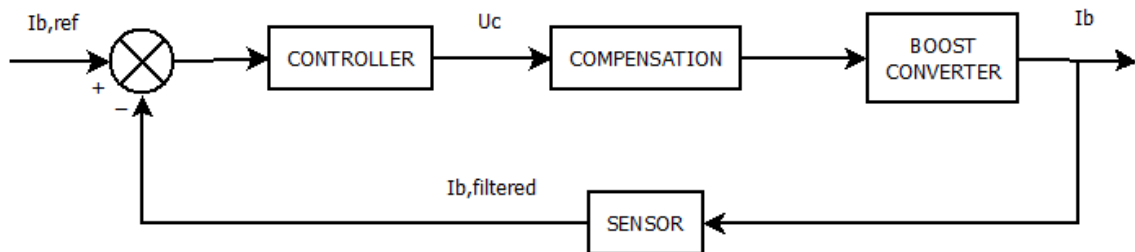


Figure 38: Simplified diagram of the inner current loop

First of all, the modelling of the inverter is created. From **Figure 36**, the following equations are obtained that are used to generate the model of the plant.

$$v_T = (1 - d) \cdot v_{DC} \quad (20)$$

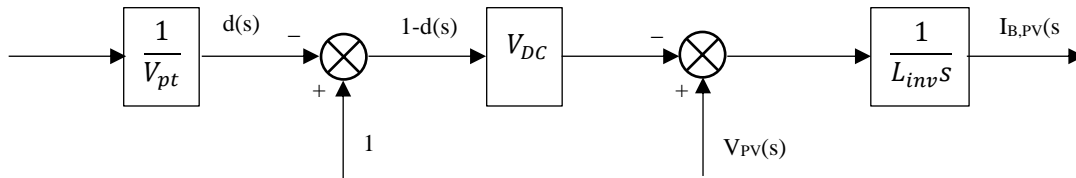
$$v_{PV} = v_T + v_{L,PV} \quad (21)$$

$$v_{Lb} = L_{B,PV} \frac{di_{B,PV}}{dt} \quad (22)$$

The combination of equations (20), (21), (22), the following equation is obtained, with which the plant model is generated.

$$I_B(s) = \frac{1}{L_{B,PV}} [V_{DC} \cdot (1 - d(s)) - V_T(s)] \quad (23)$$

From equation (23) it is obtained the block diagram of the inverter, as it is shown in **Figure 39**.



**Figure 39: Block diagram of the PV Boost (current)**

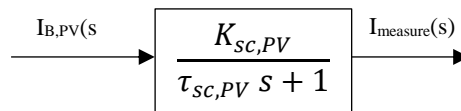
The next model to generate is the current sensor and conditioning of the measure, which is expressed by equation (24).

$$\frac{I_{measure}}{I_{B,PV}} = \frac{K_{SC,PV}}{\tau_{SC,PV} s + 1} \quad (24)$$

Where:

- $K_{sc}$ : sensor gain
- $\tau_{sc}$ : filter time constant measurement

From equation (24) it is obtained the block diagram of the current sensor and conditioning of the measure, as it is shown in **Figure 40**.



**Figure 40: Block diagram of current sensor**

The controller is, like in the inverter loop current, a Proportional-Integral Controller, as it is shown in **Figure 29**.

Once every block diagram is obtained, it is possible to create the block diagram of the voltage loop, shown in **Figure 41**.

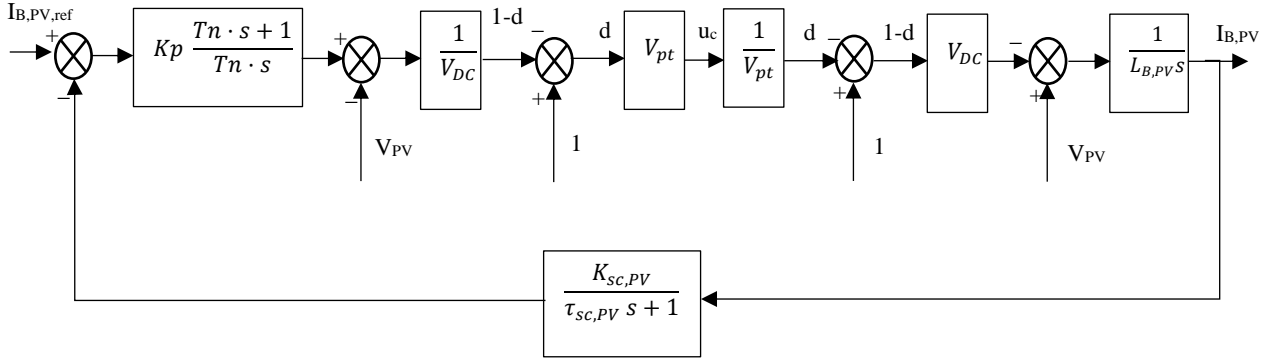


Figure 41: Complete system of internal loop current

From **Figure 41**, it is possible to obtain the transfer function open loop (25). Equation (25) is going to be used for calculate the parameters of the PI controller.

$$TF_c(s) = Kp \frac{Tn \cdot s + 1}{Tn \cdot s} \cdot \frac{1}{V_{DC}} \cdot V_{pt} \cdot \frac{1}{V_{pt}} \cdot V_{DC} \cdot \frac{1}{L_{B,PV} s} \cdot \frac{K_{sc,PV}}{\tau_{sc,PV} s + 1} \quad (25)$$

The establishment of specifications and controller design on the overall system are related to cut-off frequency ( $\omega_{cc}$ ) and Phase Margin (PM). The cut-off frequency ( $\omega_{cc}$ ) has to be the maximum possible, wise over a decade frequency reference (it will be limited by the current pole filter). The Phase Margin (PM) is used to ensure stability, the phase margin is usually taken between  $45^\circ$  and  $60^\circ$ .

Once the values of the cut-off frequency and phase margin have been elected, the constants of the PI controller can be calculated.  $Tn$  is obtained from the  $TF_c(s)$  phase to the cut-off frequency and  $Kp$  gain is calculated from the condition of unity gain  $TF_c(s)$  to the cut-off frequency.

$$\varphi[TF_c(j\omega_{cc})] = -180 + PM \rightarrow PM = \arctg(Tn \cdot \omega_{cc}) - \arctg(\tau_{sc,PV} \cdot \omega_{cc})$$

$$Tn = \frac{\text{tg}(PM + \arctg(\tau_{sc,PV} \cdot \omega_{cc}))}{\omega_{cc}} \quad (26)$$

$$|TF_c(j\omega_{cc})| = 1 \rightarrow \frac{Kp K_{sc,PV}}{Tn L_{B,PV} \omega_{cc}^2} \sqrt{\frac{Tn^2 \omega_{cc}^2 + 1}{\tau_{sc,PV}^2 \omega_{cc}^2 + 1}} = 1$$

$$Kp = \frac{Tn L_{B,PV} \omega_{cc}^2}{K_{sc,PV}} \sqrt{\frac{\tau_{sc,PV}^2 \omega_{cc}^2 + 1}{Tn^2 \omega_{cc}^2 + 1}} \quad (27)$$

This design is a good compromise between speed and stability.

### 3.1.2.2 Design voltage loop

Once the design of the inner loop current is finished and works correctly, it is time to continue with the design of the voltage loop whose simplified diagram shown in **Figure 42**. The controller used is proportional-integral type (PI). Its output is the rms value of the current through the inductance, which is used as the current reference in the inner current loop. The loop controls the voltage across the capacitor that is situated at the solar panel output ( $V_{PV}$ ).

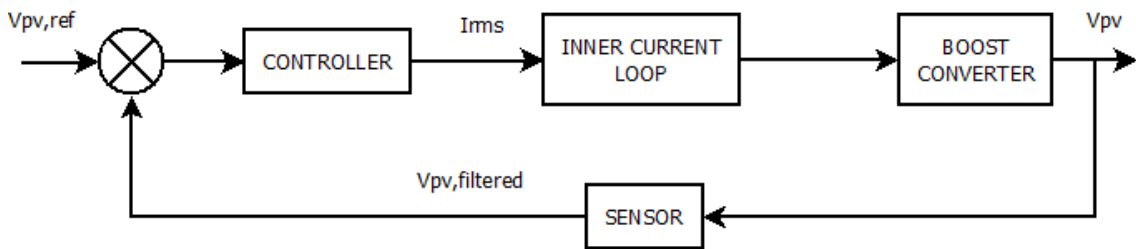


Figure 42: Simplified diagram of the voltage loop

The process for the design of the control loop follows a similar process used in the design of the current loop. First of all, the choice of the control structure, then the modelling of the system elements and finally, the establishment of specifications and controller design.

First of all, the modelling of the inverter is created. From **Figure 36**, the following equations are obtained that are used to generate the model of the plant.

$$i_{C,PV} = i_{PV} - i_{B,PV} \quad (28)$$

$$i_{C,PV} = C_{PV} \frac{d v_{PV}}{dt} \quad (29)$$

The combination of equations (28), (29), the following equation is obtained, with which the plant model is generated.

$$V_{PV}(s) = \frac{1}{C_{PV} s} [I_{PV}(s) - I_{B,PV}(s)] \quad (30)$$

From equation (30) it is obtained the block diagram of the inverter, as it is shown in **Figure 43**.

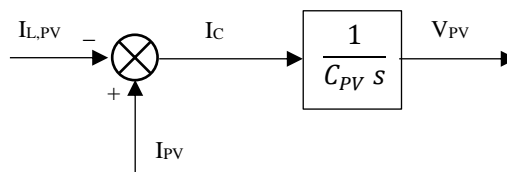
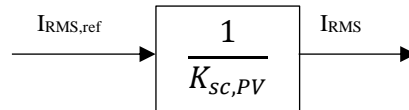


Figure 43: Block diagram of the PV Boost Converter (voltage)

The current control loop should be modelled by its transfer function in closed loop. However, since the current loop is much faster than the loop voltage (usually more than ten times), can be modelled simply as a block of constant gain. That is, for any variation in the loop voltage, the current loop is considered to react almost instantaneously. Loop gain is the inverse of the gain of the current sensor. In short, the block diagram of this loop is shown in **Figure 44**.



**Figure 44: Model current control loop**

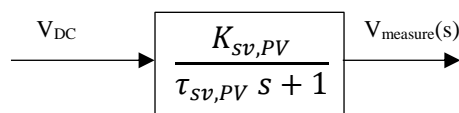
Referring to sensor voltage, the filtering of the measured voltage has no effect on the loop, since the cut-off frequency is much smaller compared with the current filter. In **Figure 45** is shown the model of the voltage filter that it is obtained from equation (31)

$$\frac{V_{measure}}{V_{PV}} = \frac{K_{sv,PV}}{\tau_{sv,PV} s + 1} \quad (31)$$

Where:

- $K_{sv}$ : sensor gain
- $\tau_{sv}$ : filter time constant measurement

From equation (31) it is obtained the block diagram of the current sensor and conditioning of the measure, as it is shown in **Figure 45**.



**Figure 45: Block diagram of voltage sensor**

The controller is, like in the loop current, a Proportional-Integral Controller, as it is shown in **Figure 29**.

Once every block diagram is obtained, it is possible to create the block diagram of the voltage loop, shown in **Figure 46**.

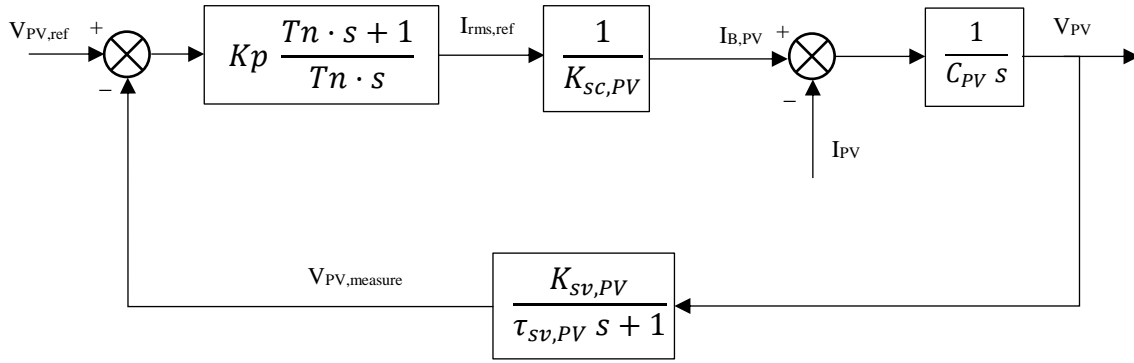


Figure 46: Complete system of voltage loop

From **Figure 46**, it is possible to obtain the transfer function open loop (32). Equation (32) is going to be used for calculate the parameters of the PI controller.

$$TF_v(s) = Kp \frac{Tn \cdot s + 1}{Tn \cdot s} \cdot \frac{1}{K_{sc,PV}} \cdot \frac{1}{C_{PV} s} \cdot \frac{K_{Sv,PV}}{\tau_{sv,PV} s + 1} \quad (32)$$

The establishment of specifications and controller design on the overall system are related to cut-off frequency ( $\omega_{cv}$ ) and Phase Margin (PM). The cut-off frequency ( $\omega_{cv}$ ) of the loop should control a DC voltage, so the cut-off frequency does not have to be high. It is advisable that this frequency is located, to least a decade below the cut-off frequency of the current loop, so that the cascade control structure does not destabilized. The value of this cut-off frequency usually represents few hertz. Referring to phase Margin (PM), the voltage loop uses a rough plant, due to balance middle powers being performed. Therefore, a phase margin is advised close to  $60^\circ$ , to ensure system stability. However, if the cut-off frequency is low, they can be lower phase margins.

Once the values of the cut-off frequency and phase margin have been elected, the constants of the PI controller can be calculated.  $Tn$  is obtained from the  $TF_v(s)$  phase to the cut-off frequency and  $Kp$  gain is calculated from the condition of unity gain  $TF_v(s)$  to the cut-off frequency.

$$\begin{aligned} \varphi[TF_v(j\omega_{cv})] &= -180 + PM \rightarrow PM = \arctg(Tn \cdot \omega_{cv}) - \arctg(\tau_{sv,PV} \cdot \omega_{cv}) \\ Tn &= \frac{tg(PM + \arctg(\tau_{sv,PV} \cdot \omega_{cv}))}{\omega_{cv}} \end{aligned} \quad (33)$$

$$|TF_v(j\omega_{cv})| = 1 \rightarrow \frac{Kp K_{sv,PV}}{Tn K_{sc,PV} C_{PV} \omega_{cv}^2} \sqrt{\frac{Tn^2 \omega_{cv}^2 + 1}{\tau_{sv}^2 \omega_{cv}^2 + 1}} = 1$$

$$Kp = \frac{Tn K_{sc,PV} C_{PV} \omega_{cv}^2}{K_{sv,PV}} \sqrt{\frac{\tau_{sv}^2 \omega_{cv}^2 + 1}{Tn^2 \omega_{cv}^2 + 1}} \quad (34)$$

This design is a good compromise between speed and stability.

### 3.1.3 DC/DC converter for Battery

The DC/DC converter designed is a bidirectional boost converter that increase the voltage stored by the battery to the required rate need in the DC bus, but also decrease the voltage from the DC bus to the required rate needed to be stored in the battery. The converter is formed by an inductor, a capacitor, and two switches with an antiparallel diode each one; as it is shown in **Figure 47**.

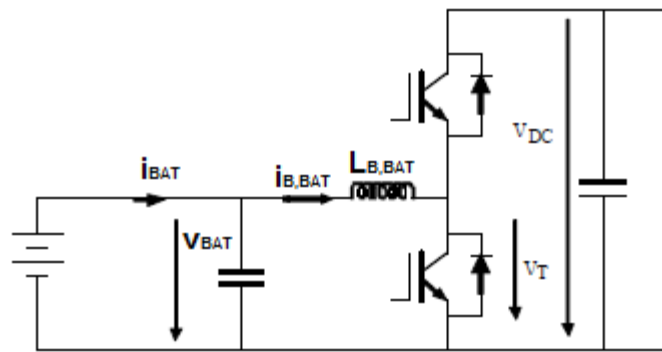


Figure 47: Modelling battery Boost converter

The Boost converter should control the voltage of the battery ( $V_{BAT}$ ). To do this, a cascade control structure is designed with an inner loop that controls the current through the inductance ( $i_{B,BAT}$ ) and an external loop that do likewise with the solar panel voltage; as it is shown in **Figure 48**. Recall that the output voltage ( $V_{DC}$ ) is the inverter's input and is controlled by the bridge itself.

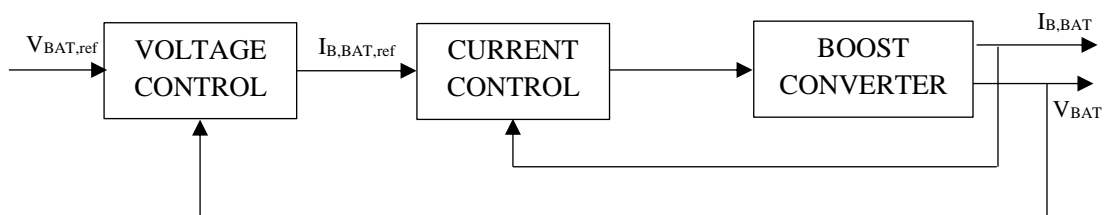


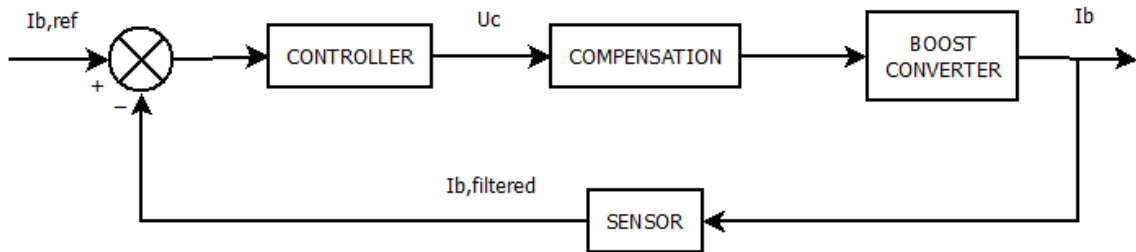
Figure 48: Battery Boost control scheme



### 3.1.3.1 Design inner current loop

The first step is to start with the design of the inner loop current, whose simplified diagram shown in **Figure 49**. The controller used is proportional-integral type (PI). Its output is the control voltage, which is compared with a triangular signal between 0 and 1 (PWM switching). The loop controls the current through the inductance ( $L_{B,BAT}$ ).

The process for the design of the control loop consists on the choice of the control structure, in the modelling of the system elements and the establishment of specifications and controller design. As it is said above, it is proposed a cascade control structure; next step is the modelling of the system elements.



**Figure 49: Simplified diagram of the inner current loop**

First of all, the modelling of the inverter is created. From **Figure 47**, the following equations are obtained that are used to generate the model of the plant.

$$v_T = (1 - d) \cdot v_{DC} \quad (35)$$

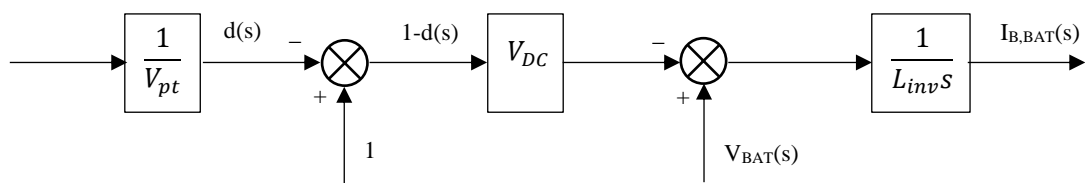
$$v_{BAT} = v_T + v_{L,BAT} \quad (36)$$

$$v_{Lb} = L_{B,BAT} \frac{di_{B,BAT}}{dt} \quad (37)$$

The combination of equations (35), (36), (37), the following equation is obtained, with which the plant model is generated.

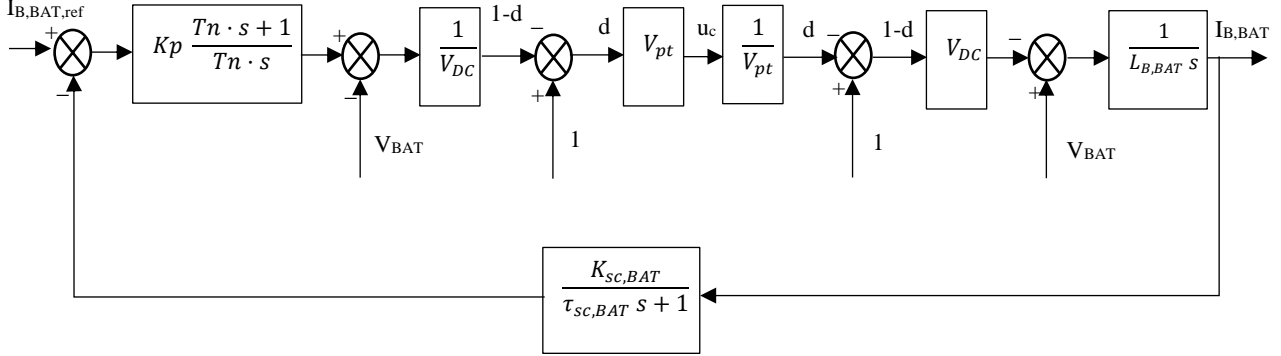
$$I_{B,BAT}(s) = \frac{1}{L_{B,BAT}} [V_{DC} \cdot (1 - d(s)) - V_T(s)] \quad (38)$$

From equation (38) it is obtained the block diagram of the inverter, as it is shown in **Figure 50**.



**Figure 50: Block diagram of the Battery Boost (current)**

Once the plant of the system has been obtained, it is necessary to design the blocks related to the sensor and controller. The design diagram is performed in the same manner as done in the previous converter, so the block diagram for the inner current loop for the battery is shown in **Figure 51**.



**Figure 51:** Complete system of internal loop current

From **Figure 51**, it is possible to obtain the transfer function open loop (39). Equation (39) is going to be used for calculate the parameters of the PI controller.

$$TF_c(s) = Kp \frac{Tn \cdot s + 1}{Tn \cdot s} \cdot \frac{1}{V_{DC}} \cdot V_{pt} \cdot \frac{1}{V_{pt}} \cdot V_{DC} \cdot \frac{1}{L_{B,BAT} s} \cdot \frac{K_{sc,BAT}}{\tau_{sc,BAT} s + 1} \quad (39)$$

The establishment of specifications and controller design on the overall system are related to cut-off frequency ( $\omega_{cc}$ ) and Phase Margin (PM) follow the same guidelines use in the design of the inner current loop of the solar panel.

Once the values of the cut-off frequency and phase margin have been elected, the constants of the PI controller can be calculated.  $Tn$  is obtained from the  $TF_c(s)$  phase to the cut-off frequency and  $Kp$  gain is calculated from the condition of unity gain  $TF_c(s)$  to the cut-off frequency.

$$\varphi[TF_c(j\omega_{cc})] = -180 + PM \rightarrow PM = \arctg(Tn \cdot \omega_{cc}) - \arctg(\tau_{sc,BAT} \cdot \omega_{cc})$$

$$Tn = \frac{tg(PM + \arctg(\tau_{sc,BAT} \cdot \omega_{cc}))}{\omega_{cc}} \quad (40)$$

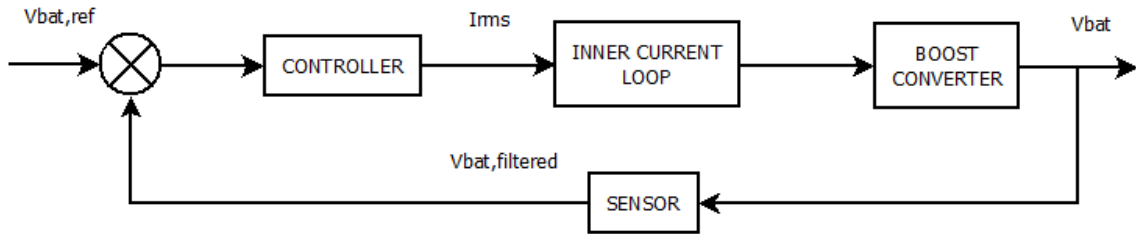
$$|TF_c(j\omega_{cc})| = 1 \rightarrow \frac{Kp K_{sc,BAT}}{Tn L_{B,BAT} \omega_{cc}^2} \sqrt{\frac{Tn^2 \omega_{cc}^2 + 1}{\tau_{sc,BAT}^2 \omega_{cc}^2 + 1}} = 1$$

$$Kp = \frac{Tn L_{B,BAT} \omega_{cc}^2}{K_{sc,BAT}} \sqrt{\frac{\tau_{sc,BAT}^2 \omega_{cc}^2 + 1}{Tn^2 \omega_{cc}^2 + 1}} \quad (41)$$

This design is a good compromise between speed and stability.

### 3.1.3.2 Design voltage loop

Once the design of the inner loop current is finished and works correctly, it is time to continue with the design of the voltage loop whose simplified diagram shown in **Figure 52**. The controller used is proportional-integral type (PI). Its output is the rms value of the current through the inductance, which is used as the current reference in the inner current loop. The loop controls the voltage across the capacitor that is situated at the solar panel output ( $V_{BAT}$ ).



**Figure 52: Simplified diagram of the voltage loop**

The process for the design of the control loop follows a similar process used in the design of the current loop. First of all, the choice of the control structure, then the modelling of the system elements and finally, the establishment of specifications and controller design.

First of all, the modelling of the inverter is created. From **Figure 47**, the following equations are obtained that are used to generate the model of the plant.

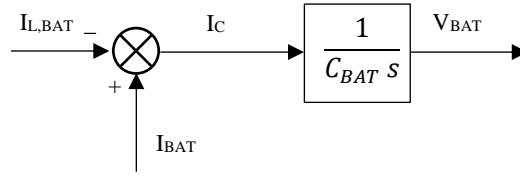
$$i_{C,BAT} = i_{BAT} - i_{B,BAT} \quad (42)$$

$$i_{C,PV} = C_{PV} \frac{d v_{PV}}{dt} \quad (43)$$

The combination of equations (42), (43), the following equation is obtained, with which the plant model is generated.

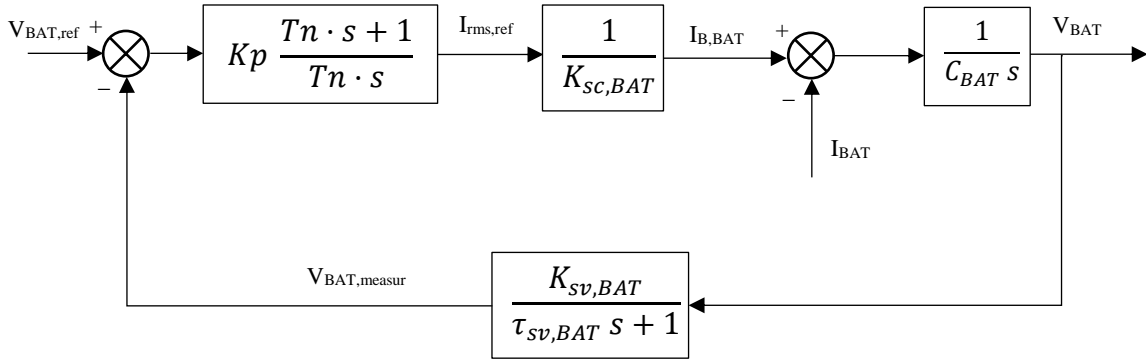
$$V_{BAT}(s) = \frac{1}{C_{BAT} s} [I_{BAT}(s) - I_{B,BAT}(s)] \quad (44)$$

From equation (44) it is obtained the block diagram of the inverter, as it is shown in **Figure 53**.



**Figure 53: Block diagram of the Battery Boost Converter (voltage)**

Once the plant of the system has been obtained, it is necessary to design the blocks related to the sensor and controller. The design diagram is performed in the same manner as done in the previous converter, so the block diagram for the inner current loop for the battery is shown in **Figure 54**.



**Figure 54: Complete system of voltage loop**

From **Figure 54**, it is possible to obtain the transfer function open loop (45). Equation (45) is going to be used for calculate the parameters of the PI controller.

$$TF_v(s) = Kp \frac{Tn \cdot s + 1}{Tn \cdot s} \cdot \frac{1}{K_{sc,BAT}} \cdot \frac{1}{C_{BAT} s} \cdot \frac{K_{sv,BAT}}{\tau_{sv,BAT} s + 1} \quad (45)$$

The establishment of specifications and controller design on the overall system are related to cut-off frequency ( $\omega_{cv}$ ) and Phase Margin (PM) follow the same guidelines use in the design of the voltage loop of the solar panel.

Once the values of the cut-off frequency and phase margin have been elected, the constants of the PI controller can be calculated.  $Tn$  is obtained from the  $TF_v(s)$  phase to the cut-off frequency and  $Kp$  gain is calculated from the condition of unity gain  $TF_v(s)$  to the cut-off frequency.

$$\varphi[TF_v(j\omega_{cv})] = -180 + PM \rightarrow PM = \arctg(Tn \cdot \omega_{cv}) - \arctg(\tau_{sv,BAT} \cdot \omega_{cv})$$

$$Tn = \frac{tg(PM + \arctg(\tau_{sv,BAT} \cdot \omega_{cv}))}{\omega_{cv}} \quad (46)$$

$$|TF_v(j\omega_{cv})| = 1 \rightarrow \frac{Kp K_{sv,BAT}}{Tn K_{sc,BAT} C_{BAT} \omega_{cv}^2} \sqrt{\frac{Tn^2 \omega_{cv}^2 + 1}{\tau_{sv,BAT}^2 \omega_{cv}^2 + 1}} = 1$$

$$Kp = \frac{Tn K_{sc,BAT} C_{BAT} \omega_{cv}^2}{K_{sv,BAT}} \sqrt{\frac{\tau_{sv,BAT}^2 \omega_{cv}^2 + 1}{Tn^2 \omega_{cv}^2 + 1}} \quad (47)$$

This design is a good compromise between speed and stability.

## 3.2 Calculating the parameters of the controllers

Once every equation has been obtained for determine the parameters of the PI controllers of each system, it is time to calculate the value of them for later use in the Simulink's simulation.

### 3.2.1 Controllers of the AC/DC converter

The control of the inverter is done by two controllers, one of them is used in the inner current loop and the other one in the voltage loop. Using the equations obtained in section 3.1.1; the parameters of the PI controller can be calculated.

#### 3.2.1.1 Controller in the inner current loop

First of all, it is important to decide the values of the constants that appear in the equations (10) and (11), where it is estimated  $Tn$  and  $Kp$  respectively. But also it is necessary to calculate the value of the inductance that is part of the inverter.

The value of the constants are:

- Switching frequency,  $f_s = 20$  kHz
- Loop cut-off frequency,  $f_{cc} = 2000$  Hz
- Loop phase margin,  $PM = 50^\circ$
- Gain current sensor,  $K_{sc} = 1$
- Frequency current filtering,  $f_{sc} = 5000$  Hz
- Peak voltage of the triangular,  $V_{PT} = 1$  V
- Bus voltage,  $V_{DC} = 400$  V
- Current ripple,  $I_{L,rip} = 2.5$ A
- $L_{inv}$  (it is necessary to calculate with equation (48))

Once the value of the inductance is obtained, it is possible to calculate the controller's parameters.

$$L_{inv} = \frac{V_{DC}}{4 \cdot f_s \cdot I_{L,rip}} = 2mH \quad (48)$$

PI controller of the inverter's inner current loop			
fs = 20k Hz	f <sub>cc</sub> = 2000 Hz	PM = 50°	V <sub>pt</sub> = 1 V
K <sub>sc</sub> = 1	f <sub>sc</sub> = 5000 Hz	V <sub>dc</sub> = 400 V	L <sub>inv</sub> = 0.002 H
T <sub>n</sub> value		T <sub>n</sub> = 0.00024	
K <sub>p</sub> value		K <sub>p</sub> = 25.7148	

**Table 3: PI controller of the inverter's inner current loop**

### 3.2.1.2 Controller in the voltage loop

First of all, it is important to decide the values of the constants that appear in the equations (18) and (19), where it is estimated  $T_n$  and  $K_p$  respectively. But also it is necessary to calculate the value of the capacitor that is located in the DC bus and which voltage is controlled by the inverter.

The value of the constants are:

- Switching frequency,  $f_s = 20 \text{ kHz}$
- Loop cut-off frequency,  $f_{cv} = 5 \text{ Hz}$
- Loop phase margin,  $PM = 45^\circ$
- Gain voltage sensor,  $K_{sv} = 1$
- Frequency current filtering,  $f_{sv} = 10 \text{ Hz}$
- Peak voltage of the triangular,  $V_{PT} = 1 \text{ V}$
- Bus voltage,  $V_{DC} = 400 \text{ V}$
- Voltage ripple,  $V_{C,rip} = 5\text{V}$
- $C_{DC}$  (it is necessary to calculate with equation (49))

Once the value of the capacitor is obtained, it is possible to calculate the controller's parameters.

$$C_{DC} = \frac{I_{grid} \cdot V_{grid}}{2\pi f_{grid} \cdot V_{C,rip} \cdot V_{DC}} = 7.32mF \quad (49)$$

PI controller of the inverter's voltage loop			
fs = 20k Hz	f <sub>cv</sub> = 5 Hz	PM = 45°	V <sub>pt</sub> = 1 V
K <sub>sc</sub> = 1	f <sub>sv</sub> = 10 Hz	V <sub>dc</sub> = 400 V	C <sub>DC</sub> = 0.00732 F
T <sub>n</sub> value		T <sub>n</sub> = 0.09549	
K <sub>p</sub> value		K <sub>p</sub> = 0.09996	

**Table 4: PI controller of the inverter's voltage loop**

### 3.2.2 Controllers of the DC/DC Boost converter for PV solar System

The control of the boost converter is done by two controllers, one of them is used in the inner current loop and the other one in the voltage loop. Using the equations obtained in section 3.1.2; the parameters of the PI controller can be calculated.

#### 3.2.2.1 Controller in the inner current loop

First of all, it is important to decide the values of the constants that appear in the equations (26) and (27), where it is estimated  $T_n$  and  $K_p$  respectively. But also it is necessary to calculate the value of the inductance that is part of the converter.

The value of the constants are:

- Switching frequency,  $f_s = 20 \text{ kHz}$
- Loop cut-off frequency,  $f_{cc} = 2000 \text{ Hz}$
- Loop phase margin,  $PM = 50^\circ$
- Gain current sensor,  $K_{SC} = 1$
- Frequency current filtering,  $f_{sc} = 5000 \text{ Hz}$
- Peak voltage of the triangular,  $V_{PT} = 1 \text{ V}$
- Output PV voltage,  $V_{PV} = 145 \text{ V}$
- Current ripple,  $I_{L,rip} = 2.5\text{A}$
- $L_{boost,PV}$  (it is necessary to calculate with equation (50))

Once the value of the inductance is obtained, it is possible to calculate the controller's parameters.

$$L_{boost,PV} = \frac{V_{PV}}{4 \cdot f_s \cdot I_{L,rip}} = 0.7mH \tag{50}$$

PI controller of the PV boost converter's inner current loop			
$f_s = 20k \text{ Hz}$	$f_{cc} = 2000 \text{ Hz}$	$PM = 50^\circ$	$V_{pt} = 1 \text{ V}$
$K_{sc} = 1$	$f_{sc} = 5000 \text{ Hz}$	$V_{PV} = 145 \text{ V}$	$L_{boost,PV} = 0.002 \text{ H}$
Tn value		Tn= 0.00024	
Kp value		Kp= 32.1435	

**Table 5: PI controller of the PV boost converter's inner current loop**

#### 3.2.2.2 Controller in the voltage loop

First of all, it is important to decide the values of the constants that appear in the equations (33) and (34), where it is estimated  $T_n$  and  $K_p$  respectively. But also it is necessary to calculate the value of the capacitor that is located in parallel with the output of the PV Solar Panel and which voltage is controlled by the boost converter.

The value of the constants are:

- Switching frequency,  $f_s = 20 \text{ kHz}$
- Loop cut-off frequency,  $f_{cv} = 5 \text{ Hz}$
- Loop phase margin,  $PM = 45^\circ$
- Gain voltage sensor,  $K_{sv} = 1$
- Frequency current filtering,  $f_{sv} = 10 \text{ Hz}$
- Peak voltage of the triangular,  $V_{PT} = 1 \text{ V}$
- $C_{boost,PV}$  (it is necessary to calculate with equation (51))

Once the value of the capacitor is obtained, it is possible to calculate the controller's parameters.

$$C_{boost,PV} = \frac{1}{(0.01 \cdot f_s \cdot 2 \cdot \pi)^2 \cdot L_{boost,PV}} = 0.873 \text{ mF} \quad (51)$$

PI controller of the PV boost converter's voltage loop			
$f_s = 20 \text{ kHz}$	$f_{cv} = 5 \text{ Hz}$	$PM = 45^\circ$	$V_{pt} = 1 \text{ V}$
$K_{sc} = 1$	$f_{sv} = 10 \text{ Hz}$		$C_{boost,PV} = 0.000873 \text{ F}$
Tn value		$T_n = 0.09549$	
Kp value		$K_p = -0.53314$	

**Table 6: PI controller of the PV boost converter's voltage loop**

### 3.2.3 Controllers of the DC/DC Boost converter for Battery

The control of the boost converter is done by two controllers, one of them is used in the inner current loop and the other one in the voltage loop. Using the equations obtained in section 3.1.3; the parameters of the PI controller can be calculated.

#### 3.2.3.1 Controller in the inner current loop

First of all, it is important to decide the values of the constants that appear in the equations (40) and (41), where it is estimated  $T_n$  and  $K_p$  respectively. But also it is necessary to calculate the value of the inductance that is part of the converter.

The value of the constants are the same values that have been chosen in section 3.2.2.1; therefore, the controller's parameters are going to be the same.

PI controller of the battery boost converter's inner current loop			
$f_s = 20 \text{ kHz}$	$f_{cc} = 2000 \text{ Hz}$	$PM = 50^\circ$	$V_{pt} = 1 \text{ V}$
$K_{sc} = 1$	$f_{sc} = 5000 \text{ Hz}$	$V_{PV} = 145 \text{ V}$	$L_{boost,PV} = 0.002 \text{ H}$
Tn value		$T_n = 0.00024$	
Kp value		$K_p = 32.1435$	

**Table 7: PI controller of the battery boost converter's inner current loop**



### 3.2.3.2 Controller in the voltage loop

First of all, it is important to decide the values of the constants that appear in the equations (46) and (47), where it is estimated  $T_n$  and  $K_p$  respectively. But also it is necessary to calculate the value of the capacitor that is located in parallel with the output of the PV Solar Panel and which voltage is controlled by the boost converter.

The value of the constants are the same values that have been chosen in section 3.2.2.2; therefore, the controller's parameters are going to be the same.

PI controller of the battery boost converter's voltage loop			
$f_s = 20\text{k Hz}$	$f_{cv} = 5\text{ Hz}$	$PM = 45^\circ$	$V_{pt} = 1\text{ V}$
$K_{sc} = 1$	$f_{sv} = 10\text{ Hz}$		$C_{\text{boost,PV}} = 0.000873\text{ F}$
Tn value		Tn= 0.09549	
Kp value		Kp= -0.53314	

**Table 8: PI controller of the battery boost converter's voltage loop**

## 3.3 Design and implementation of converters in MATLAB® & SIMULINK®

Every component that is necessary in the design and implementation of converters has been calculated, the values of inductances and capacitors are obtained, the parameters of the controllers too; in addition, it is known the structure of inverter and both boost converter. So, it is time to use SIMULINK® application to design and implement the converters and a MATLAB® Script to introduce there the values of the components.

First of all, each converter is going to be design separately. The inverter will be the first, then the boost converter of PV solar panel and finally the boost converter of the battery. Due to they are separated, a DC voltage source is used to generate the DC bus.

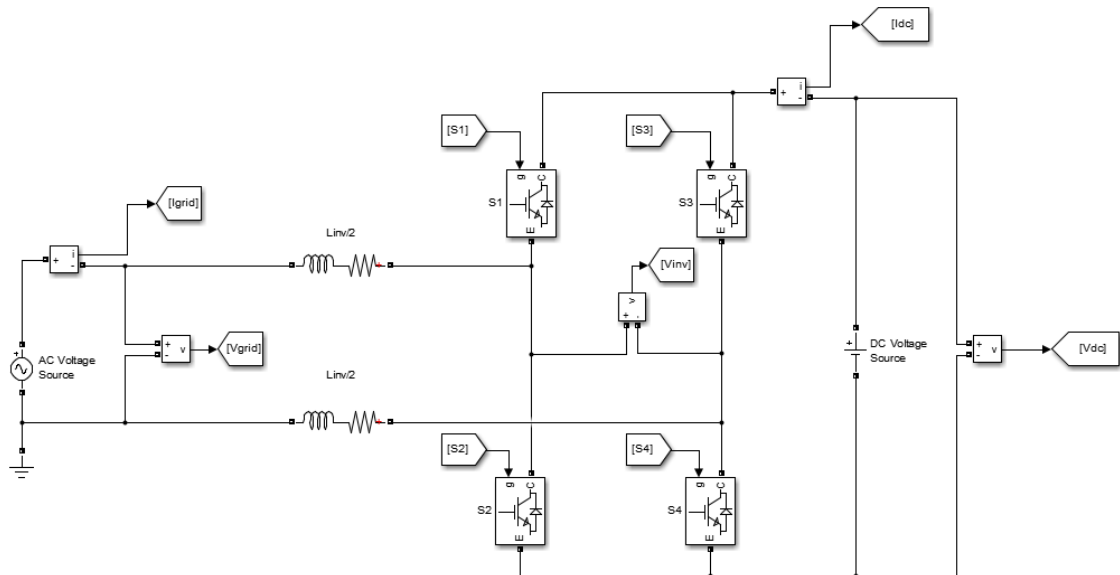
Related to the control of each converter, it has been explained in section 3.1. So, in SIMULINK® it is necessary to generate the blocks diagram described in that section to ensure proper operation of the simulation.

Once each system works correctly in a separate way, next step consists on connect the inverter system with the PV solar panel system. In this moment it is time to implement the inverter voltage loop to control the voltage in the DC bus.

When the join of both systems works properly, the battery system can be connected. The result of this design will be a sizing tool for distributed ESS.

### 3.3.1 Design of the inverter

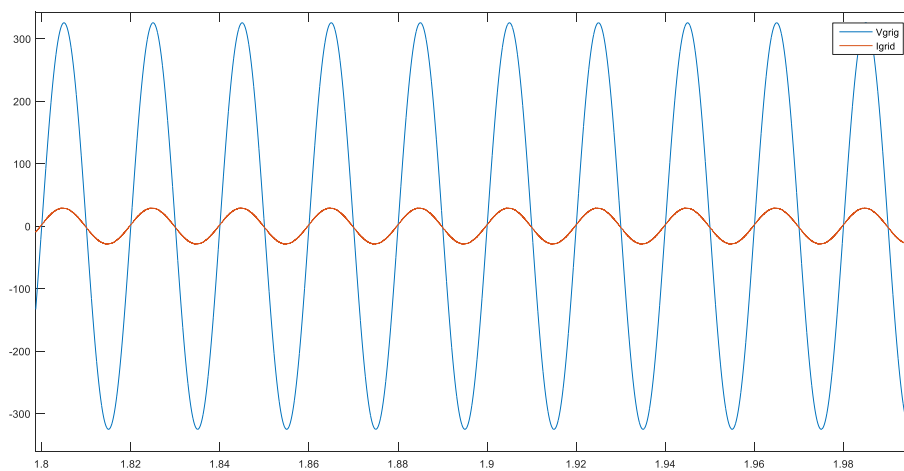
Following the structure that has an inverter as it is explained in section 3.1.1, it is possible to obtain in SIMULINK® the design shown in **Figure 55**.



**Figure 55: Design of the inverter in SIMULINK®**

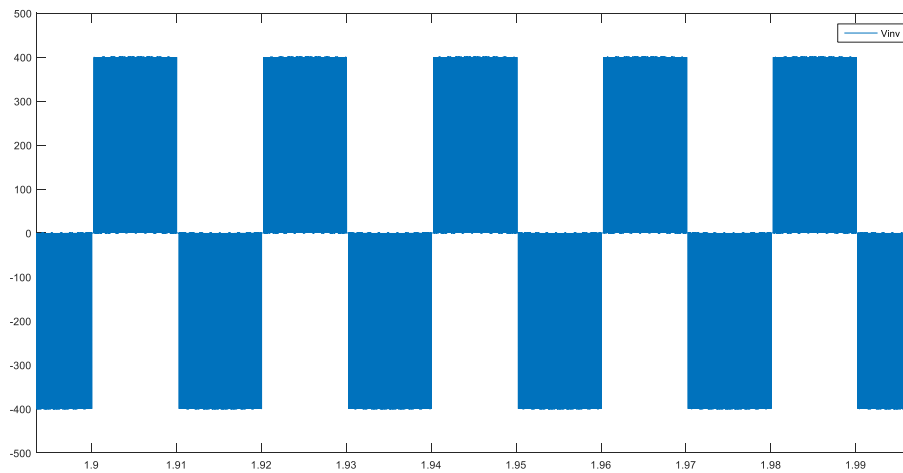
Once the inverter is designed and the block diagram implemented, it is time to show that the simulation works correctly. Then, it will be shown some graphs of voltage and current that will demonstrate that the design of the inverter and control works well.

The first graph is focused in the relation between the voltage and current of the grid. In **Figure 56**, it is shown that the current is on phase with the voltage and they have the same frequency. Therefore, there is no capacitive or inductive load that cause a phase shift.



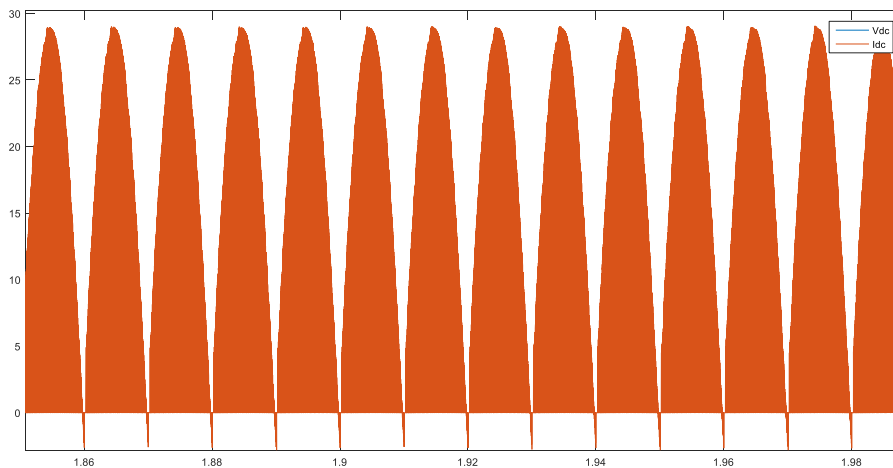
**Figure 56: Voltage and current of the grid**

Next graph is about the voltage that appear at the inverter output. Due to the unipolar modulation, there are three levels of modulation; as it is shown in **Figure 57**. And if the wave is filtered, it appears a wave similar to grid voltage.



**Figure 57: Voltage at the inverter output**

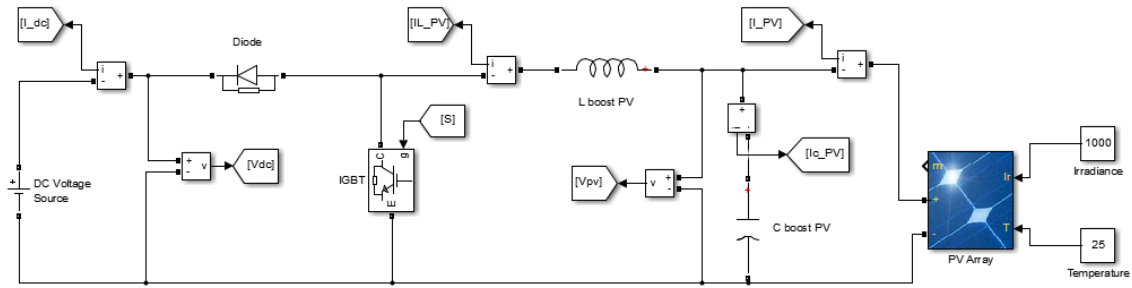
Finally, the last graph is about the voltage and current on DC bus. It is known that the voltage is imposed by the DC source, but the current also has to be in a continuous wave, so **Figure 58** shows what happens with the current.



**Figure 58: Current on DC bus**

### 3.3.2 Design of the boost converter used for the PV Solar Panel

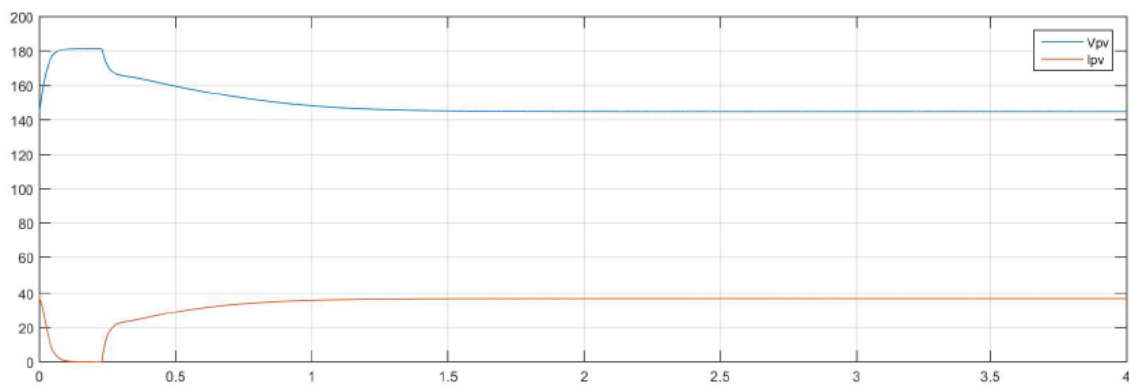
Following the structure that has a boost converter as it is explained in section 3.1.2, it is possible to obtain in SIMULINK® the design shown in **Figure 59**.



**Figure 59: Design of the boost converter for PV panel solar in SIMULINK®**

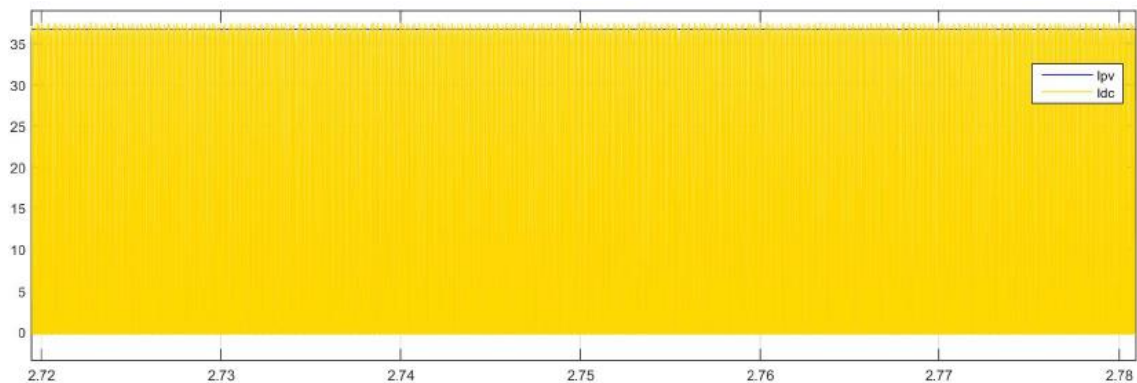
Once the boost converter is designed and the block diagram implemented, it is time to show that the simulation works correctly. Then, it will be shown some graphs of voltage and current that will demonstrate that the design of the inverter and control works well.

The first graph is focused on the relation between voltage and current that come from the PV solar panel. In **Figure 60**, it is shown that the current is growing at the same time that the voltage is decreasing till the moment that the system is stabilized and they generate a continuous wave.



**Figure 60: Voltage and current of the PV solar panel**

Next graph is about the comparison between the current that goes out from the PV panel and the current the flows on the DC bus. In **Figure 61**, it is shown that while the PV current is continuous with a constant value, the current from the DC bus has not a constant value due to it has an oscillation.



**Figure 61: Current from the PV solar panel and the DC bus**

Finally, the last graph is about the voltage on DC bus and the PV solar panel. It is known that the voltage is imposed by the DC source, but it is possible to see in **Figure**

**58** the increased voltage that makes the boost converter to reach the voltage required on the DC bus.

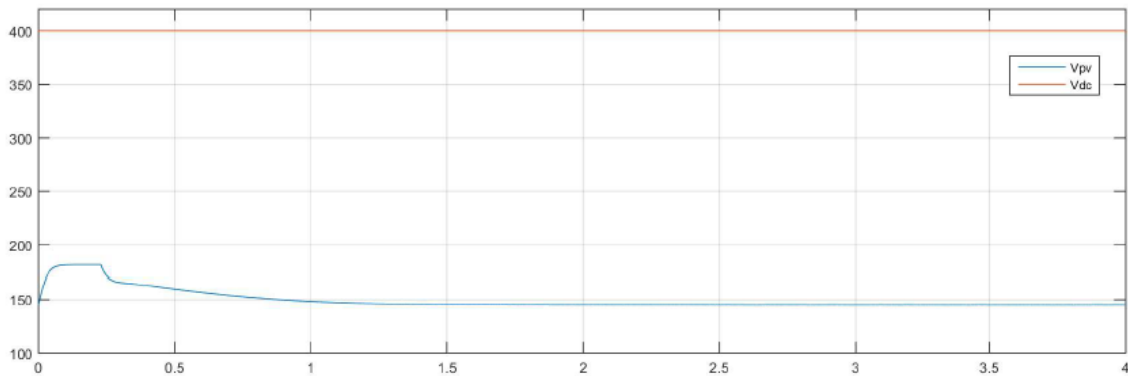


Figure 62: Voltage from the PV solar panel and the DC bus

### 3.3.3 Design of the boost converter used for the Battery

Following the structure that has a boost converter as it is explained in section 3.1.3, it is possible to obtain in SIMULINK® the design shown in **Figure 63**.

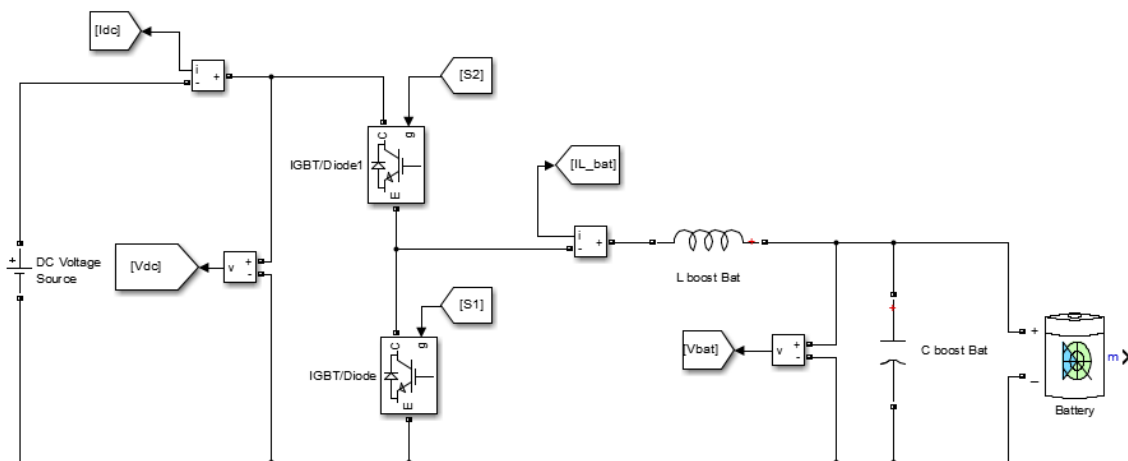
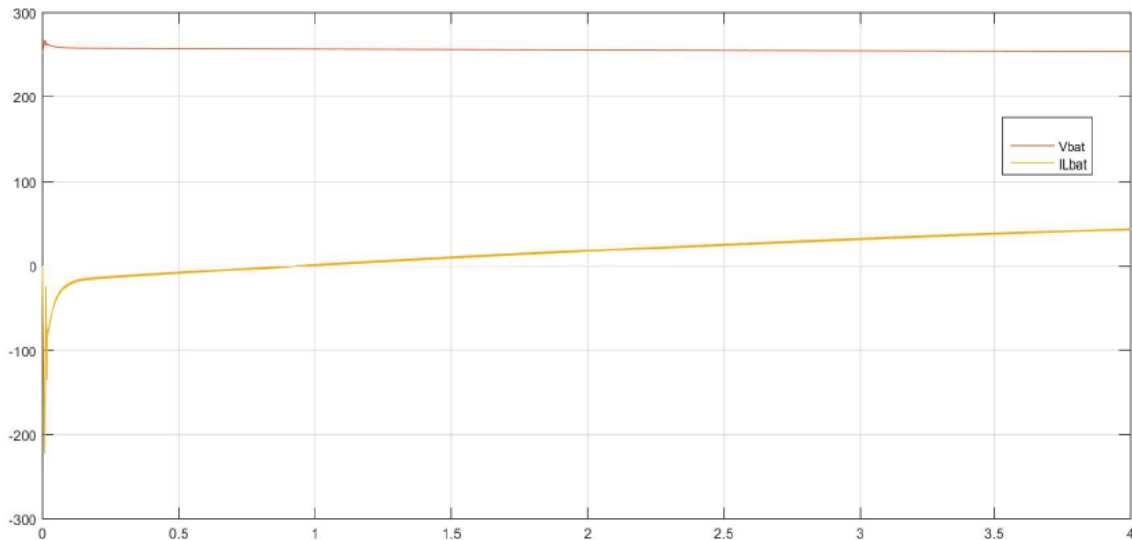


Figure 63: Design of the boost converter for battery in SIMULINK®

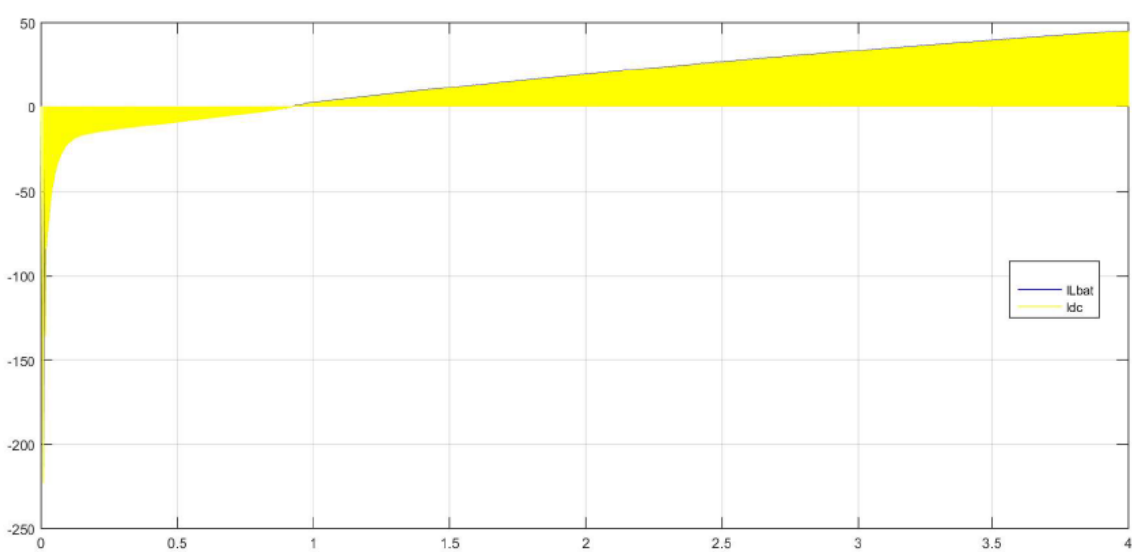
Once the boost converter is designed and the block diagram implemented, it is time to show that the simulation works correctly. Then, it will be shown some graphs of voltage and current that will demonstrate that the design of the inverter and control works well.

The first graph is focused on the relation between voltage and current that come from the battery. In **Figure 64**, it is shown at the beginning that the current is below zero, but after a while it is above zero; that occurs because when the simulation starts the battery is not full charged and has to reach the voltage required by the control, once it has that voltage, it starts the discharge due to the value of the current increase and the voltage decrease.



**Figure 65: Voltage and current of the battery**

Next graph is about the comparison between the current that goes out from the battery and the current the flows on the DC bus. In **Figure 65**, it is shown that while the battery current is continuous with a constant value, the current from the DC bus has not a constant value due to it has an oscillation.



**Figure 64: Current from the battery and the DC bus**

Finally, the last graph is about the voltage on DC bus and the battery. It is known that the voltage is imposed by the DC source, but it is possible to see in **Figure 66** the increased voltage that makes the boost converter to reach the voltage required on the DC bus.

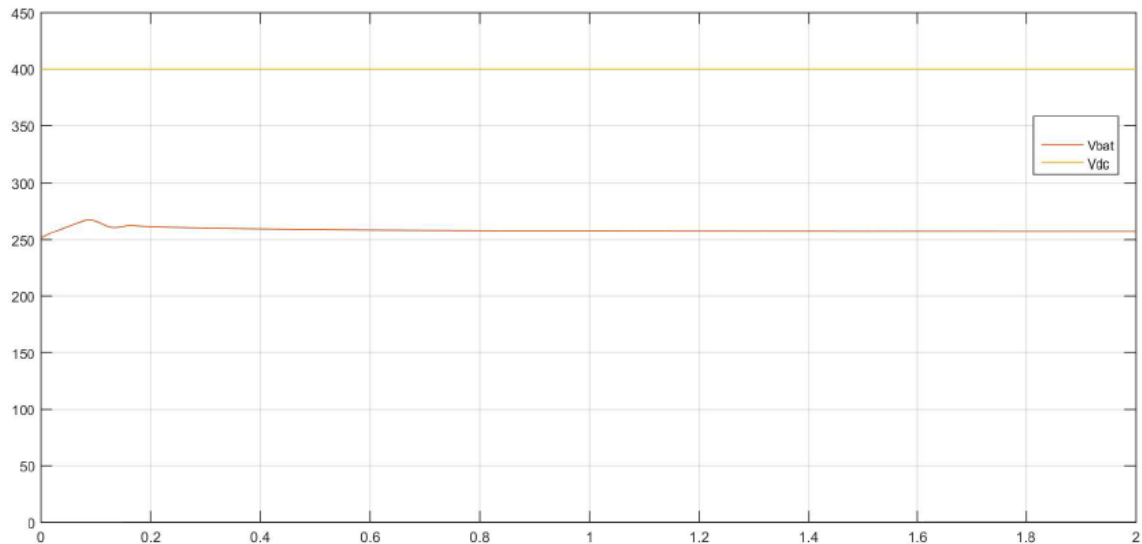


Figure 66: Voltage from the battery and the DC bus

### 3.3.4 System formed by the inverter and the PV solar panel

As it is said at the beginning of this section, once each converter has been designed and works correctly next step consists on connect the inverter with PV solar panel through the DC bus. In **Figure 67** is shown how the scheme in SIMULINK® is done, with all the parameters that are measure and plotted in the following graphic.

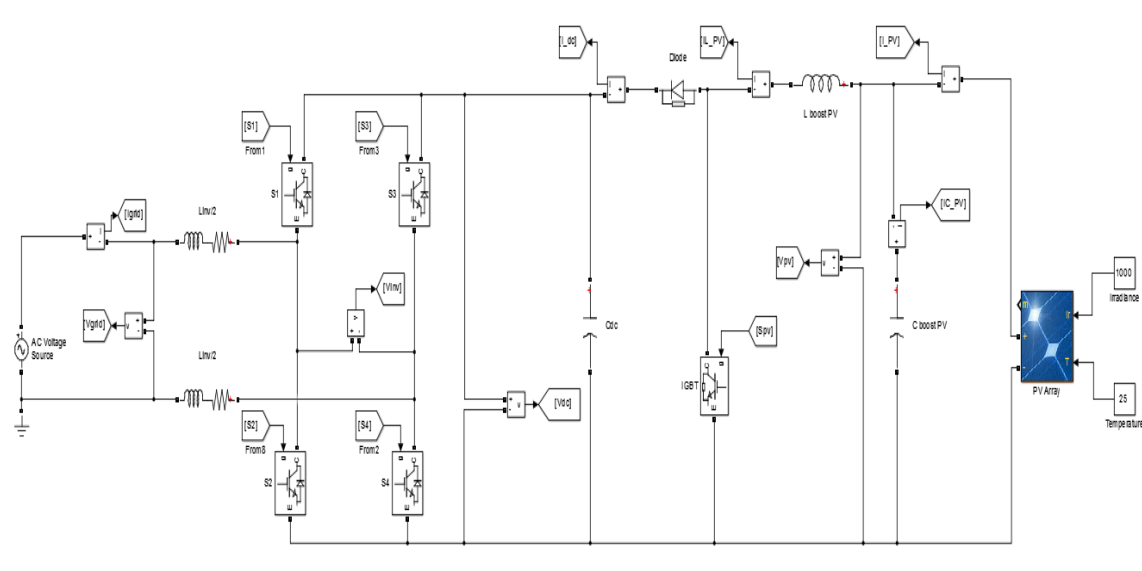
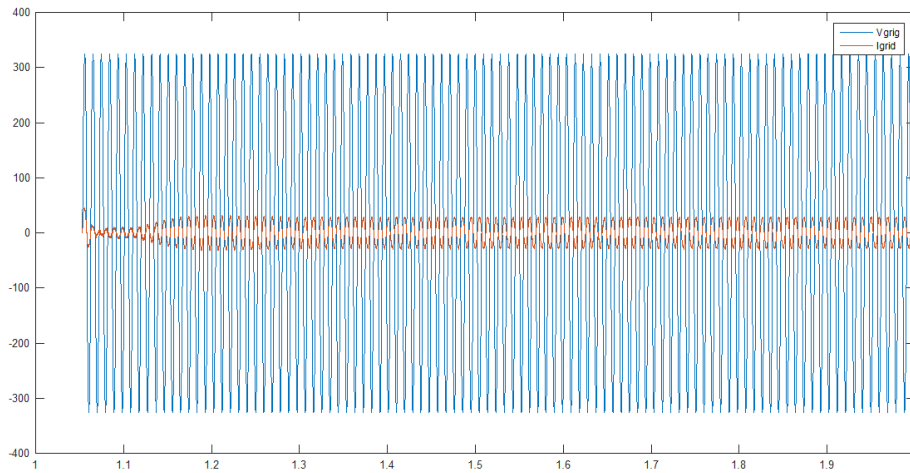


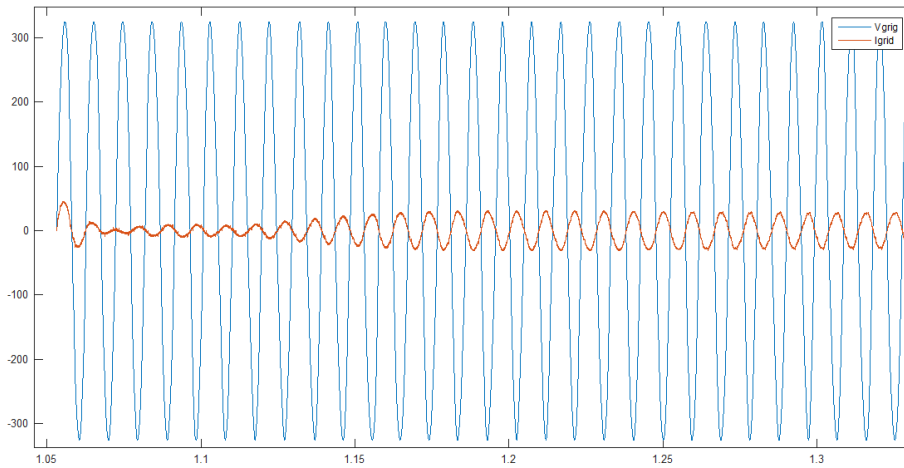
Figure 67: System formed by the inverter and the PV solar panel

Designed the system, it is time to make sure that it works correctly. The way, which check that everything is right, consists of plotting every parameter that give information of the system.

The first graph that is shown in **Figure 68** is the voltage and current of the grid. At the beginning both of them are in phase, but immediately the current change and it has a phase shift of  $180^\circ$ , as it is shown in **Figure 69**. This is because at the beginning, the grid current is going into the DC bus, but then it is going outside the bus.

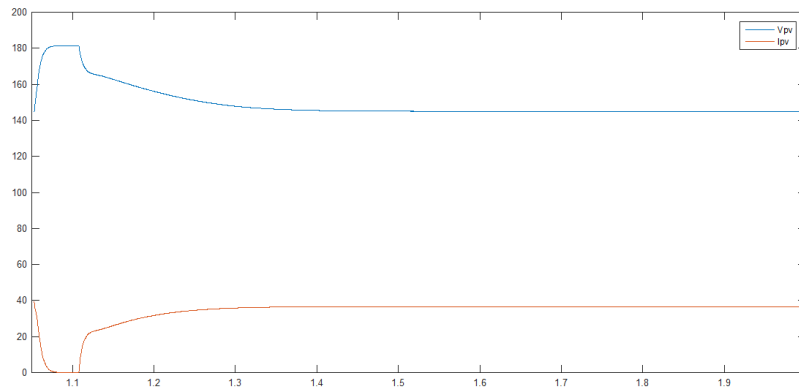


**Figure 68: Voltage and current of the grid**



**Figure 69: Voltage and current of the grid focused on the phase shift**

Next graph is focused on the relation between voltage and current that come from the PV solar panel. In **Figure 70**, it is shown that the current is growing at the same time that the voltage is decreasing till the moment that the system is stabilized and they generate a continuous wave.

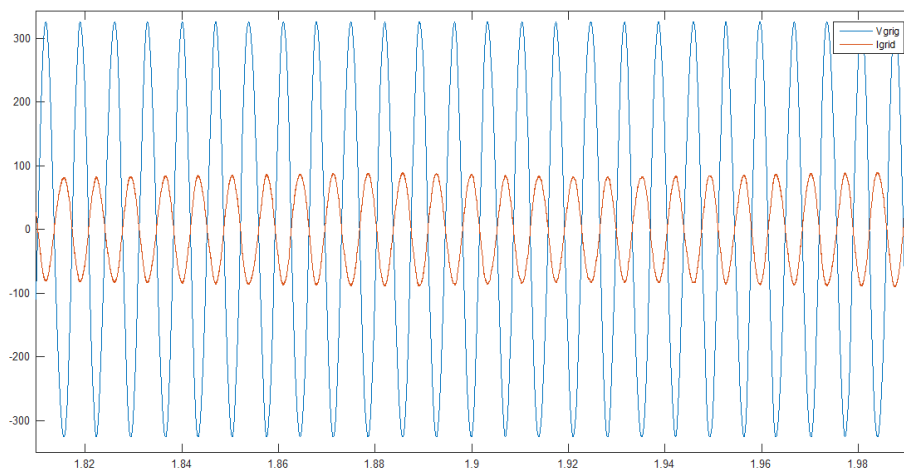


**Figure 70: Voltage and current from the PV solar panel**



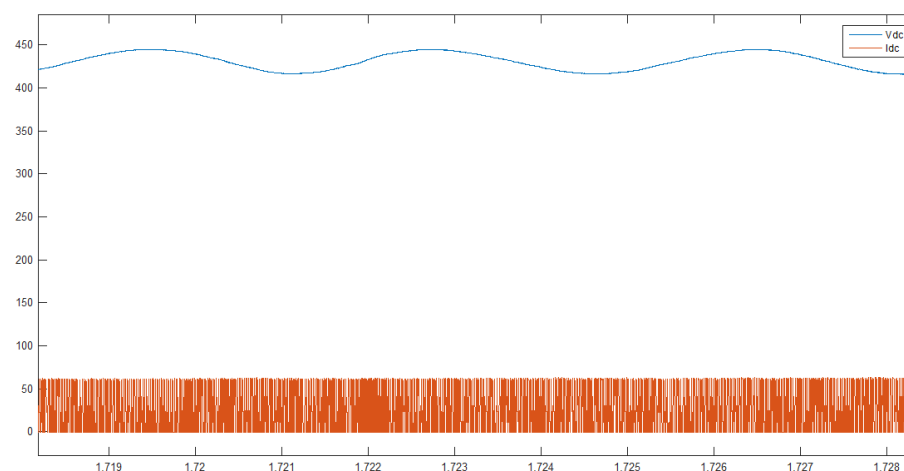


First graph that is shown in **Figure 73** is the voltage and current of the grid. It is possible to see that both waves do not have oscillations, but the current has a phase shift of  $180^\circ$  because it is going outside the DC bus.



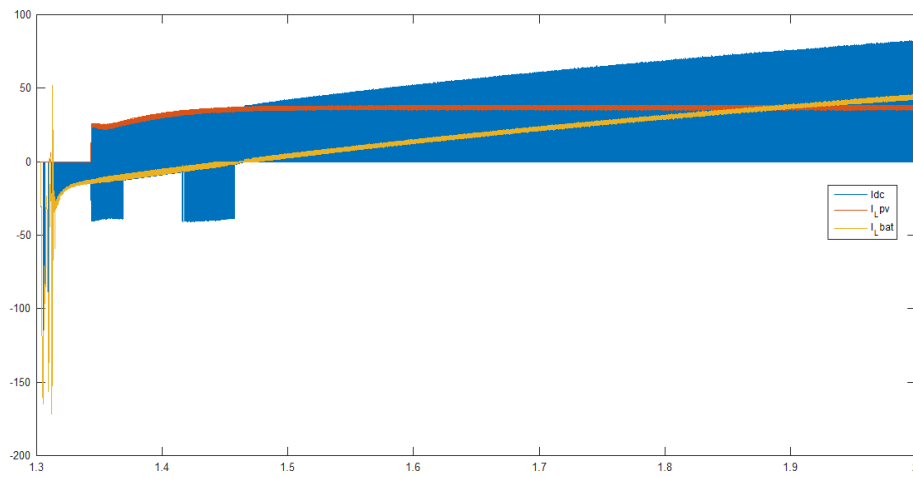
**Figure 73: Voltage and current of the grid with a phase shift**

Next graph is focused on the relation between voltage and current that are measured in DC bus. In **Figure 74**, it is shown that voltage has an oscillation due to charging and discharging the capacitor that is located on the DC bus and acts as a voltage source. However, the current has ups and downs very strong, which can generate a continuous wave.



**Figure 74: Relation between voltage and current of the DC bus**

Finally, the last graph is about the comparison between three currents, the currents that come from the converter of the PV solar panel and the converter of the battery, but also the current of the DC bus. The current from the PV solar panel gets a constant value once the voltage of the panel is constant too. The battery current, firstly is negative because the battery needs current to get charged, but after that the current is positive because the battery has started its discharge. The current of the DC bus is the sum of the two currents mentioned before, with increasing the value of the battery current, the value of DC bus current also increase. In **Figure 75** it is shown what has been explained.



**Figure 75: Relation between the currents of the DC bus, PV solar panel and battery**

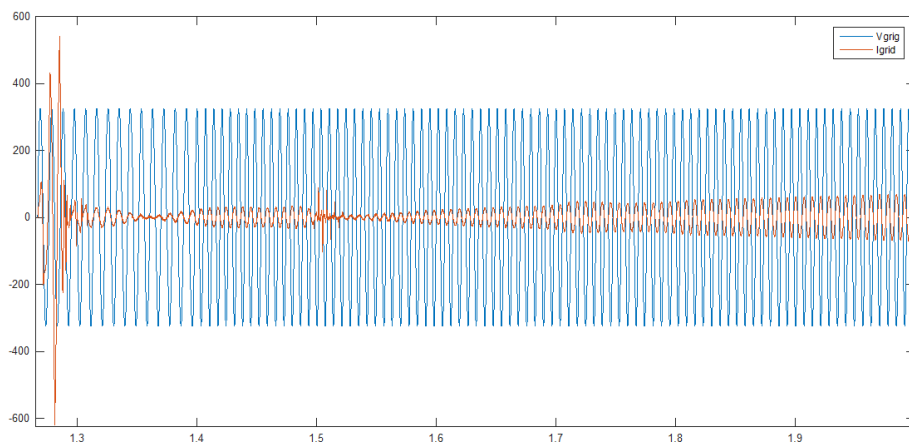
## CHAPTER 4: CONCLUSIONS

### 4.1 Results

To verify that the simulation works correctly with any changes in the system. A simulation is performed to see what happens when the irradiance has a steep descent and passes from a value of  $1000 \text{ W/m}^2$  to  $100 \text{ W/m}^2$ .

To validate the correct operation, some parameters of the system are going to be measured and graphed to show what happens inside the system and watch if it is correct.

First graph that is shown in **Figure 76** is the voltage and current of the grid. It is possible to see at the end of the graph that both waves do not have oscillations, but the current has a phase shift of  $180^\circ$  because it is going outside the DC bus. But at the beginning the current wave has two big oscillations. The first corresponds with change direction of current, that it means, the grid current is going into the DC bus, but then it is going outside the bus. The second oscillation corresponds with the decline of the irradiance, and the control corrects it in less than half a tenth of a second.



**Figure 76: Voltage and current of the grid with a phase shift**

Next graph that is analysed is the one related to the voltage and current of the DC bus, which is shown in **Figure 77**. In this graph it is possible to watch the variations that has the voltage and current due to the decreasing irradiance, but finally the control can stabilize the value of the DC bus voltage.

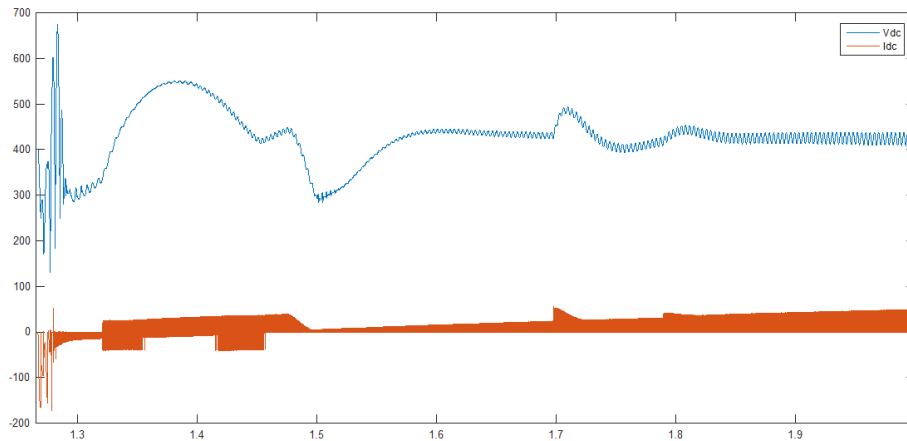


Figure 77: Voltage and current from the DC bus

Another graph that is interesting to remark is about the comparison between three currents, the currents that come from the converter of the PV solar panel and the converter of the battery, but also the current of the DC bus. The current from the PV solar panel suffers a variation once the value of the irradiance is decreased, but once it is stabilized the current begins to grow again. The battery current, firstly is negative because the battery needs current to get charged, but after that the current is positive because the battery has started its discharge. The current of the DC bus is the sum of the two currents mentioned before, with increasing the value of the battery current, the value of DC bus current also increase. In **Figure 78** it is shown what has been explained.

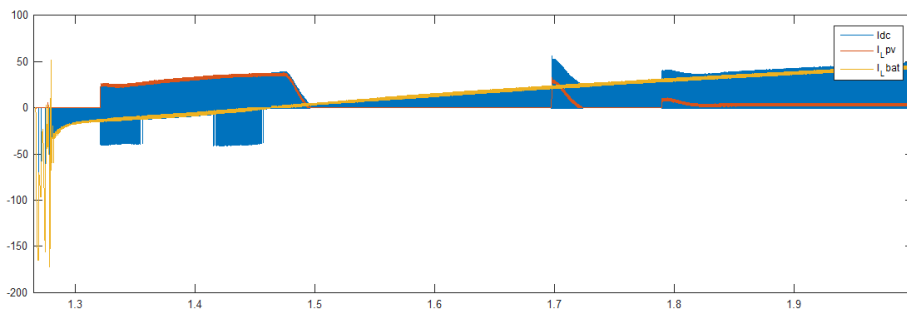
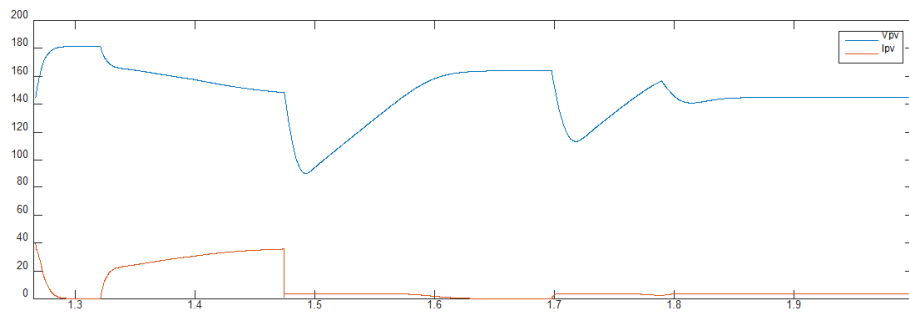


Figure 78: Relation between the currents of the DC bus, PV solar panel and battery

Finally, the last graph is focused on the relation between voltage and current that come from the PV solar panel. It is known that the power that can be given by PV solar panel is always the same, reducing or increasing values of voltage and current. The controller that rules the converter has a reference voltage that has to follow, for this reason, when the irradiance decreases the maximum power decreases too, but not the reference voltage forcing the value of the current is so small. In **Figure 79**, it is shown how it occurs. Finally, the system is stabilized and reaches the reference voltage at the expense of reducing the current.



**Figure 79: Voltage and current from the PV solar panel**

## 4.2 Summary

Once it is shown that the simulation works well, that is to say, controllers are able to control the switches to keep close to the imposed reference values; it is possible to say that it has been designed a sizing tool for distributed ESS.

After the study of different types of renewable energy, the analysis of the technologies that are used nowadays to design ESS and market research focused on companies that dominate the energy market, it concludes that this is a very broad world in which there are still many things to discover and investigate. The results are not obtained from one day to another.

Designing a MATLAB® & SIMULINK® simulation, it has achieved a very simplified approach model of what could happen in reality, but not wrong. A situation that every day is more typical in family homes, and which tends more every day.

In future lines of this thesis, Defining the optimum energy storage system topology and size, based on modular energy storage elements and based on different load profiles and scenarios, would be a good situation to continue with the improvement of the sizing tool designed in MATLAB® & SIMULINK®.

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