Analysis, Design and Implementation of Grid Connected PV Inverter System

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Abstract

Solar power holds great potential for the future in the realm of renewable energy. The solar energy has room for improvement, due to the low efficiency of the solar panels. It can be implemented everywhere from calculators, buildings, cars, etc. Solar energy is a field that has to be studied and continually researched until the maximum efficiency is reached.

This project can help for further developments in photovoltaic system components. This thesis focused on the implementation and design of the components of a photovoltaic system. These components are the MPP tracker, different topologies of DC-DC converters and inverters connected to the grid.

More specifically, the implementation of an MPP tracker algorithm, and boost converter was carried out at the end of this thesis.

For the algorithm of the maximum power point tracker, the Perturb and Observe algorithm has been used. It is one of the most used algorithms due to its simplicity of its implementation with analogue and digital circuits.

After the MPP tracker, the boost converter has been designed in relation to the objective of this project of feeding electricity to the grid. The boost converter will increase the voltage of the solar panel so then it can be transformed from DC to AC, and transformed with different controls synchronized to the grid.

Declaration

I certify that this thesis which I now submit for examination for the award of Bachelor of Sciences, is entirely my own work and has not been taken from the work of others save and to the extent that such work has been cited and acknowledged within the text of my work.

This thesis was prepared according to the regulations for Bachelor studies of the University of Applied Science Darmstadt and has not been submitted in whole or in part for an award in any other Institute or University.

The work reported on in this thesis conforms to the principles and requirements of the Institutes guidelines for ethics in research.

Darmstadt, August 2013

(David Curdi)

Candidate

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I want to sincerely thank all of the people who supported me throughout this bachelor thesis.

Especially I thank Dr. Juan Jose Marcuello for giving me the opportunity to come to Darmstadt to finish my studies. Also to Prof. Dr. Christian Jakob for his advice and recommendations on this thesis.

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To my family, that without them I couldn't be studying in Germany my last year of the career.

And finally to Maggie, for supporting me on the last days of this thesis.

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Introduction

In this chapter, the energy crisis, the photovoltaic energy and a little overview of the project will be described. The first point covers an overview of society and the repercussions of using non-renewable energies and the problems that result from them. The second part will be an explanation of the photovoltaic energy. This is important so people can understand a little more of this energy of the future. The last point is the overview of the thesis.

1.1 Energy Crisis

The development of society is related directly to the energy availability and consumption. This is the reason energy is an essential factor for the development and the growth of the economy. The appearance of an energy crisis leads to an economic crisis. That is why the effective use of energy is essential for sustainability [1].

Through history, every discovery and technological advancement has given us: in one hand, many devices to improve or maintain our comfort and reduce our efforts; and in the other hand, it has provided new sources of energy that have slowly replaced energy sources that could not keep up with the growth of consumption [1].

Today, world energy is primarily produced from non-renewable resources such as coal, crude oil and natural gas. Those energies provide more than 85% per cent of the world's primary energy demand [2]. Depending on non-renewable energies has several disadvantages. The distribution of resources is limited by their geographical location, which causes geopolitical conflicts. Moreover, the change to a new energy source involves more infrastructure changes.

Due to the population growth, there is more pollution created using non-renewables energies such as the use of petrol cars. Because of that, people start thinking about other sources that may help to reduce the pollution and there will also be a large problem of electricity shortage. These problems will persist because of the amount of people is bigger, so more electricity is needed.

People started thinking about solutions to have more electricity. The renewable energies were a really good option. The uses of water, wind and sun power as sources to generate electricity were solid options. The production of electricity from wind farms was growing fast. There were more and more improvements including different blade shapes, different orientations, more or less turbine blades… The good thing about the wind power is that this energy is very consistent every year. As an alternative to fossil fuels it is renewable, clean, has no greenhouse effect, and it can be offshore and inland.

Besides wind power, solar power is a really good energy that is improving its performance each year. Solar power also is a renewable energy, clean, etc. The problem is that in solar energy, there is not much performance so the energy of the sun is not well used. This is something that is trying to improve because if that is solved, solar energy will be the leader of energies. Solar panels can be installed everywhere, including buildings, cars, calculators, parking meters …

Nowadays, there are some people that own the petrol energies with a focus on getting richer. With the solar energy everyone could have their own energy at home. Solar energy is simple to install.

In conclusion, improving the renewable energies will lead to a peaceful place due to the non-renewable energies being limited. When they finish, a focus on cleaner energies will be needed. That can be through producing a lot of energy in the summer and storing that so in the winter it will be able to use.

That is why, for me it’s really important to study this energy of the future so I can help to improve the earth to be a better place. For that, the photovoltaic energy has to be studied to understand a little more of solar energy.

1.2 Photovoltaic Energy

The word "photovoltaic" is made of two words: "Photo", which in Greek means light and "Volta" which comes from Alessandro Giuseppe Antonio Anastasio Volta, the physicist that developed the battery. These two words together mean the direct conversion of sunlight to electricity [3].

The photovoltaic systems consist of mechanical, electrical and electronic devices whose principal function is to capture the solar energy and transform it into electrical energy. This system can be divided into two categories: grid connected systems and off grid systems. In this project it will be simulated with a grid connected system [5].

The photovoltaic energy is a clean renewable source of energy, with a long lifetime and a high reliability [5]. The photovoltaic energy is, after hydro and wind power, the third most important renewable energy source installed globally. The problem that this energy has is that it doesn't produce enough energy as other sources.

However, due to the technological progress and the environmental commitment of developed countries, the energy contribution of the solar energy is getting higher and faster thanks to research and development [1].

The solar energy is an interesting energy to study. It is an energy that is growing every day. The performance of it is not enough to depend only on the solar energy but it has the potential to it. If it will be possible to use the whole energy of the sun that will be solar power with an 85 % of performance, the solar energy could solve a lot of problems in the future. It is 85 % because the sun loses 15 % of its energy while entering to the earth.

The solar panel doesn't have good efficiency due to the different wavelengths of the light. The materials used on the solar cells do not transform all the wavelengths of the light but only a small part. That is something that is in study because when it is solved or the right material is found, there will be a big boom of solar energy.

1.3 Overview of the thesis

The goal of this project is to learn the characteristics and functions of control systems (MPP Trackers), converters and inverters through simulations designed with Matlab/Simulink.

Matlab/Simulink has been chosen for this project, because it's a powerful and flexible tool that offers the possibility to create similar models to the existing ones.

The structure of this thesis starts with the modeling of a solar cell. This solar cell has been designed so that it depends on the irradiance of the sun and temperature of the cell. In this part, it will be possible to see the different behaviors of the cell with diverse irradiances and temperatures in order to see how the voltage and current change.

The next part of the thesis is the MPP Tracker. Different algorithms will be explained such as perturb and observe, and incremental conductance. This has been designed with a subsystem of Matlab where it is possible to write a script.

The third point is the DC-DC converters. Three different converters will be explained: the boost converter, the buck converter and the buck-boost converter. The boost converter is the one used in this thesis and the buck converter as well as the buck-boost converter will be clarified in the theoretical part.

At the end of the thesis, a description and explanation of the entire photovoltaic system will be provided with mathematical processes and graphics.

Theoretical Part

In this chapter, the theory of several points of the project will be discussed. First, an overview of PV cells with different structures. Secondly, the different topologies of the MPP Tracker will be explained. After that, the structure of the Buck/Boost converters will be described. And at the end of this chapter the inverter system will be discussed.

2.1 PV Cells

2.1.1 Cell structure

A solar cell is a device capable of converting the light into electricity. The conversion is performed by the physical phenomenon known as the photovoltaic effect, which generates an electromotive force when the surface of the cell is exposed to solar irradiation. The voltage will be in between 0.3 V – 0.7 V depending on factors such as the illumination, the temperature and age of the cell [5].

A more specific explanation of how the electricity is made from the sunlight will be the photons from the sunlight reaching the solar cell. These ones are absorbed due to the semiconductor material of the solar cell as silicon (different crystalline structures), Cadmium Telluride and copper indium gallium selenide (alternative material for solar cell in thin-films). Then the photons extract electrons passing by a hole. Normally, the electron finds a hole to refill, but the principle of the photovoltaic cell is to force the electrons and the holes to move toward the opposite side of the material, not to just recombine. This will create an electrical potential difference. Current starts flowing and the electricity is cached. The structure of the cell allows the electrons to move only in one direction [6].

As shown in figure 1, the structure of the cell is normally formed by a P-N junction made of monocrystalline silicon or another semiconductor component. A photovoltaic cell is made of two layers of silicon, one with boron (P) and with phosphorus (N). The top layer is the phosphorus and this one is the negative layer. The lower layer is boron and it’s the positive layer [5].

In the next figure the movement of the electrons and holes can be seen that are moving in a single direction.

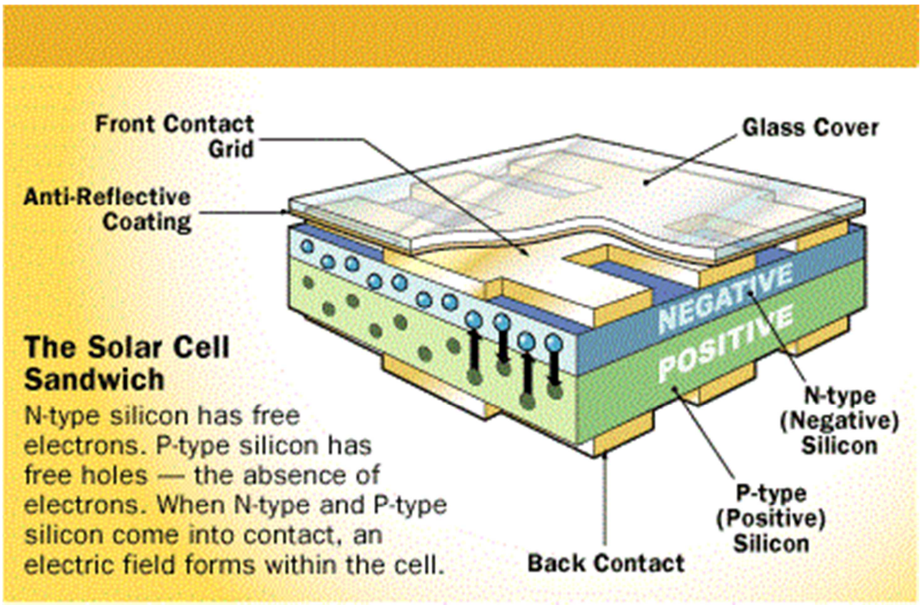


Figure 1. Cell structure [11]

A solar cell can also be made of Cadmium Telluride (CdTe) that is made up of thin cells. Enterprises are improving the efficiency of these thin panels as seen a couple months ago when an enterprise achieved 18.7% of efficiency [7]. The problems of this cell are the cadmium toxicity, lower efficiency (around 15% manufacturing), and the lack of abundance of tellurium on Earth (although the source may be found under the sea). Apart from these problems, the cells have a good advantage such as lower costs of manufacturing than silicon and good absorption of sunlight [3].

The Photovoltaic cells can be classified in 3 groups depending on the silicon:

- Monocrystalline silicon cell: their performance is 14% - 18%.
- Polycrystalline silicon cell: their performance is 12% - 14%.
- Amorphous silicon cell: their performance is 8% [6].

2.1.2 Solar cell modeling

2.1.2.1 Ideal Solar Cell

The structure of a solar cell is similar to the one of the diode. When the cell receives the irradiance of the sun, it acts like a current generator whose value increases depending on the quantity of light absorbed [6]. The ideal solar cell can be seen in figure 2.

The current of an ideal solar cell can be described with the following equation:

$$I = Il - Id \qquad (2.1)$$

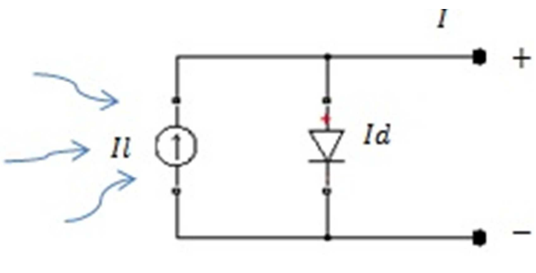


Figure 2. Ideal solar cell.

The equation that describes the I-V characteristics of most of the solar cells:

$$I = Il - Io\left(e^{\frac{qV}{mKT}} - 1\right) \qquad (2.2)$$

Where:

- Il: photogenerated current
- Io: reverse saturation current
- q: electron charge
- V: output voltage
- m: diode ideality factor
- k: Boltzmann’s constant
- T: Absolute temperature

The modeling of the solar panel in this project will be designed in Simulink using subsystems, so at the end of the design it will be possible to change the temperature of the cell and irradiance of the sun to see the I-V and P-V characteristics of the panel. This panel, not only can change the temperature and irradiance but also the number of cells that the panel has. This will be explained and described in Chapter 3.

2.1.2.2 Solar cell with series and parallel resistance

The equivalent circuit of a solar cell will be approximately the same circuit as the ideal cell but now counting the losses that are in the circuit as series resistance and parallel resistance.

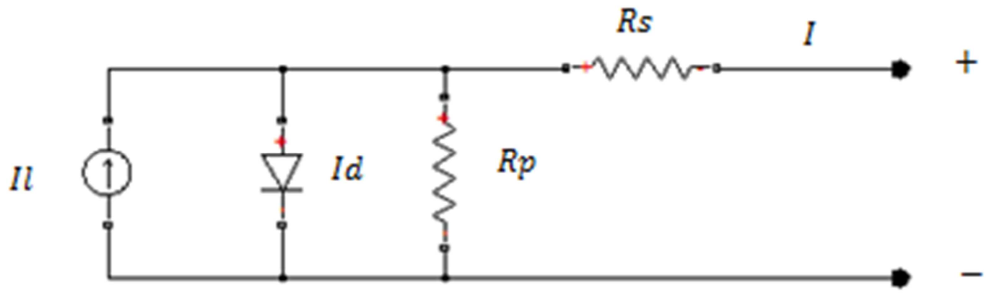


Figure 3. Equivalent solar cell circuit.

The mathematical model that described the behavior of one non ideal solar cell is given by the next expression:

$$I = Il - Id - I_{Rp} \qquad (2.3)$$

$$I = Il - Io\left(e^{\left(\frac{V+IRs}{Vt}\right)} - 1\right) - \frac{V+IRs}{Rp} \qquad (2.4)$$

Where:

- Il: photogenerated current
- Io: reverse saturation current
- V: output voltage
- I: output current

- Rs: series resistance. It is the sum of several components of the material themselves and the effects of design and internal manufacturing of the cell, semiconductor resistance and the resistance of the front metal grid [1].
- Vt: this is the thermal voltage. Vt is equal to k (Boltzmann constant; $k = 1.381x10^{-23}$ J/K) by the temperature of the cell in Kelvins divided by q (magnitude of the electrical charge of the electron; $q = 1.602x10^{-19}$ C). The thermal voltage at a temperature of 25ºC is Vt = 25.7 mV [1].
- Rp: parallel resistance. It is mainly due to leakage of current by the side surfaces. This could also be caused by metallic short circuits or diffusion peaks from dislocations or grain boundaries [1].

2.1.3 Solar cell characteristics

The characteristics of a solar cell can be seen in a nonlinear curve. The parameters that determine the performance of a solar cell are reflected in the I-V and P-V curves, where “Isc”, ”Voc”, “Im”, “Vm”, “Pm” and “MPP” can be detected. If the solar cell is acting in ideal conditions, that means the irradiance is the maximum (1000 W/m2), the cell temperature is the same as the ambient temperature (25 ºC), and the diode ideal factor is 1, the cell will start in Isc and finish in Voc. If that is not the case it will start lower than Isc and finish before Voc. The characteristics of a solar cell can be seen in the next figures.

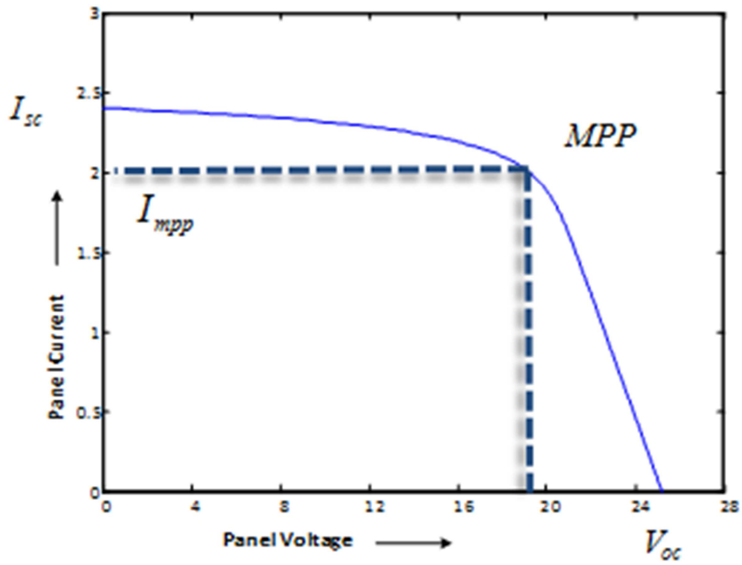


Figure 4. I-V cell characteristic [2].

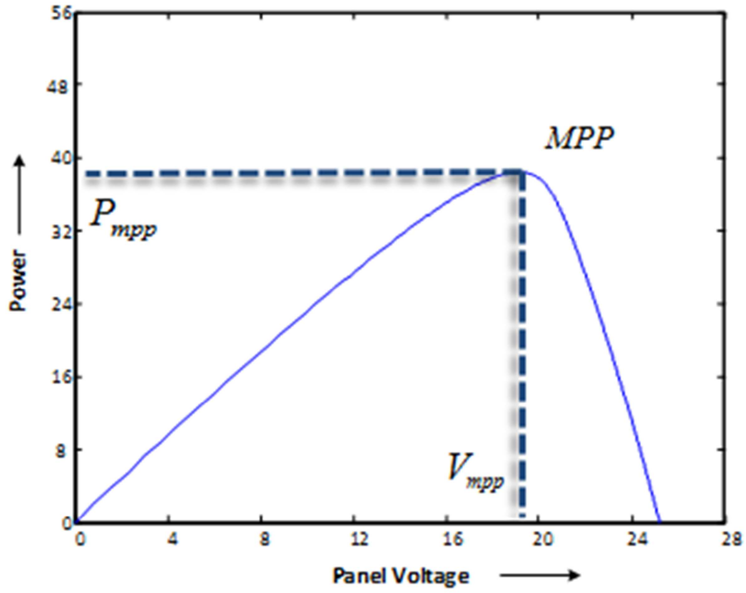


Figure 5. P-V cell characteristic [2].

The short circuit current “Isc” is the current that is obtained from the cell when the voltage at its terminals is 0V. This is the maximum current that can be obtained from this solar cell.

The open circuit voltage “Voc” is the voltage obtained when the cell current is 0A. This is the maximum voltage that can be extracted from this solar cell.

The maximum power point “MPP” is defined by the product of the maximum current “Im” and the maximum voltage “Vm” [2].

$$Pm = Im * Vm \tag{2.5}$$

The characteristics of the cell can be changed, depending on the irradiance, the temperature and age of the cell. Decreasing the irradiance decreases the current as shown in Figure 6, and increasing the temperature decreases the voltage also shown in Figure 7.

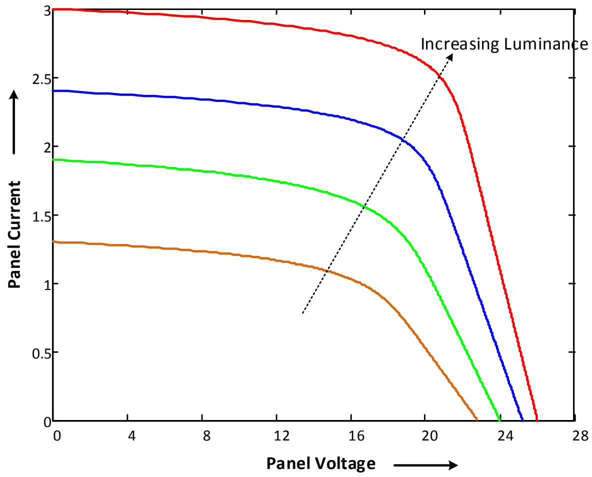


Figure 6. I-V characteristics increasing G [2]

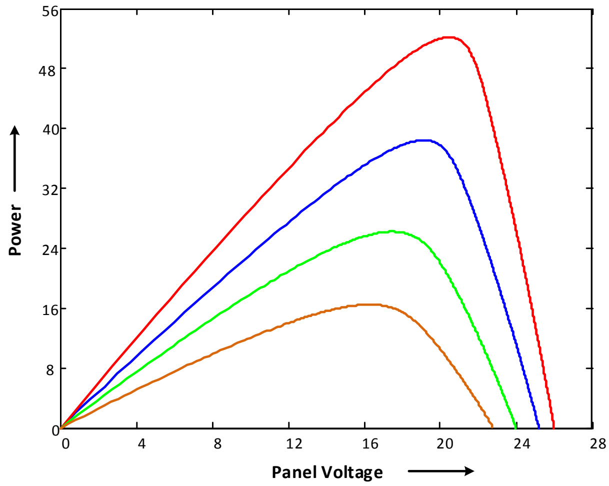


Figure 7. P-V characteristics increasing Tc [2]

To know where the MPP is on the cell, a load has to be applied on it. After some time, the right R may be found. When the straight line of the resistor crosses the MPP (where the knee of the curve is) that is called the "characteristic resistance of the cell".

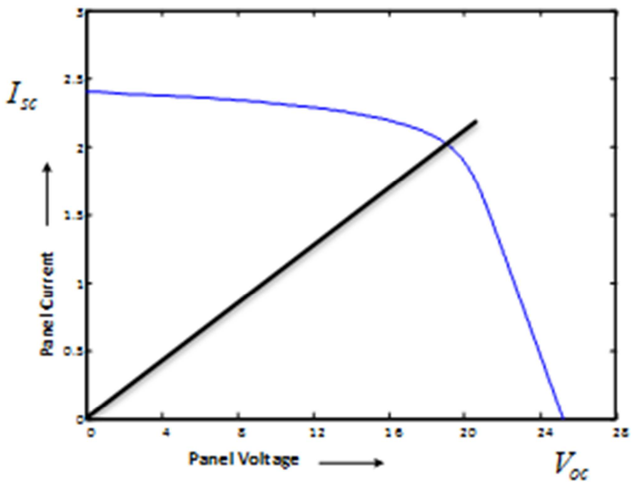


Figure 8. Characteristic resistance of a cell

2.2 MPP tracker

The main function of a MPP tracker is to adjust the output voltage of the solar panel so that it can extract the maximum power. The MPP tracker is designed to track the maximum power point from a solar panel which external conditions are unknown for the MPP [1].

The characteristics of the solar panel are changing every moment. Different irradiance and temperature will give a different MPP. So the MPPT will have to search where the solar panel is working and in which direction it has to move so it reaches the maximum power point. This will be done with an algorithm that will know which changes are necessaries [1].

A MPP tracker algorithm is a finite operation of steps that requires optimizing and controlling de maximum power point of the solar panel. A MPP tracker reads the input voltage and the input current. Additionally, within its internal circuit, there are some changes that modify the input impedance and that make a change in the voltage and current at the input of the MPP. Also a MPP tracker has to be careful with the speed adaptation due to the solar panel changing conditions [1].

There are many types of MPPT today, but the most used are Perturb and Observe, and Incremental Conductance.

In this project both of them will be explained and Perturb and Observe is the one used in this project because it is the most used in industry and easier to implement.

2.2.1 Perturb and Observe

The efficiency of a solar panel can be improved by using a hill-climbing MPP tracker such as Perturb and Observe. This is an algorithm that does not need to know the previous characteristics of the solar panel or the cell temperature and irradiance. It is an easy method to implement with analogue and digital circuits [2].

The algorithm perturbs the point where the solar panel is working by increasing or decreasing the duty cycle by a small amount and then measures the output of the solar panel before and after the perturbation. If the power increases, the algorithm perturbs in the same direction otherwise it will perturb in the opposite direction [3].

The Perturb and Observe algorithm will increase the output voltage if the difference between the input voltage and the output voltage is positive and the power difference is also positive, or if both voltage difference and power difference are negative. Otherwise it will reduce the voltage.

This can be seen in the following figure. In figure 9, the Perturb and observe algorithm is explained in a graphic way, so it is easier to understand and follow the path to know how to find the maximum power point.

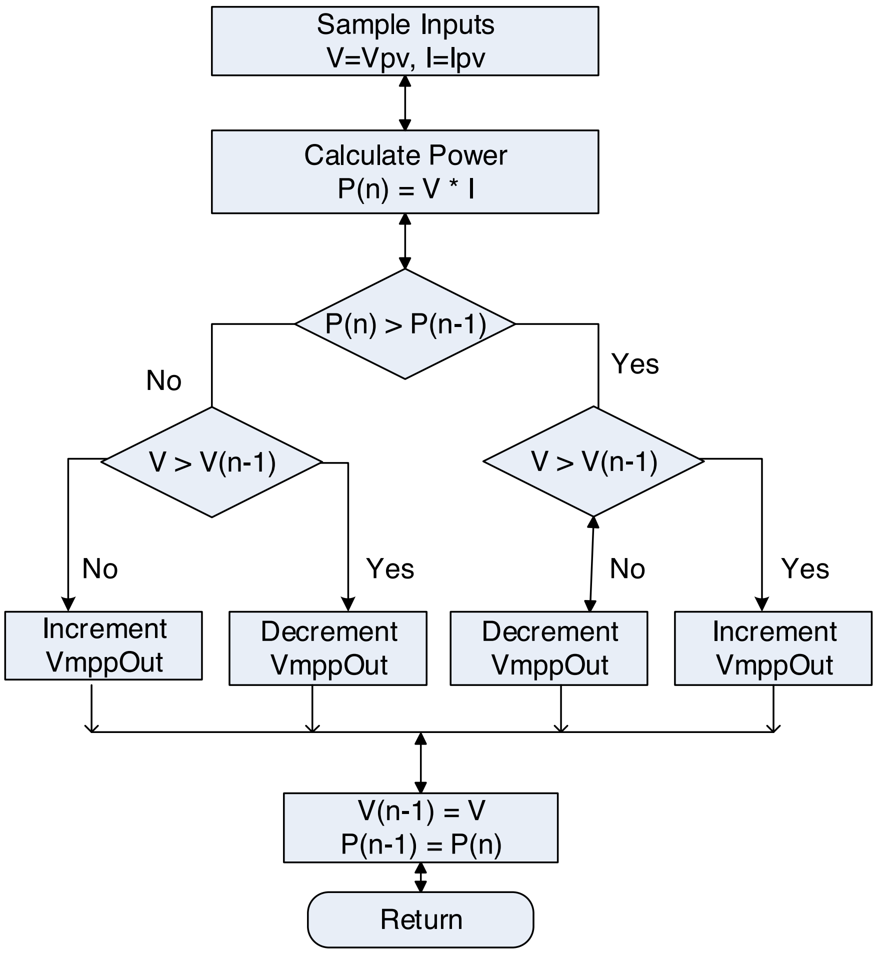


Figure 9. Perturb and Observe algorithm [2]

2.2.2 Incremental Conductance

The Incremental Conductance algorithm has a more complex method than the Perturb and Observe algorithm. This method measures incremental changes (dI/dV) to predict the result of voltage changes. This one more rapidly detects the change that the solar panel has, compared to the Perturb and Observe algorithm.

$$\frac{dP}{dV} = \frac{d(I*V)}{dV} = I + V\frac{dI}{dV} \cong I + V\frac{\Delta I}{\Delta V} \qquad (2.6)$$

In the incremental conductance method, the array terminal voltage is always adjusting according to the MPP voltage. It is based on the incremental and instantaneous conductance of the solar panel. When $\frac{dP}{dV}$ is equal to 0 then it's in the MPP. The MPP increases when it goes to the left and decreases to the right of the MPP. This can be seen in figure 10 [2].

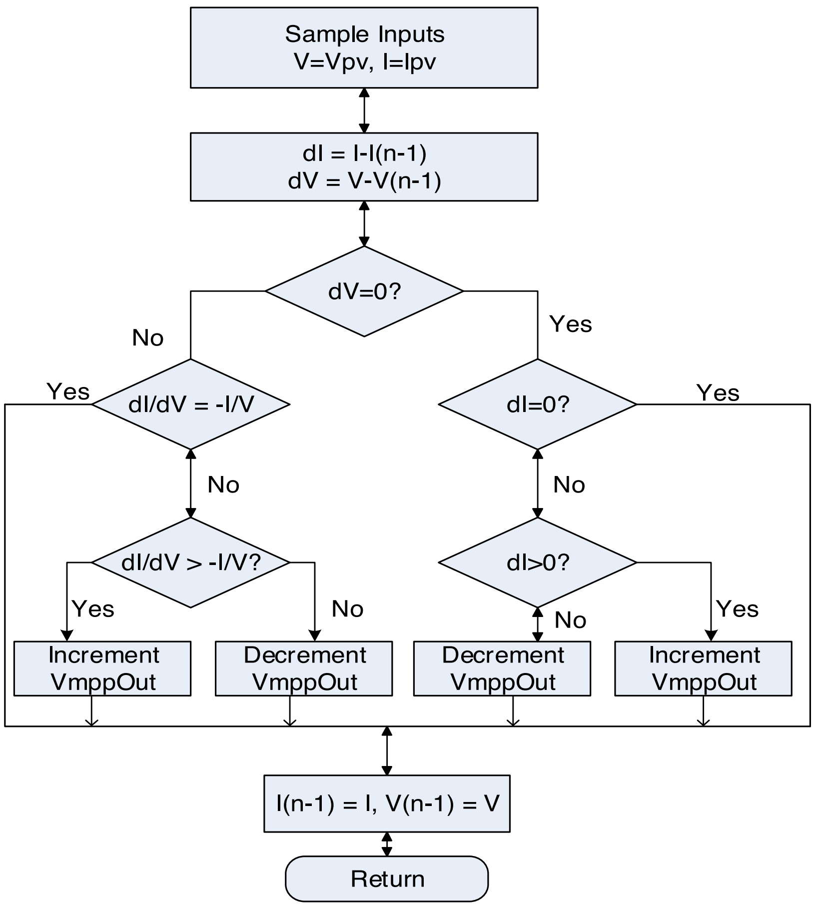


Figure 10. Incremental conductance algorithm [2]

2.2.3 Differences between P&O and Incremental conductance

For perturb and observe method: The voltage of reference is all the time perturbed, and changes the power that is observed. The perturbations will make this algorithm know which direction it has to go whether it increases or decreases. The voltage is oscillating near the maximum power point. This can be seen in figure 11[2].

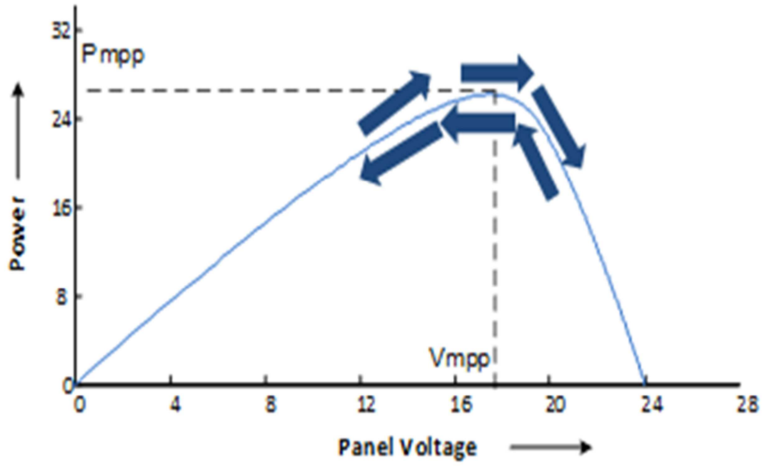


Figure 11. Perturb and Observe P-V graphic [2]

For incremental conductance: It is working with slopes. If the slope is zero then is at the MPP, positive will be at the left side of the MPP and negative to the right side. The incremental conductance method, once it reaches the MPP, it will maintain there until there is a change in AI. That means an atmospheric change and that leads to another maximum power point. This can be seen in the following figure 12 [2].

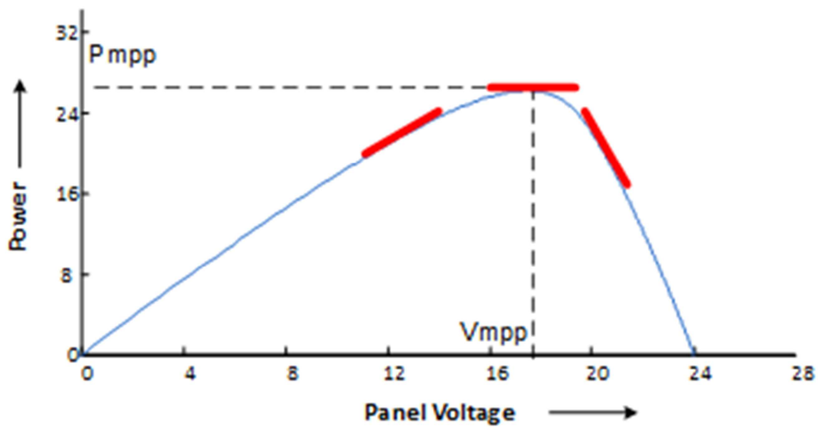


Figure 12. Incremental conductance P-V graphic [2]

2.3 DC-DC Converters

A DC-DC converter is a device that transforms direct current to another one. These devices can increase the output voltage or decrease the output voltage if it is connected between a photovoltaic generator and a load. It doesn't have to be a photovoltaic generator to work but in this case, the photovoltaic generator needs a converter to step up the output voltage to feed to the grid [3].

A DC-DC converter needs a control so the efficiency improves in the system and the output voltage can be controlled. With control systems it is possible to have the same output voltage having different input voltages (with different irradiances and temperatures in a solar panel system). Normally a MPPT and a PWM (pulse width modulation) are used to have that control, reading the current and voltage at the input and output so it changes the duty cycle so there is an output voltage control [1].

When a device is supplied by a battery, there are elements that need a smaller voltage or a higher voltage so the voltage has to be reduced or increased by a converter. These devices can be phones, laptops,… The PWM is used as a modulation technique for changing the width of the pulse. The main use of it is to allow some kind of control of the power given to motors, electronic devices.

The duty cycle is the percentage of time that the pulse is on compared to how long it's off. The triangular wave that comes from the duty cycle is transformed to a rectangular wave with the PWM. The PWM has a frequency. On that frequency, the period can be known and the duty cycle is going to change when it is going to be on and off.

This can be seen in figure 13.

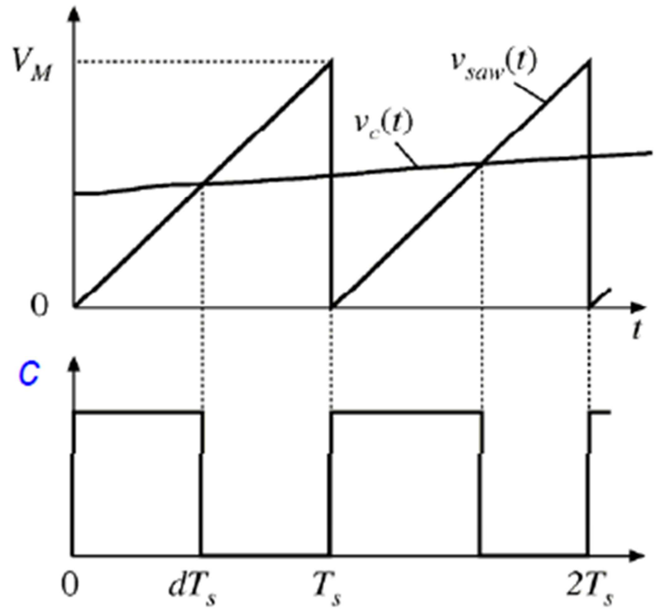


Figure 13. Sawtooth wave and PWM graphic [8].

The PWM acts like a comparator. The time passed until the vc reaches the sawtooth wave will be Ton time. In other words the duty cycle and then the Toff will last until the end of that period [8].

The principle of the DC-DC converter commutation consists on the commutation in a constant frequency with a Ton = D; a period Ts and Toff = (1 - D)*Ts; where Ts = 1 / fs and D is the duty cycle, which is defined as [1]:

$$D = \frac{Ton}{Ts} \tag{2.7}$$

Depending on the conversion ratio M (D), it can be classified in different types of DC-DC converters like Boost, Buck and Buck– Boost.

2.3.1 Boost converter

A boost converter is a DC-DC converter that increases the output voltage. This converter is useful for systems connected to the grid [2].

The ideal circuit of a boost converter is:

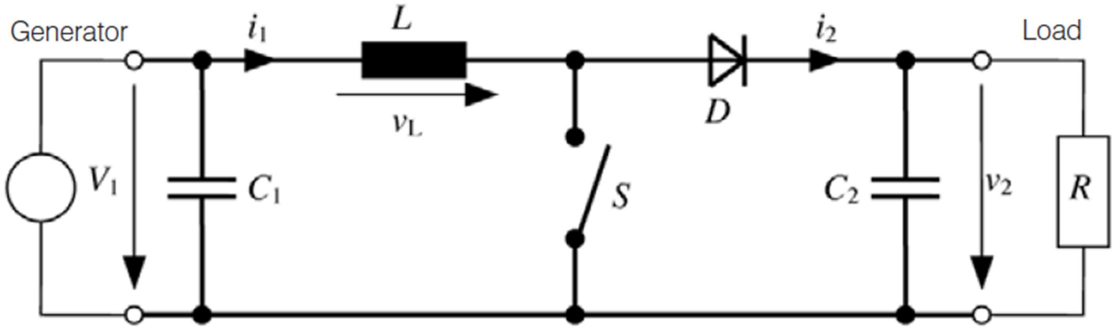


Figure 14. Circuit of a boost converter [3]

The converter operates in a steady state. To understand how this converter works, it has to be analyzed when the MOSFET is on and off [4].

If the MOSFET is on, the diode is in short circuit, so the current at the output is “ic” and if the MOSFET is off, the diode conducts, and the energy stored in the inductor goes through the capacitor. The result of the circuit is [4]:

$$Vout = \frac{\text{Vin}}{1-D} \qquad (2.8)$$

$$M(D) = \frac{Vout}{Vin} = \frac{1}{1-D} \qquad (2.9)$$

The boost converter can be improved by changing the diode to a MOSFET due to the large voltage losses from the diode.

2.3.2 Buck converter

If the output voltage is lower than the input voltage given by the solar panel, this converter is a buck converter. A buck converter reduces the voltage and can be used in a computer to convert the voltage from the battery to an element that needs lower voltage (12 V desktop; 12-24 V laptop) down to the 0.8-1.8V needed by the CPU system [10].

The buck converter works with an inductor controlled by two devices whether the energy passes through the switcher or through the diode. When the switch is closed, the voltage of the inductor is $Vl = Vin - Vout$ and the diode is in reverse current thus no current flows through the diode. When the switch is open, the diode is conducting and the voltage of the inductor is $Vl = -Vout$ [10].

After analyzing the circuit the result of this one is [10]:

$$Vout = Vin * D \qquad (2.10)$$

The circuit of a buck converter is similar to the boost converter, except that the diode is located where the inductor is.

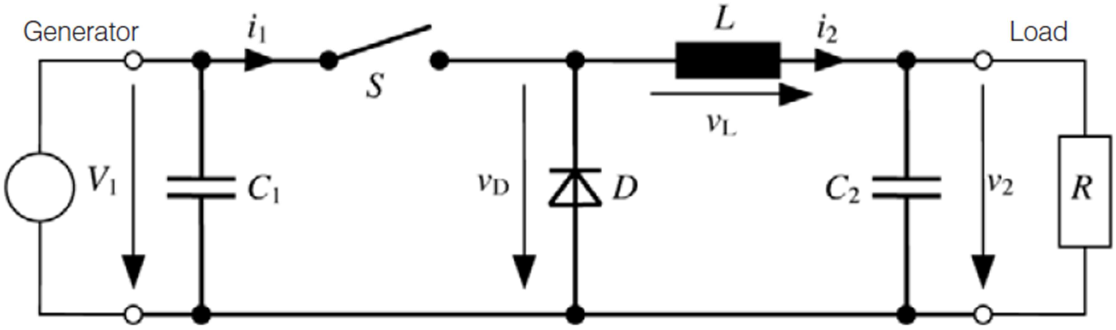


Figure 15. Circuit of a buck converter [3]

In this project the boost converter has been chosen due to the voltage of the photovoltaic panel needs to be increased to be feed to the grid.

2.3.3 Buck-boost converter

Not only are there boost and buck converters but also the buck-boost converter. This one has an output voltage that can be greater or lower than the input voltage. The structure of the buck-boost converter is similar to the other ones. As seen in the rest of converters, the converters need a certain control so the output voltage can be modified for the use that is going to have.

Normally the buck-boost converter is used for the electrical system in the vehicles or where it is needed to regulate direct current flow through a machine or a device [1].

The buck-boost converter has a simple operation. When it is in the ON state, the current goes to the inductor and the capacitor gives energy to the load. In the OFF state, the energy that has the inductor is transferred to the capacitor and the load [1].

After calculating the circuit, the result is:

$$Vout = -Vin * \frac{Ton}{Toff} = -Vin * \frac{D}{1-D} \qquad (2.11)$$

The figure 16 will show the circuit of the buck-boost converter.

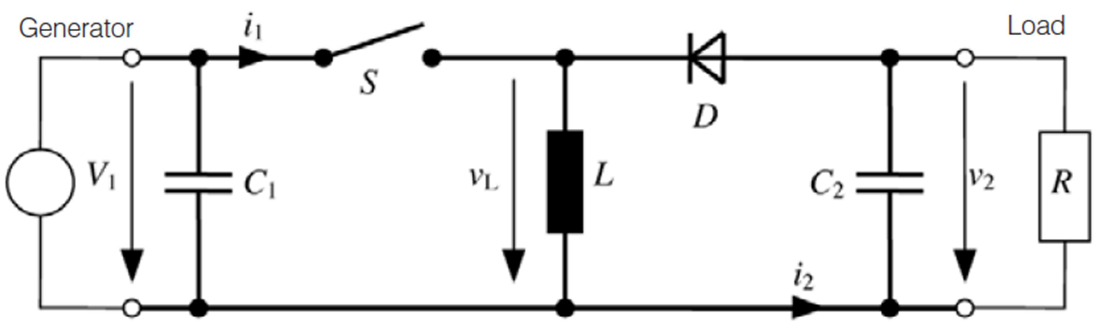


Figure 16. Circuit of a buck-boost converter [3]

2.4 Inverters

An inverter is an ensemble of switchers connected in bridge. The function of an inverter is to convert a DC signal to AC. This AC signal is a sinusoidal waveform and it can be fed to the grid or to an AC load. Before injecting the current to the grid, a certain filter and control have to be there so the signal is clean and in sync with the grid [2].

Normally a full bridge inverter is used when using a single phase system. The full bridge inverter consists of four switchers like MOSFET, IGBTs …They generate a sinusoidal wave by opening and closing the different switchers with the inverter controls. This signal is then filtered by a LCL filter, generating 50 or 60 Hz AC waveform [2].

The inverters can be classified by different controls of inverters: the stand alone inverters and grid-tie inverters.

2.4.1 Stand alone operation

The objective of the stand alone operation is to insert an AC fixed voltage to the output of this one. The stand alone operation is used for AC loads. To be able to have a fixed AC voltage waveform, two control loops will be needed. One will control the voltage and the other one will control the current [2].

2.4.2 Grid tied operation

The objective of the grid tied operation is to feed power into the grid. In this operation the voltage of the grid will be assumed to be constant. The control of the grid tied operation can be done with two loops: DC voltage loop and phase lock loop [2].

The DC voltage loop is used to estimate the power from the input so it can change the current reference for the stage.

The phase lock loop (PLL) estimates the phase of the grid and the inner current loop is there to assure that a clean AC current signal is delivered [2].

2.4.3 Grid synchronization

To synchronize the inverter to the grid, the inverter has to verify some conditions because some changes can occur on the grid such as the connection and disconnection of loads, harmonics injected by some equipment, faults,…..

The quality of the grid can affect the voltage and current of the equipment connected to the grid. Thus, the grid parameters including phase and magnitude must be measured at all times to ensure that a correct connection can be made [2].

2.4.4 Grid detection

To know and detect the grid status, this can be made by monitoring the voltage and the frequency of the grid. If there is a fault on the grid, the voltage and the frequency will drift.

Nevertheless, there is a non-detection zone where the voltage and frequency cannot be detected by the inverter. With this problem, the inverter cannot detect if the grid is there or not [2].

There are different zones that the inverter can detect. When the AQ is positive, there is an over frequency, but if it is negative there is an under frequency. Additionally if the AP is positive there is an over voltage. Otherwise there will be an under voltage.

This can be seen in figure 17:

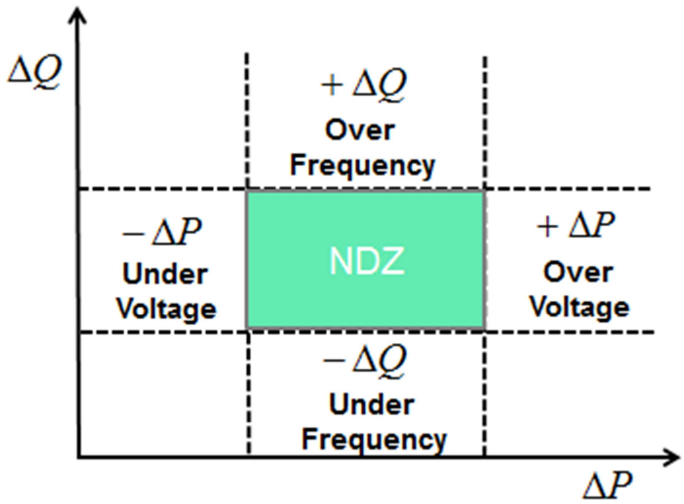


Figure 17. Non-detection zone graphic [2]

2.4.5 Examples of inverters

- The first example will be the H4 topology. This one is the simple one, and it was explained in this chapter.

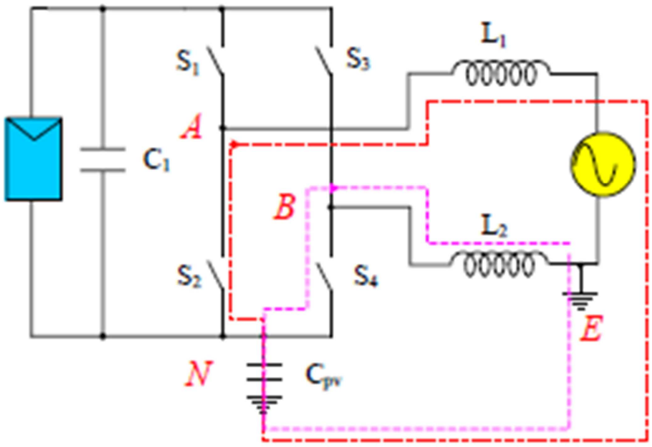


Figure 18. H4 inverter topology [9]

- The second example will be the H5 topology. This topology improves the efficiency of the inverter. This one has four switchers S1, S2, S3, S4 and the DC-bypass switcher. The peak of efficiency is around 98%. The H5 topology is based on the concept of disconnecting the Solar panel from the grid during freewheeling periods. This topology is patent by SMA [9].

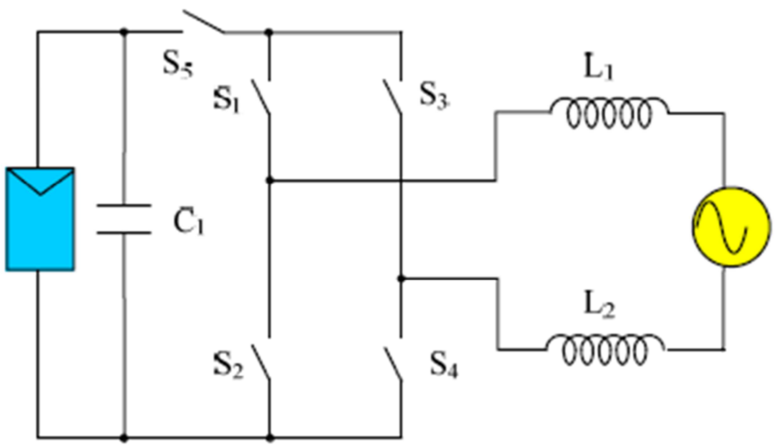


Figure 19. H5 bridge, topology from SMA [9].

- The third example is the H6 topology, or HERIC. HERIC means Highly Efficient and Reliable Inverter Concept. With this structure it can avoid potential fluctuations on the DC terminals of the solar panel by disconnecting from the grid. As the name says, it is very efficient around the 98-99% [9].

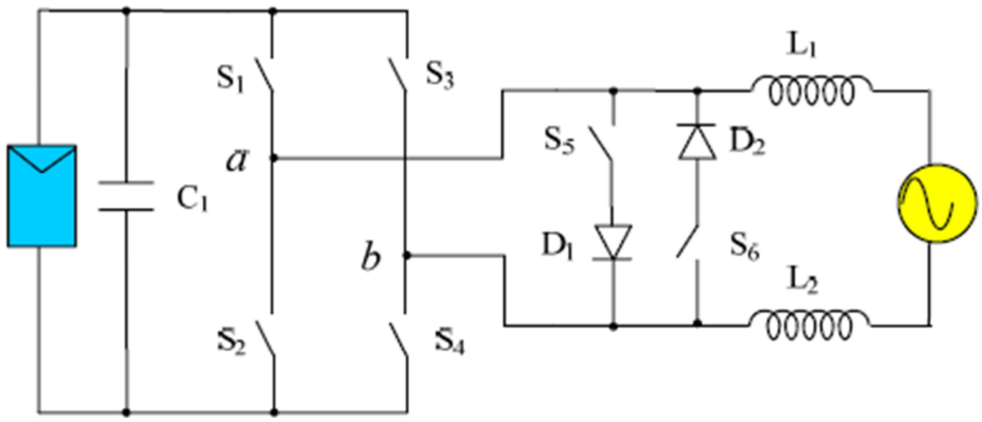


Figure 20. HERIC topology [9].

Implementation

In this chapter, the Simulink model will be described and explained. First, there will be a description of the process of making the solar cell and implementing a factor into the equations so that the number of series cells can be changed in the main solar cell block. The formulas that have been used in the PV cell block will also be explained.

Then, the algorithm used in this project for the MPPT will be described. The MPP algorithm was written with a script in MATLAB.

And the third point will be the boost converter block, explaining the calculus behind the circuit.

3.1 PV cell block

The solar cell has been designed to depend on two variables: irradiance and cell temperature. It has been made with Simulink. A lot of subsystems are present inside the solar cell block. It contains different blocks describing the solar cell equation.

The problem that the equation 2.4 has is that it does not depend directly on the irradiance or cell temperature. The photogenerated current (IL) and the reverse saturation current (Io) are not components that can be measured directly. That is the reason why some changes have to be made.

To be able to use the solar cell equation some approximations are necessary:

- First of all, the parallel resistance can be neglected in the equation due to the parallel resistance being higher than the operation of the voltage of the cell plus series resistance for current of the cell. In this Simulink model this equation has been used because it will get more accuracy at the end of the circuit and it will have a more realistic behavior [1].

$$\text{If} \quad Rp \gg (V + I * Rs) \quad \text{then} \quad \frac{V+I*RS}{Rp} \cong 0 \qquad (3.1)$$

- Secondly, the photogenerated current (IL) and the short circuit current (Isc), can be considered equal. The photogenerated current is equal to the short circuit current multiplied by the irradiance and divided by 1000 (that is the earth's surface irradiance and also the optimal for solar cell). And when the voltage in the output on the solar cell is 0, it's working on the short circuit region; $I \cong Isc$ [1];

  Supposing that the solar cells are:

$$Voc > I * Rs \qquad (3.2)$$

- The third point is when the solar cell is in open circuit the current is equal to 0. The resulting equation is [1]:

$$Voc = Vt * ln(\frac{Isc}{Io} + 1) \cong Vt * ln(\frac{Isc}{Io}) \qquad (3.3)$$

Assuming that the short circuit current is much bigger than the reverse saturation current:

$$Io = \text{Isc} * e^{(-\frac{Voc}{Vt})} \qquad (3.4)$$

And changing this expression in the equation 3.4 and assuming $e^{(\frac{Voc}{Vt})}$ is greater than 1, the solar cell equations change to [1]:

$$Ipv = Iscg - Iscg * e^{(\frac{Vpv - Vocg + Ig * Rsg}{Vt})} \qquad (3.5)$$

The Simulink model is based on the mathematical model of the equation 2.4. This can be written as:

$$I = Il - Id = Isc(g,Tc) - Isc(g,Tc) * e^{(\frac{Vpv - Voc(g,Tc) + I * Rs}{Ns * Vt * m^2})} \qquad (3.6)$$

The value Isc(g,Tc) is equivalent to iL that corresponds to the short circuit current and G,Tc are the irradiance and cell temperature. To be able to calculate Isc(g,Tc) and Voc(g,Tc), they have to be extrapolated with the next equations so that they become standard test conditions (STC). The STC are conditions where the solar cells are certified and pass through measurement so they can be sold [1].

$$Isc(g, Tc) = \mathrm{Isc} * \frac{G}{1000} + \alpha c * (Tc - Tamb) \quad (3.7)$$

$$Voc(g, Tc) = Voc + \beta c * (Tc - Tamb) + Vt * m^2 * (ln \frac{G}{1000}) \quad (3.8)$$

Where:

- Isc(g,Tc): Short circuit current depending on the irradiance and cell temperature. It's the STC short circuit current.
- Isc: It's the short circuit current of the solar panel
- G: Irradiance of the sun. It is measured in W/m2. The maximum irradiance is 1000 W/m2.
- αc: Coefficient of the current variation with the cell temperature. The value of this coefficient can be 1 mA/ºC if there is no measurement.
- Tc: It's the cell temperature. Measured in (ºC).
- Tamb: Ambience temperature. It will be taken normally as 25 ºC for measurements.
- Voc(g,Tc): Open circuit voltage depending on the irradiance and cell temperature. It's the STC open circuit voltage.
- Voc: It's the open circuit voltage of the solar panel.
- βc: Coefficient of the voltage variation with the cell temperature whose value is -2.3mV/ºC

Now that the Isc(g,Tc) and Voc(g,Tc) have been extrapolated to standard test conditions, another component of the equation 3.6 can be calculated. That is the series resistance. The value of the series resistance can be calculated using the Green's approximation [1].

The Green's approximation determines Rs from the maximum power conditions. It is a good and accurate method [1].

First, open circuit voltage has to be normalized for the ideal form factor with the following equation:

$$voc = {}^{Voc}/_{Vt * m^2} \quad (3.9)$$

This equation works for the ideal form factor “FFo” if voc > 15V. The equation for the ideal form factor is:

$$FFo = \frac{voc - ln(voc + 0.72)}{voc + 1} \qquad (3.10)$$

And the real form factor:

$$FF = \frac{Im * Vm}{Isc * Voc} \qquad (3.11)$$

Where:

- Im: It’s the current when the solar cell is working in the MPP.
- Vm: It’s the voltage when the solar cell is working in the MPP.

These measurements are in standard test conditions measured in a lab. These values are provided by the manufacturer [1].

After these equations, Rs can be calculated with the next expression:

$$Rs = \frac{Voc * (1 - \frac{FF}{FFo})}{Isc} \qquad (3.12)$$

The Simulink model of the solar cell formed with the described equations above is the following one:

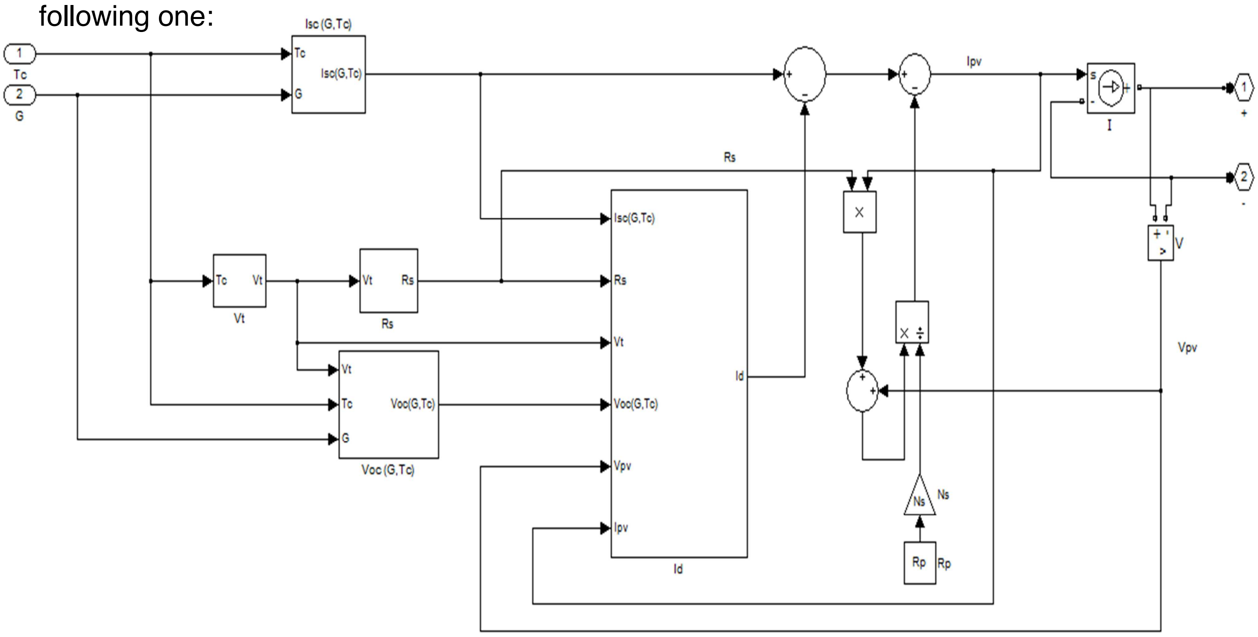


Figure 21. Simulink model of the solar cell

The whole model is made with Simulink. Each element of the equation is with subsystems. The problem that the solar cell has is that the voltage and the current are inside the equation that will lead to the creation of a loop on the system. A current generator is used so the loop is partially fixed.

The loop that the solar cell has can be solved with the Newton - Raphson Method. The Newton-Raphson method is an iterative method that allows an approximate solution for an equation like f(x) = 0. The method starts with an initial estimation of the solution with a value x0. Then it builds a sequence of approximations repeating the method. The more it is repeated, the more accurate the solution is.

Because of the current generator, the solar cell model finishes with two terminals. These terminals are the positive and negative. In Simulink a model can't be simulated if the circuit is open. For this solar cell, a variable resistor has to be placed so the I-V and P-V characteristics can be seen. The graphics and results of the solar cell will be explained in chapter 4.

3.2 PV panel block

To be able to build a solar panel in Simulink, a lot of solar cells in parallel and series have to be put together so the current and voltage increase. Cells in series will increase the voltage and cells in parallel will increase the current. After knowing which elements of the equation 3.6 are going to change and depending on how many cells the panel has in series or parallels, it will be easier to implement a factor so the Simulink model can work as a solar panel. The changes that have to be carried out are:

- One factor that will increase the solar panel series cells. That means this factor has to change the voltage and the series resistance. On this Simulink model the factor is called Ns (number of series cells). This factor was implemented in the different elements of the equation 3.6. Voc(g,Tc) has the Ns factor due to it needing to change the voltage. The Rs equation also has the Ns factor because the losses of the series resistance will change depending on how many series cells are. Also in the equation 3.6 it will be multiplying Vt.
- The second factor that will increase the solar panel parallel cells. This factor has to change the current. In this Simulink model this factor has not been added because in parallel only two solar panels have been used. So by only putting the PV cell blocks in parallel, the current increases.

The next figure represents a solar panel. Two arrays block are in parallel and inside of each block is the same number of series cells.

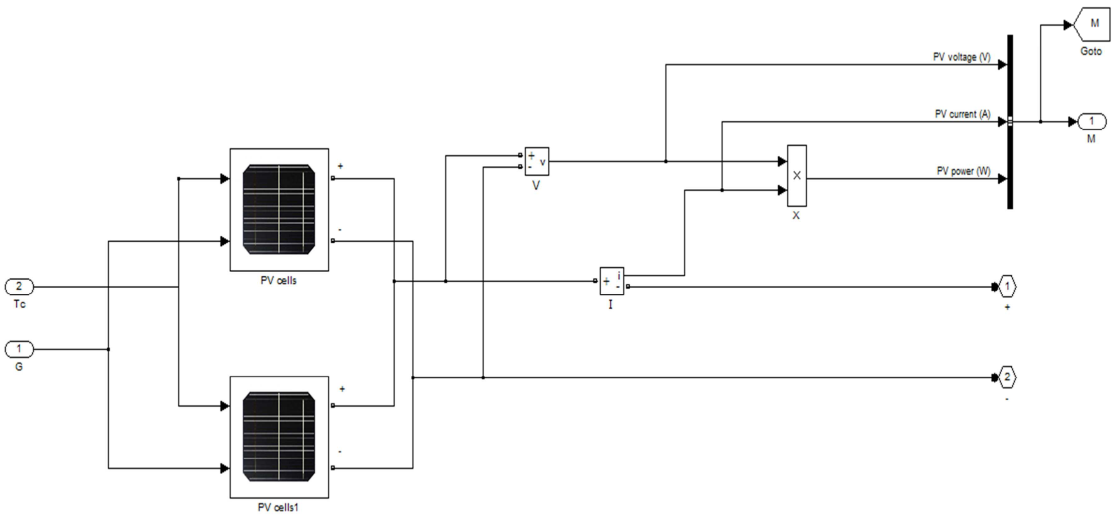


Figure 22. Simulink model of the solar panel

3.3 MPPT block

The MPP tracker, as described in chapter 2, is a device that makes the solar panel work in the maximum power point. The MPP tracker is used to improve the performance of the photovoltaic panels.

The MPP is going to read the input voltage and the input current in the MPP that are the current and voltage of the solar panel, and then search where the maximum power point is. With this, it will change the duty cycle of the boost converter so it will extract more power while if the MPP is not implemented, it will convert less power.

In this thesis, the MPP has been designed with a MATLAB script. In the script, the algorithm of the MPP has been written. The algorithm used in this project is the Perturb and Observe algorithm. This algorithm is one of the most used in solar panels. Although, this MPP has a problem. The problem is that if a solar panel has some cells with shadow, the graphic will have different hills of maximum power point. Of course, only one will be right but if this MPP finds one maximum power point, the other one will not see it. This is what other MPP trackers do; they read the entire I-V characteristic so they will know where the maximum power point is.

The next figure is the MPP block. This block has the MPP script written in MATLAB, and a saturation block. The saturation block defines limits for the duty cycle. The saturation limits are 0.05 and 0.95. If the duty cycle arrives to 0, the boost converter is not going to work well.

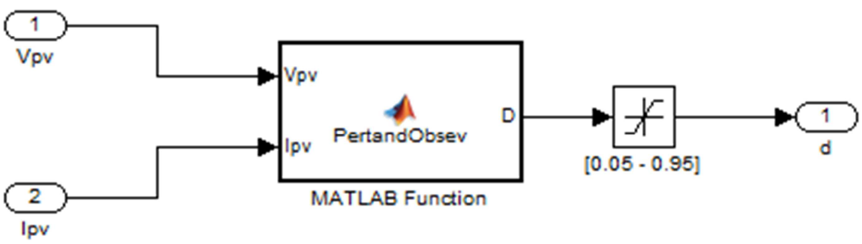


Figure 23. Simulink model of the MPP block.

The MPP algorithm is in the MATLAB function block. In this block, MATLAB language can be written. To start using this block, first the input and output have to be defined as a simple equation. This equation is going to be like:

$$\text{Function} \quad Output\ signal = \ Name\ of\ the\ block\ \ (input\ 1, input\ 2)$$

After defining the input and output of the algorithm, some variables have to be defined so the algorithm can be compared with these ones. The Perturb and Observe algorithm say that first the power of the solar panel has to be higher than the previous power. Depending on if it's higher than the previous power, it will go to a path or another one. If the voltage of the solar panel is greater than the previous voltage, the duty cycle will be reduced; if not then the duty cycle will increase the value. But if the solar panel power is lower than the previous one then the voltage is compared. If that's true then, if the voltage is greater than the previous voltage the duty cycle will increase; if not, then the duty cycle will reduce the value.

At the end of the algorithm the previous values have to be updated with the new ones. This process will carry out the algorithm until it finds the maximum power point so that it will stay around that point. If the sun conditions change, then the algorithm will start looking again for the maximum power point.

The algorithm used on this project is the following one:

```
function D    = PertandObserv(Vpv,Ipv)
persistent P  Pprev  dP d h Vprev V;

if isempty(P)
    P=0;
    Pprev=0;
    dP=0;
    d=1;
    h=0;
    Vprev=0;
    V=0;
end
%%%%%%%%%%%%%%%%%%%%%
    Vprev = V;
    V = Vpv;
    Pprev=P;
    P=Vpv*Ipv;
    dP=P-Pprev;
```

```matlab
if dP>0.1
    if (V-Vprev)>0
        h=-0.01;
        d=d+h;
        h=0;
    else
        if (V-Vprev)<0
            h=0.01;
            d=d+h;
            h=0;
        else
            h=0;
            d=d+h;
        end
    end
else
    if dP<-0.1
        if (V-Vprev)>0
            h=0.01;
            d=d+h;
            h=0;
        else
            if (V-Vprev)<0
                h=-0.01;
                d=d+h;
                h=0;
            else
                h=0;
                d=d+h;
            end
        end
    else
        if ((dP<0.1)&&(dP>-0.1))
            h=0;
            d=d+h;
        else
            h=0;
            d=d+h;
        end
    end
end
D=d/(d+1);
```

Figure 24. MATLAB script of the MPP tracker

3.4 Boost converter block

As said in the theoretical part, a converter is an element that transforms a DC voltage to another DC voltage. This other voltage can be greater than the input voltage or lower. Depending on the value of the voltage, the converter used is a boost or a buck converter. The boost converter is the one that transforms the dc voltage to a higher value at the output and the buck converter transforms the input dc voltage to a lower value.

The converter chosen in this thesis is the boost converter. The boost converter has been chosen because the objective of this project is the simulation of a solar panel with the MPP tracker transforming the duty cycle to the boost and converting the signal dc to ac with an inverter so the signal can be injected to the grid if it's synchronized with it.

Normally, the boost converter has to be designed for a solar system that at the output of the boost, the signal is constant. The boost converter designed in this project doesn't work that way. This boost converter works by increasing the input voltage of the solar panel to another one depending on the duty cycle. The duty cycle is going to be changing with the MPP connected to the solar panel. To control the boost converter a PWM is needed. A PWM, or pulse-width modulation, is a technique where the duty cycle is changed to control the quantity of energy sent to a load. The PWM can be created with a comparator with two inputs and one output. One input will be the duty cycle and the other one will be a saw-tooth wave. The result of this will be a rectangular wave that will be connected with the MOSFETS [8].

In this project, two boost converters have been designed. One designed as a boost converter circuit and the second was designed with a MATLAB script. The difference between the first one and the second boost is that the first one is simulated with inductor, MOSFETS, capacitors and the second one is programed with the circuit equations so MATLAB calculate the value with the programed equations. Both converters work by increasing the output voltage. Although, both boosts have a problem when the solar panel is connected with the boost. The solar panel designed in this project has a non-solved loop and this generates a lot of problems with the rest of elements. Those problems will be explained in the simulation results chapter.

First, the boost converter designed with circuit will be explained. The boost designed with the circuit is designed with two MOSFETS so the performance of the converter is better. Because it has two MOSFETS, it needs two PWM signals. In SIMULINK there is a block that can transform the duty cycle with two PWM signals, one high frequency and the other one low frequency.

Figure 25 is the SIMULINK circuit of the first boost converter.

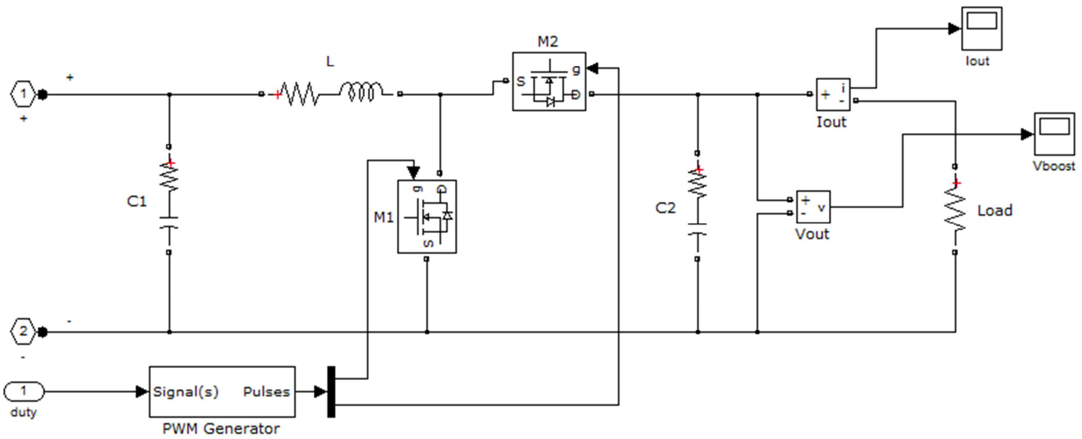


Figure 25. Simulink model of the boost converter circuit

To be able to understand the circuit and what is behind it, it has to be analyzed. First of all, to analyze the circuit some assumptions have to be made. The assumptions are: the converter operates in steady state and the current that is on the inductor is always a positive current so the converter will be operating in continuous conduction mode (CCM) [4].

After the assumptions, to analyze the Kirchhoff's voltage and current laws have to be used. At first, the MOSFET 1 will be ON and the MOSFET 2 in reverse current. With this, the circuit will be [4]:

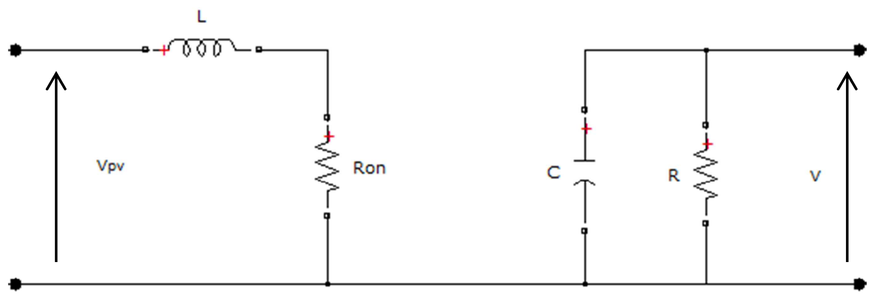


Figure 26. Circuit of the boost converter when M1 ON and M2 OFF

With this circuit the equations that result:

$$Vl = Vpv - il * (Rl + Ron) \tag{3.13}$$

$$ic = -\frac{V}{R} \tag{3.14}$$

Then, the circuit will change. The MOSFET 1 will be in reverse current and the MOSFET 2 switch ON. So the energy of the inductor goes to the capacitor. The circuit will be [4]:

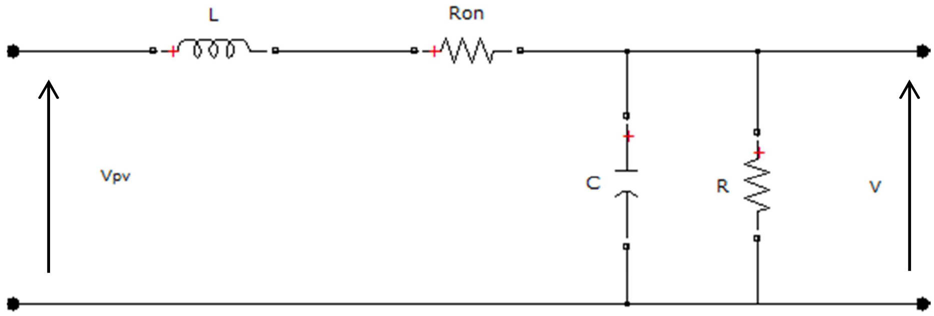


Figure 27. Circuit of the boost converter when M1 OFF and M2 ON

The equations applying again to the Kirchhoff's laws are:

$$Vl = Vpv - il * (Rl + Ron) - V \tag{3.15}$$

$$ic = il - \frac{V}{R} \tag{3.16}$$

After getting these equations, the principle of capacitor charge balance has to be used. Knowing the capacitor relation over one period is [4]:

$$ic(t) = C * \frac{dvc(t)}{dt} \tag{3.17}$$

But when it's a steady state period the average capacitor current is zero [$ic(t)_{avg} = 0$];

$$-\frac{V}{R}DTs + (il - \frac{V}{R}) * (1 - D)Ts = 0 \tag{3.18}$$

$$(il - \frac{V}{R}) * (1 - D) = \frac{V}{R}D \tag{3.19}$$

$$il = \frac{V}{R(1-D)} \tag{3.20}$$

This equation is easier to understand with figure 28.

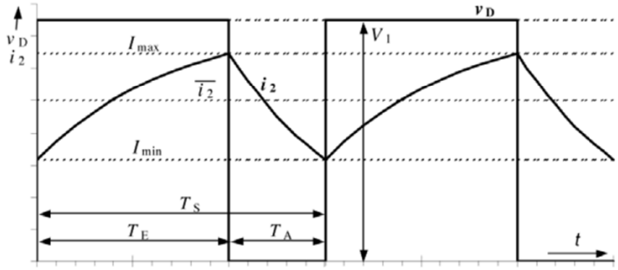


Figure 28. Graphic of the inductor current [3].

Now, the inductor-volt second balance has to be applied. The inductor relation over a period is [4]:

$$vl(t) = L * \frac{dil(t)}{dt} \tag{3.21}$$

But over a cycle in steady state period the average inductor voltage is zero $vl(t)_{avg} = 0$:

$$(Vpv - il * (Rl + Ron)) * DTs + (Vpv - V - il * (Rl + Ron)) * (1 - D) * Ts = 0 \tag{3.22}$$

$$Vpv - V + VD - il(Rl + Ron) = 0 \tag{3.23}$$

$$Vpv = V(1 - D) + \frac{V}{R(1-D)}(Rl + Ron) \tag{3.24}$$

$$V = \frac{Vpv}{(1-D) + \frac{Rl+Ron}{R(1-D)}} \tag{3.25}$$

The result of applying the inductor-volt second balance is the equation 3.25. If the circuit is been calculated or analyzed ideally, then the resistor Ron is not on the MOSFET. So the equation will result [4]:

Ideal MOSFETS $$V = {}^{Vpv}/_{1 - D} \tag{3.26}$$

After solving the equations, now it is possible to determine the inductor current ripple that changes from the minimum current to maximum current for $0 \leq t \leq DTs$.

This can be calculated seeing the line-segment in the previous figure 28.

$$2\Delta il = (slope\ of\ the\ inductor\ current) * DTs \qquad (3.27)$$

$$\Delta il = \frac{1}{2L} * (Vpv - \frac{V}{R(1-D)}(Rl + Ron)) * DTs \qquad (3.28)$$

$$\Delta il = \frac{D}{2Lfs} * (Vpv - \frac{V(Rl+Ron)}{R(1-D)}) \qquad (3.29)$$

After reaching this point, with this equation and implementing this to $ilmin \geq 0$, the minimum inductance is possible to calculate [4].

$$Ilmin \geq 0; \longrightarrow Il - \Delta il \geq 0 \quad (3.30)$$

$$\frac{V}{R(1-D)} \geq \frac{D}{2Lfs} * (Vpv - \frac{V(Rl+Ron)}{R(1-D)}) \qquad (3.31)$$

$$Lmin \geq \frac{D}{2Vfs} * (Vpv(1-D)R - V(Rl + Ron)) \qquad (3.32)$$

The equation 3.32, determines the minimum value of inductance so the converter operates in continuous conduction mode.

After explaining the circuit of the boost converter, it is easier to understand the second boost created with a MATLAB script.

Figure 29 is the script implemented in MATLAB.

```
function y = Boost_Converter(u,L,C,RL,Ron,Rc)
% Inputs:
% u = [Vg D iout v_C i_L]
% Parameters: L,RL,C,Resr,Ron
% Outputs: y = [dv_C/C di_L/L Vo Ig]

Vpv = u(1);        % Photovoltaic panel voltage
D = u(2);          % Duty control
iout = u(3);       % Load current
vC = u(4);         % Capacitor voltage
iL = u(5);         % Inductor current

dD = 1-D;

% Boost equations
Vout = vC + Rc*((iL*dD) - iout);
Ipv = iL;
iC = (iL*dD) - iout;
vL = Vpv - (Vout*dD) - iL*((Ron*D) + RL);

% Output
y = [iC/C vL/L Vout Ipv];
```

Figure 29. Script of the boost converter

As it can be seen, the equations used in this boost are the same ones that were in the other boost. In this boost, it is necessary to implement the d created by the MPPtracker by converting the signal with a PWM.

To be able to implement this model, it is necessary to program all the values of the inductor, capacitor and the resistances of it. Then the equations are written in MATLAB language. These equations are:

- The equation of the output boost voltage can be written with the branch of the capacitor or the equation obtained with the inductor-volt second balance 4.25.
- Then, equaling the current from the solar panel and the inductor of the boost.
- The other equation is the current passing through the capacitor. The equation is equal to 4.16 but only changing the $V/_R$ with iout.
- The last equation is the inductor voltage. This equation is obtained by the assumption of the first MOSFET is on and the second MOSFET off.

After explaining how the different parts of the project were implemented in Simulink, the results of the graphics of them have to be explained.

Simulation results

In this chapter, the results of the simulation in Simulink will be explained. First, there will be an explanation why the solar cell has different results depending on the irradiance and the temperature. Then, the understanding of the results of a complete solar panel will be described.

After that, there will be an explanation of the duty cycle generated by the MPP tracker with and without a solar cell. And the last point will be the description of the different circuits of the boost converter. The different circuits are: the boost without a solar panel or MPP tracker, then the boost with a constant duty cycle implementing the solar cell. The third one will be with the MPP tracker.

And after these three circuits, a resistance is implemented in the solar cell so a constant voltage is created and the graphic will be explained.

4.1 Results of the Solar Cell

First of all, to be able to get the result, it is necessary to choose the solar panel that is going to be used. In this project the panel Shell Power Max Ultra 175-PC has been used. More information about the solar panel will be put in the annexes at the end of the project. The parameters of the panel that are going to be programed in Simulink are: Short-circuit current (Isc), open-circuit voltage (Voc), MPP current (Im), MPP voltage (Vm), parallel resistance (Rp), N° series cell (Ns), temperature ambient (Tamb), standard test conditions irradiance (G0) and ideality diode factor (m).

The solar cell is implemented so it is possible to change the parameters of it by just a step. By clicking twice on the solar cell, Simulink will open a new window with the programed information. There, it will be possible to change the parameters. In the next figure the parameters are shown from a picture of the solar cell. Those values are for one cell. Due to the panel having 72 series cells, the voltages have to be divided by 72 and the value is for one cell. Only the voltage has to be divided, not the current.

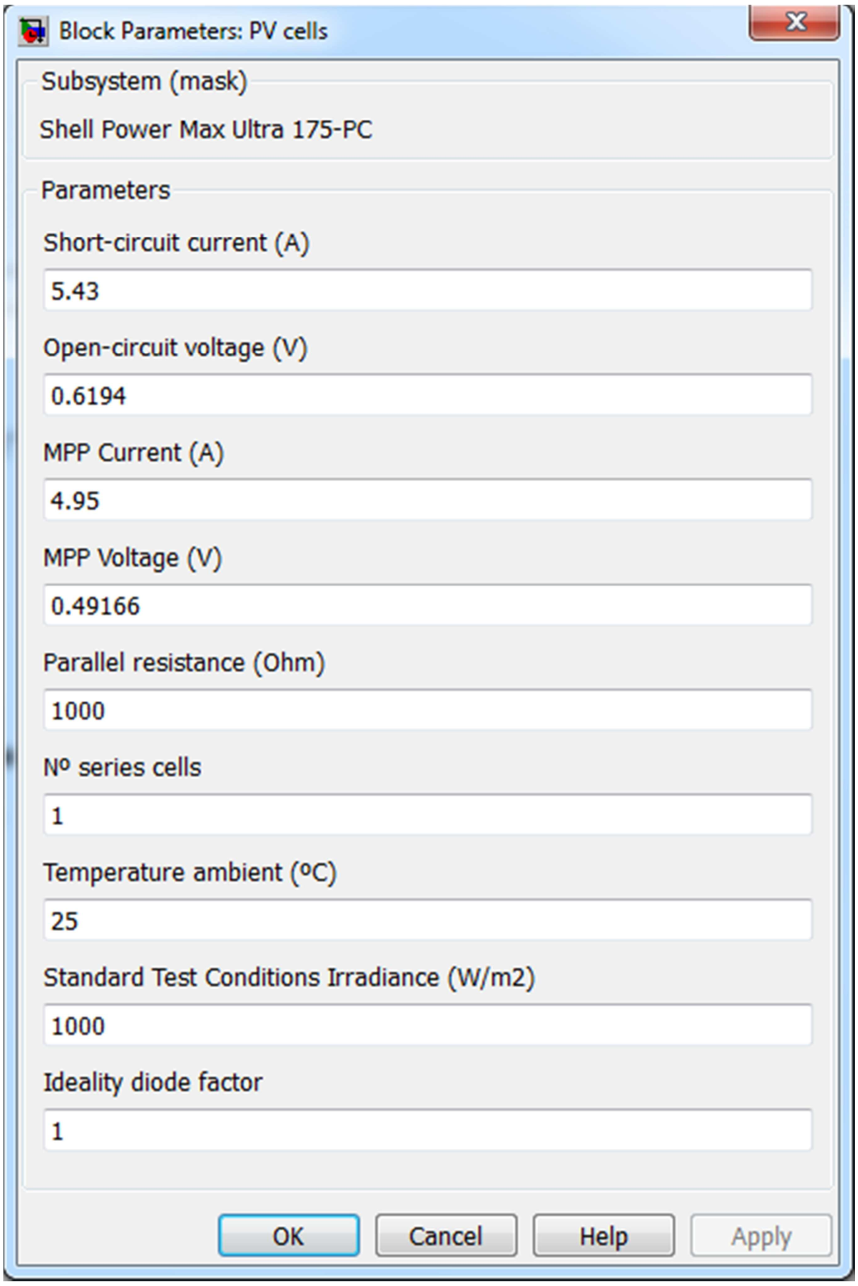


Figure 30. Parameters of the solar cell

With these parameters, it will be possible to simulate them on the PV cell. By putting a constant irradiance (G) and a constant temperature (T), the solar cell will give the I-V and P-V characteristics of the cell.

These graphics can be seen in figure 31 and figure 32.

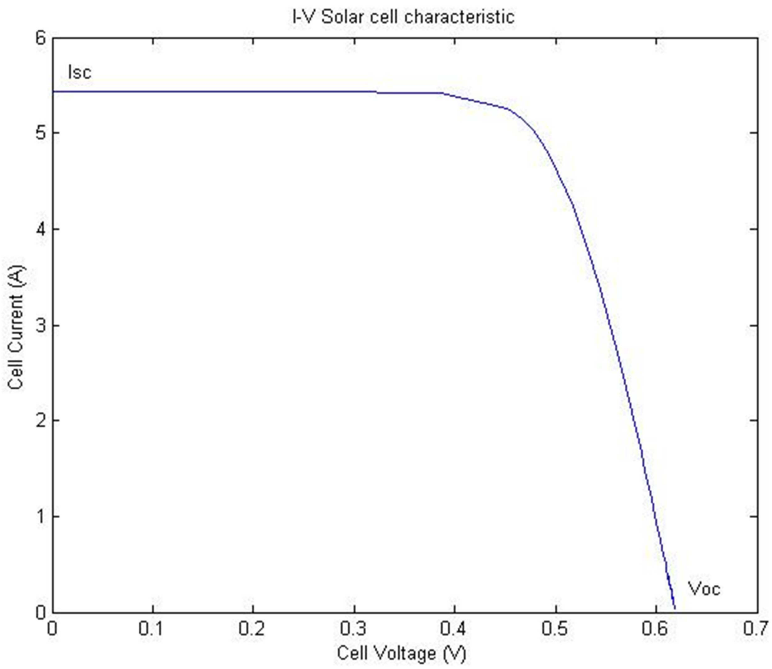


Figure 31. I-V characteristic of the cell

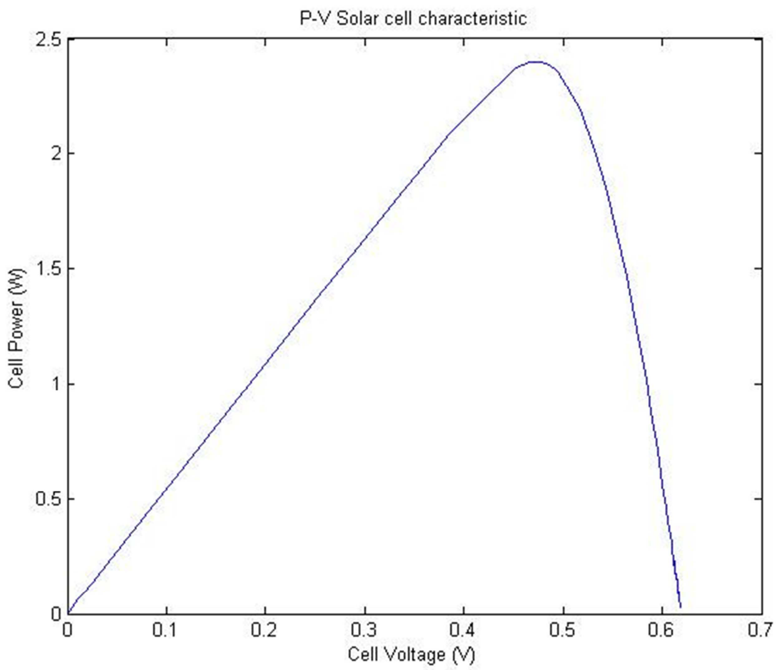


Figure 32. P-V characteristic of the cell

The G and Tc chosen were for an ideal behavior for the solar cell. So it is possible to see on the graphic the values of Isc and Voc of this cell. Those values are Isc = 5.43 A, Voc = 0.6194 V. With the block scope it is possible to calculate I maximum and V maximum, by searching for the maximum power point in the graphic of the cell.

The results of the scope are:

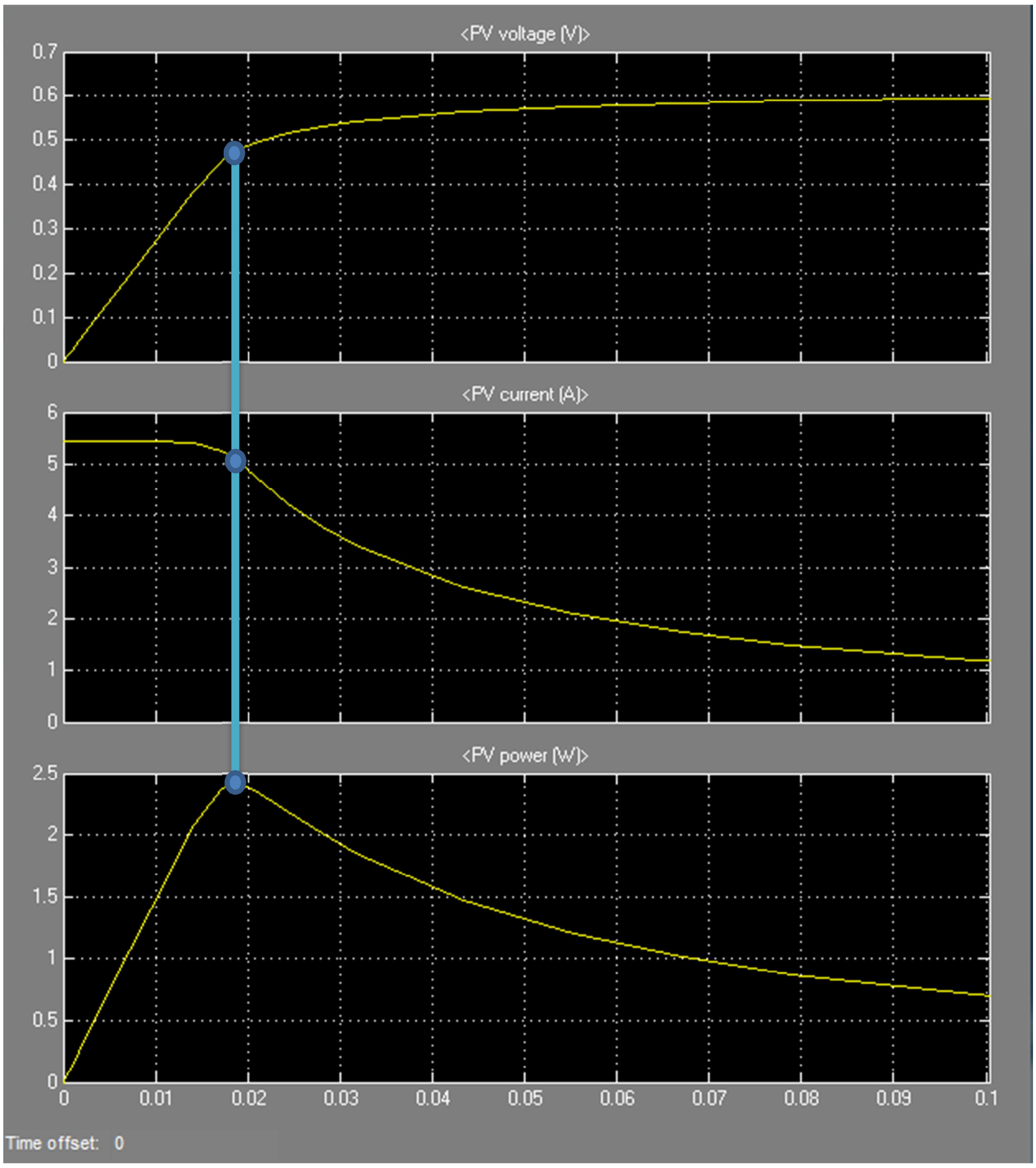


Figure 33. Solar cell scope of the voltage, current and power

Where the maximum power point is, it doesn't mean that the current and voltage are maximum too, but those are the MPP values for that irradiance and temperature.

After seen how the cell acts with the ideal parameters, it is possible to see how it acts with different irradiances and temperatures as shown in the next figures. The cell is going to be first with different irradiances and a constant temperature that will be 25 ºC. The irradiances are 400, 600, 800, 1000 W/m2. And then the cell is going to be studied with different temperatures and a constant irradiance that will be 1000 W/m2. The temperatures are 25,40,60,70 ºC.

In the figure 34, it is possible to see that the lower the irradiance, the lower is the characteristic of the cell. And with a higher irradiance, the graphic gets higher.

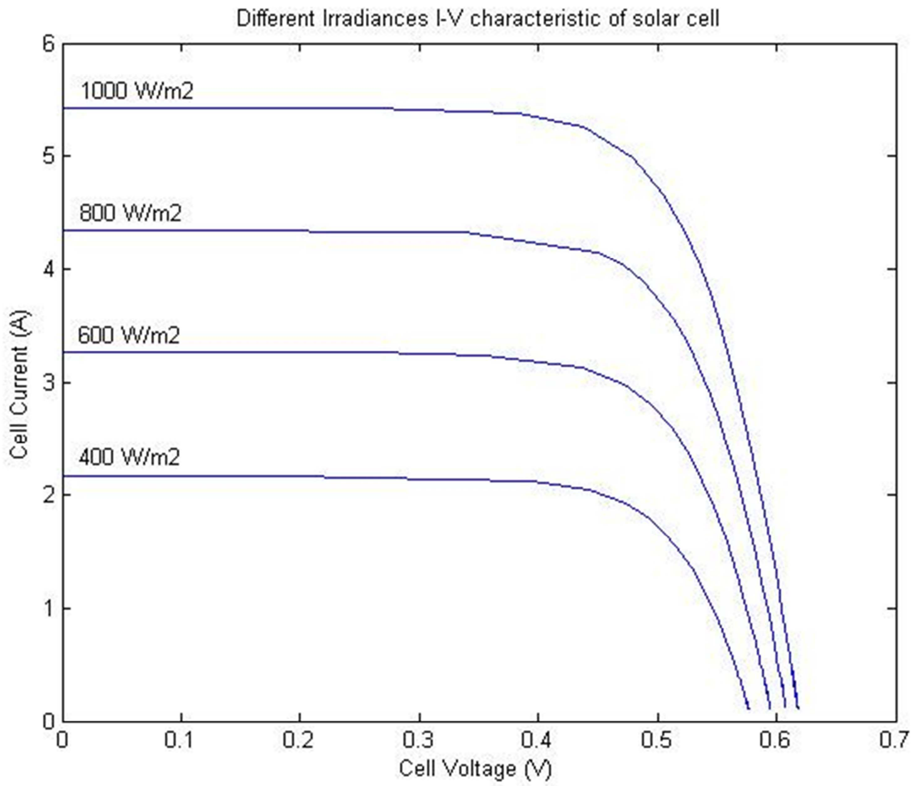


Figure 34. Different Irradiances I-V characteristic of the cell

And in the figure 35, it is changing with the temperature. The higher the temperature is, the characteristics of the cell are lower. The best moments are when the cell is acting with a 25 ºC temperature.

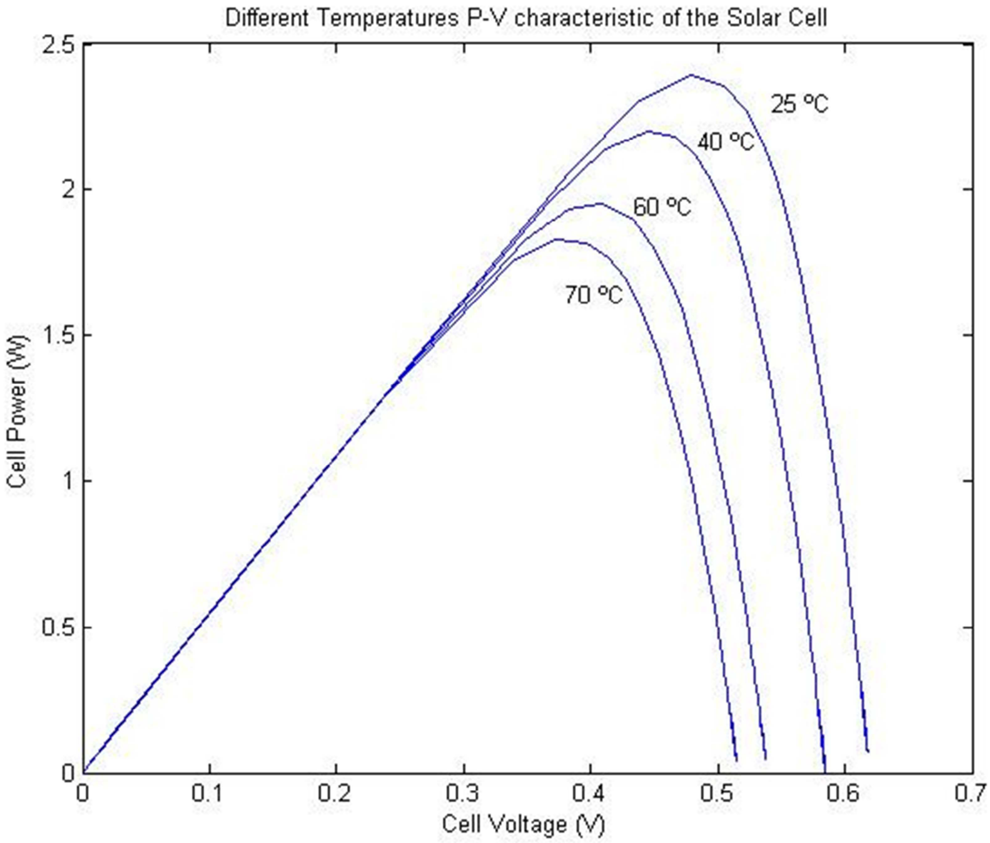


Figure 35. Different Temperatures P-V characteristic of the cell

So, as seen in the theoretical part when the irradiance is decreasing, the current also decreases. And, when the temperature increases, the voltage decreases. This conclusion can be seen in the graphics and also in the equations.

In the equation 3.7, if the temperature is constant and the irradiance is lower than 1000, then the Isc gets lower, as it can be seen ($Isc(g, Tc) = Isc * \frac{G}{1000} + \cdots$).

In the equation 3.8, if the irradiance is constant and the temperature is getting higher, the difference between Tc-Tamb is multiplied by the constant βc that is negative, then the Voc (g,Tc) decreases.

After studying the function of the cell, the next point will be to study the panel.

4.2 Results of the Solar Panel

The parameters of the panel that are in the annexes are for a 72 series cell converging into a panel. In the project when the panel and MPP and the panel with boost and MPP are studied, the panel will consist of two parallel panels of 72 cells each.

So with that, the current increases so it will be double of one panel and the voltage will be the same for two panels of 72. To see how the panel acts with two parallel panels of 72 cells, it will first be studied with the ideal parameters. The two panels' graphics are:

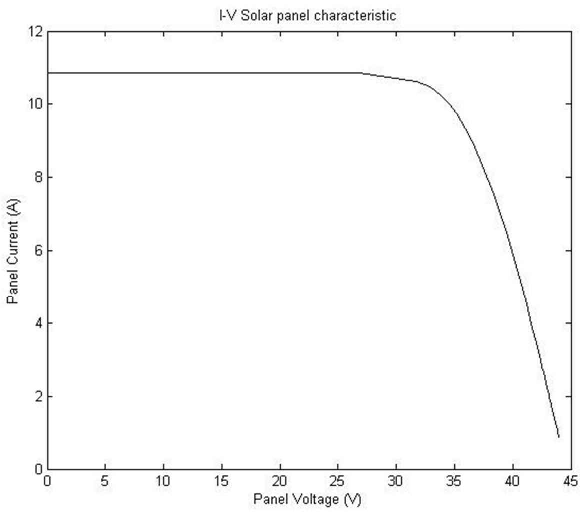


Figure 36. I-V characteristic of the panel

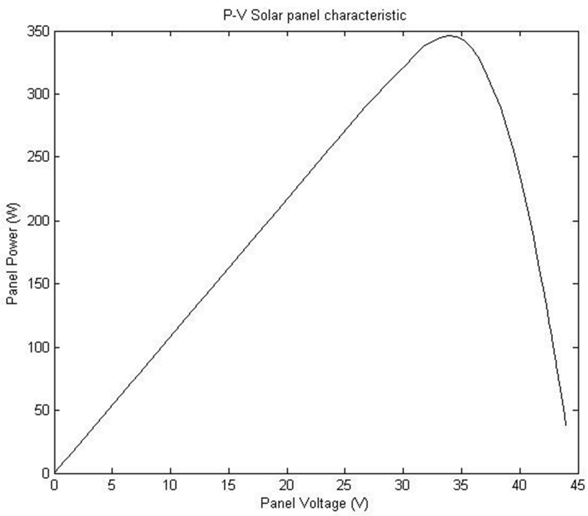


Figure 37. P-V characteristic of the panel

The current is the double as it was with one panel and the voltage is the same as one panel. What increased with this is the MPP current and power MPP.

4.3 Results of the MPP tracker

The MPP tracker implemented in this project was designed with MATLAB block in Simulink. This block allows writing in MATLAB code.

As explained before, the algorithm used is the Perturb and Observe one. To be able to understand the algorithm, first some simulations have to be done before implementing with the solar panel.

The simulations are carried out with constant values of the voltage and the current. The simulations will be done by adding a signal builder, so it's possible to change the signal and adapt them as it wants to be simulated.

In the first simulation, the voltage will remain constant with the value of 30 V. The current will be changing its value in different points of the period, from 0 to 0.3s the value of the current is 6 A, from 0.3 to 0.6s the value of the current is 9 A and from 0.6 to 1s the value of the current is 14 A. The graphic of these values is:

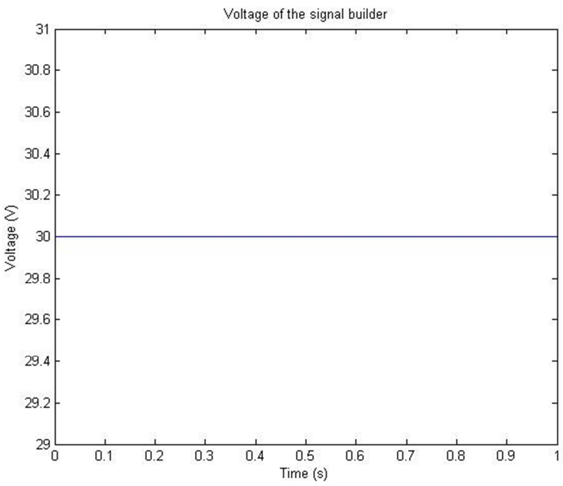


Figure 38. Constant voltage of the signal builder

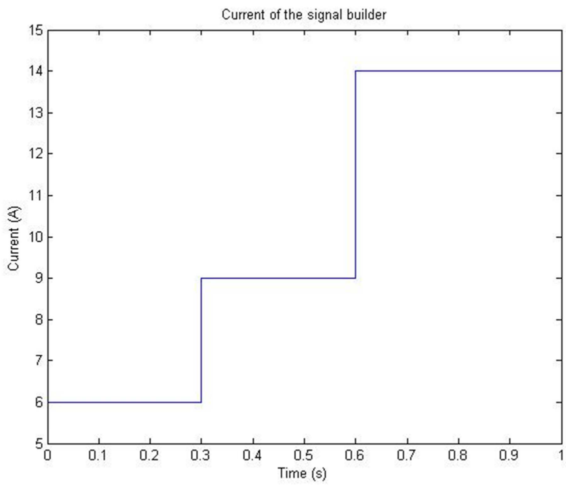


Figure 39. Variable current of the signal builder

With this simple system, the MPP should change when the current changes and remains constant until a new change comes. At the end of the MPP, a scope is implemented so it's possible to see the duty cycle signal.

The graphic that the scope, connected to the duty cycle, is going to create is the following one.

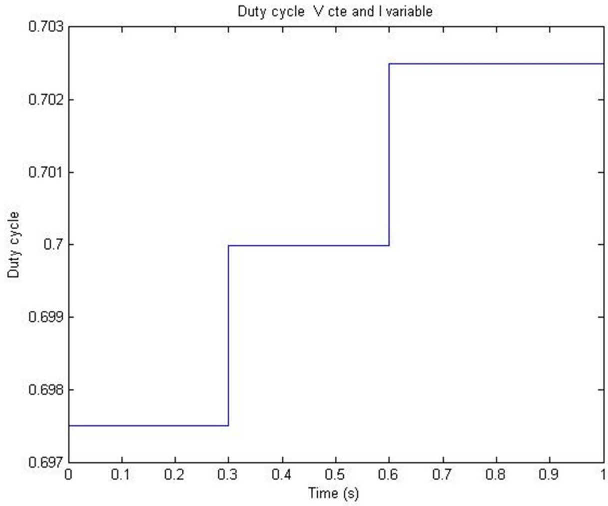
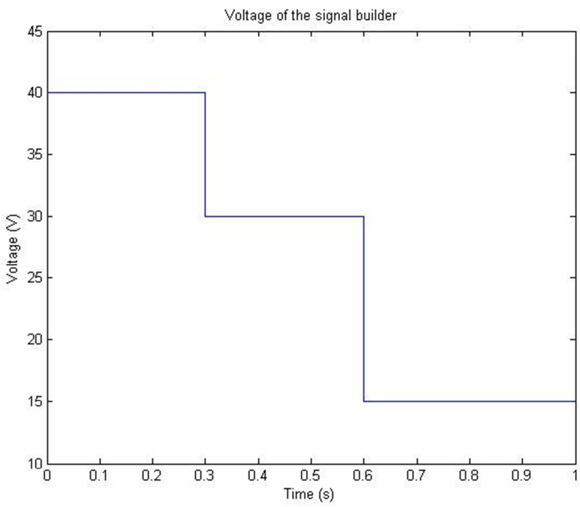


Figure 40. Duty cycle when V constant and I variable

The second simulation, the voltage is the one going to change and the current will remain constant the whole period. The value of the current will be 10 A and the voltage as the current before this simulation was doing, will change in different points of the period. The voltage will be from 0 to 0.3s 40 V, from 0.3 to 0.6s the value of the voltage is 30 V, and from 0.6 to 1s the value of the voltage is 15 V. The graphic of the value is:



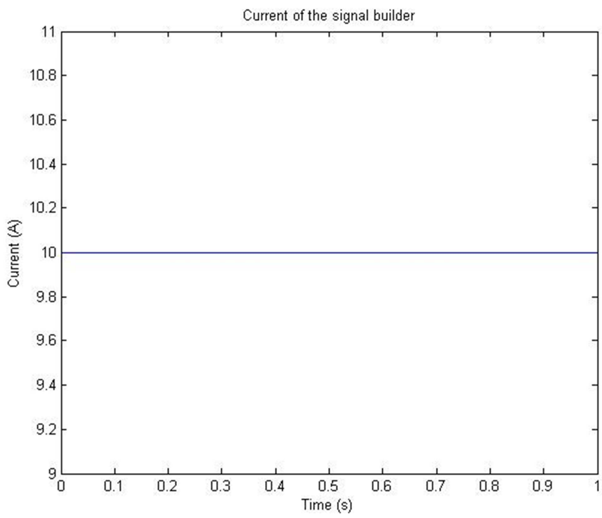


Figure 41. Variable voltage of the signal builder *Figure 42. Constant current of the signal builder*

The MPP tracker, this time should act like the other simulation by changing at the different periods where the voltage is different. The signal that the scope gives for this simulation is:

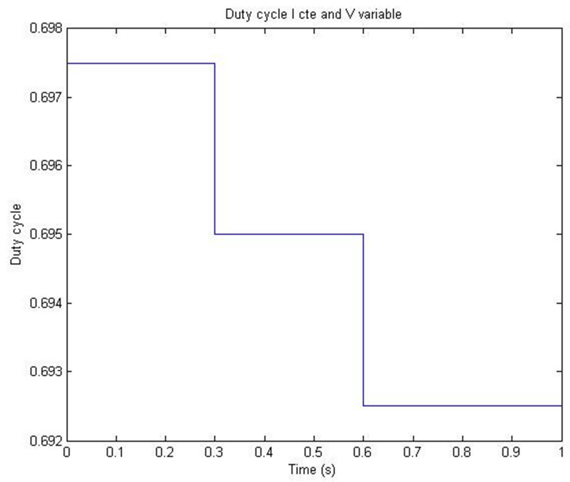


Figure 43. Duty cycle when V variable and I constant

After seeing how the MPP acts, now it can be seen how it acts when the solar panel is connected.

In this simulation, one cell is going to be connected to the MPP tracker. The irradiance value is G=718.5 W/m2, and the cell temperature is 52.5 ºC.

When the cell and the MPP are connected, the results that it will show are not adequate as it can be seen in the next figure.

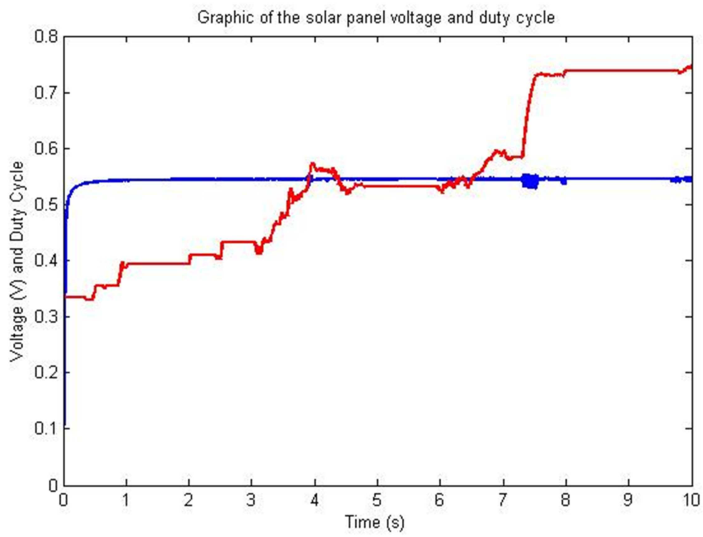


Figure 44. Graphic of the solar panel voltage and duty cycle

This figure shows the graphic of the cell voltage and the duty cycle given by this simulation in a time of 10 seconds. With this graphic it's possible to see that it is not working because when the cell has a noise in the signal, the mpp is reacting. Also with the problems of the loop that the solar cell has, it is difficult to be able to connect them and get the right results.

4.4 Results of the Boost Converter

As explained before, in chapter three, two boost converters have been designed. The first one was designed as a circuit, the second one with a MATLAB script.

Looking to the results of the two boosts designed and different problems appear.

At first, the boost converter designed as a circuit has to be studied with constant input so it's possible to know whether it is working or some values have to be changed. The circuit is going to be simulated with a constant voltage of 15 V and a constant duty cycle of 0.5. With these values in theory, if the circuit acts like a boost converter the voltage should increase until 30 V. This can be calculated by the equation 2.8.

Figure 45 will show the results of the circuit.

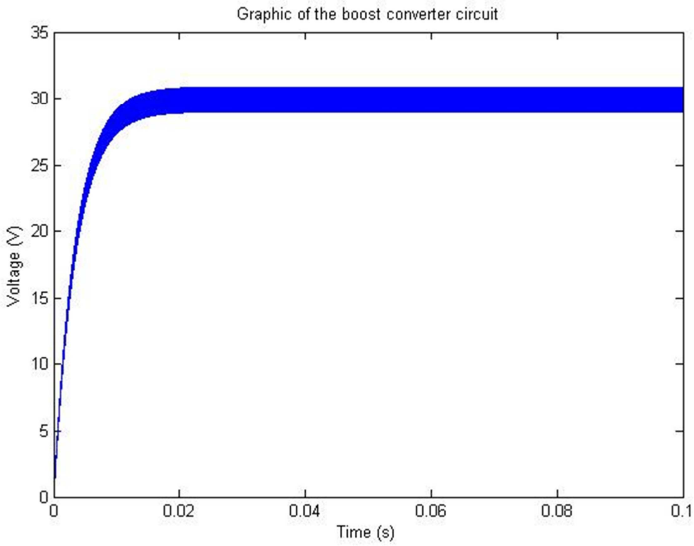


Figure 45. Graphic of the boost converter when V and duty cycle are constant values

As it can be seen, the boost increased the voltage to 30 V as expected. After this simulation the boost has to be connected to the solar panel. Due to the design of the solar panel, it has a positive port and a negative port. With this circuit it is easier to connect directly to the boost, but due to the problem that this solar panel has with a loop, it is not possible to get results from it. Although, it is possible to simulate the circuit if the loop is hidden. To do that a transfer function like $\frac{1}{0{,}0001s+1}$ is needed.

With this block, the loop is not going to appear and it is possible to simulate the circuit. The results that the boost shows don't make sense. The voltage of the solar panel is not the one it should be so at the end, the boost doesn't work as it should be.

This circuit can only be simulated with this panel by connecting a resistor to the panel. The panel with the resistor will generate a constant voltage and current and with the controlled voltage source block in Simulink, the voltage is converted to a signal that can be connected with this boost. The results that this circuit gives are normal and expected. The boost is increasing the voltage and then it will remain constant at a certain value that will be controlled by the duty cycle.

The simulation is carried out with a 1.5 Ohm resistor connected to the solar panel. The voltage that the panel will give is 16.29 V and a constant duty cycle is connected to the boost with the value of 0.5.

These values can be seen in the following graphics.

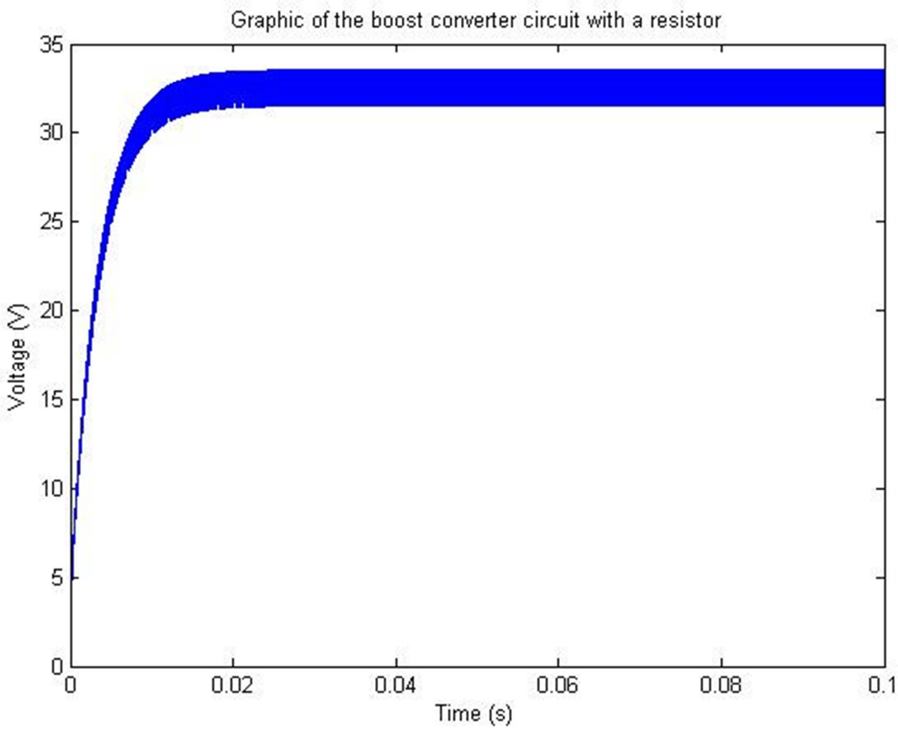


Figure 46. Graphic of the boost converter when PV connected with a resistor

So it is possible to see that the voltage has increased from 16.29 V to the values in between 31.5 and 33.5 V.

The second boost converter, the one implemented with a MATLAB script, has to be studied too as the first one. By connecting constant values to the boost, it will be possible to see the behavior of the boost converter. To this boost converter a voltage of 15 V and duty cycle of 0.5 have been connected to carry out this simulation. The voltage that it should have is 30 V.

The next figure will show the behavior of the second boost converter connected with constant values of voltage and duty cycle.

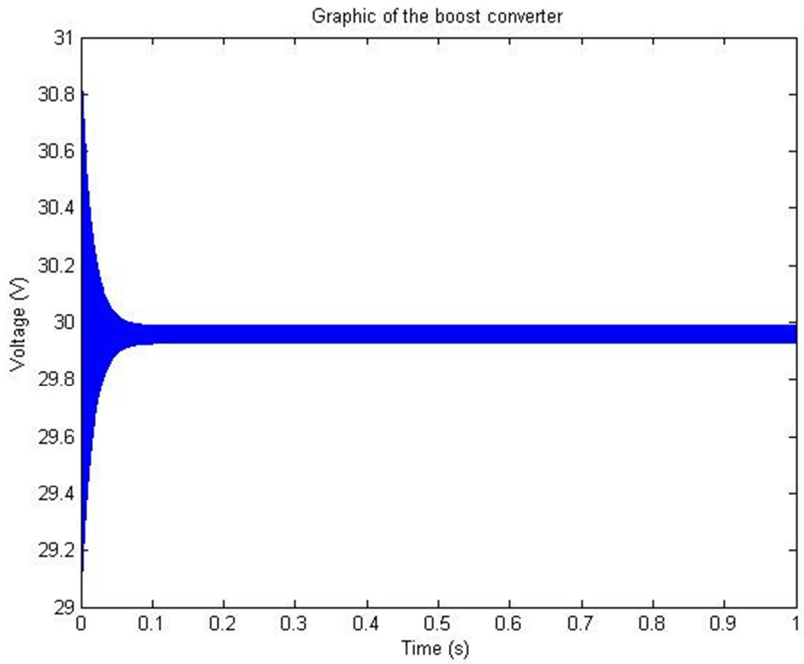


Figure 47. Graphic of the second boost when V and duty cycle are constant values

As it can be seen in figure 47, the voltage that this boost converter gives is 30 V as expected.

After studying the boost converter with constant values, the solar panel will be connected. By connecting the solar panel it will be possible to test out the behavior of this boost versus a photovoltaic system.

The solar panel will show the voltage of it. First, the voltage will increase and until a certain point, it will remain constant. The duty cycle will be constant with a value of 0.5. With these values, the boost will have to increase the voltage of the solar panel all the way until it becomes constant and it will be possible to see the final boost result.

The next figures will show the graphics of the boost converter connected with the solar panel.

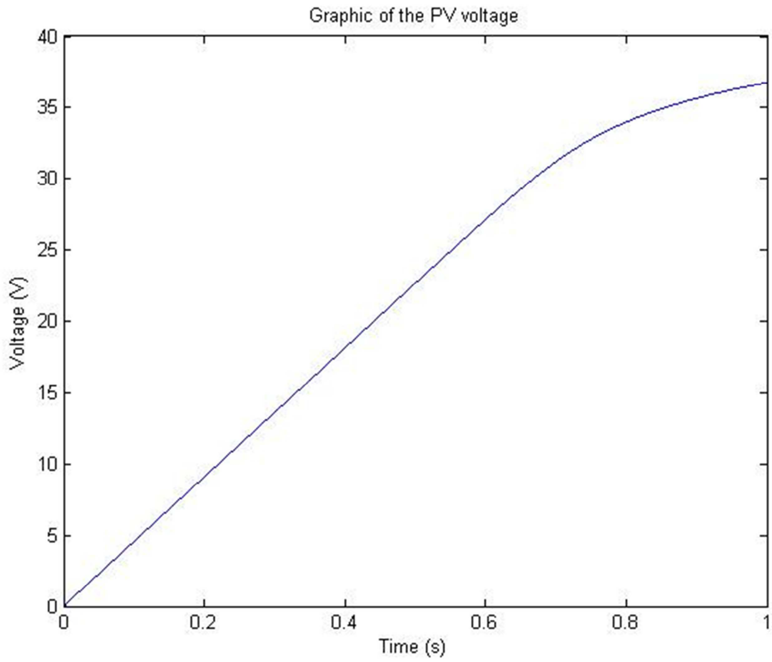


Figure 48. Voltage of the PV connected to the boost

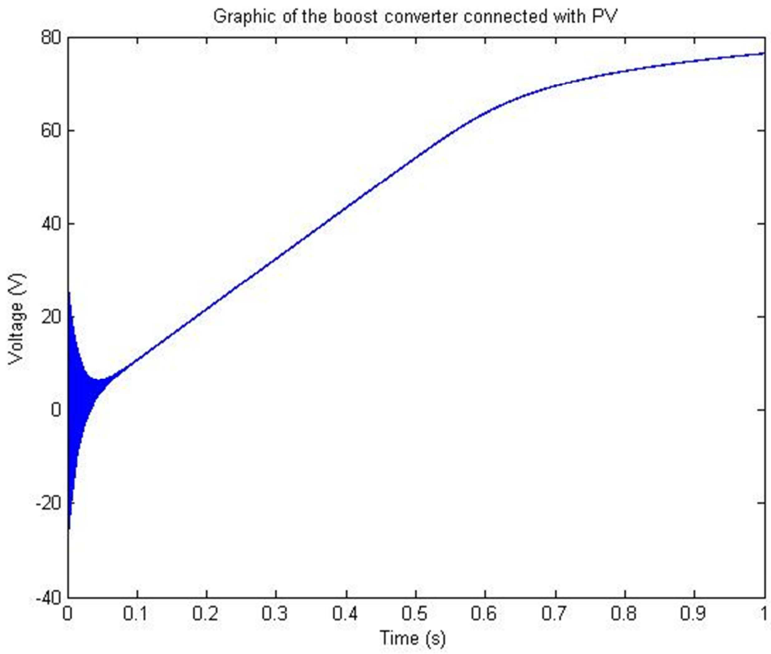


Figure 49. Boost Voltage when the solar panel is connected

As the figure shows, the boost converter was increasing the voltage of the solar panel all the time until the voltage remains constant in the solar panel, in that moment the boost converter stops increasing and remain constant too.

The last step is to connect all the three parts of the project, the solar panel, the MPP tracker, and the boost converter. In this step, only the irradiance and the temperature will remain constant. The voltage and current will be connected to the MPP to generate the duty cycle to obtain the maximum efficiency of the panel. This duty cycle and the solar panel voltage will be connected to the boost that will have to increase the voltage depending of the duty cycle.

These are the results that the system gives.

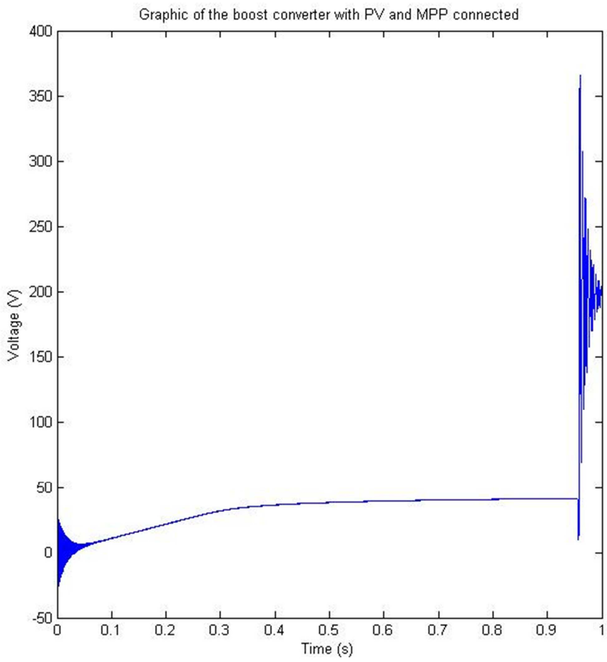


Figure 50. Boost voltage when MPP and PV connected

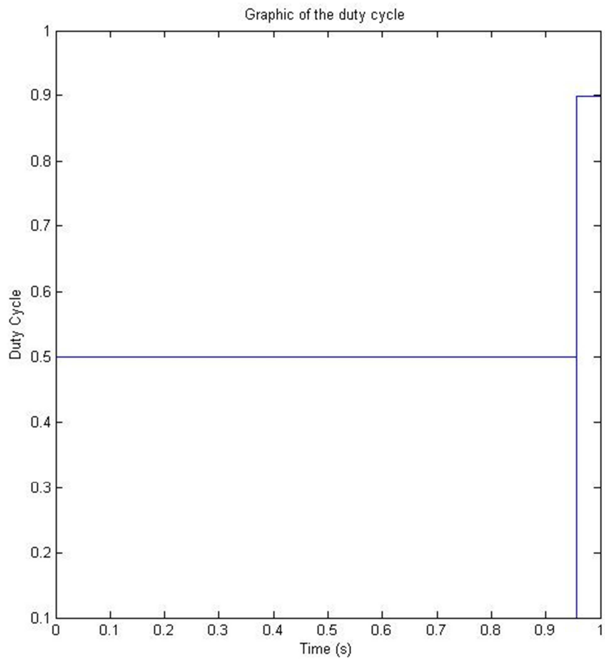


Figure 51. Duty cycle of Boost-MPP-PV system

The results obtained in this system are not good. The MPP doesn't move, but rather it stays in 0.5, so the duty cycle that is giving to the boost converter is just a normal value but not the optimal one.

Conclusion

5.1 Conclusion

Through the study and development of this photovoltaic system, I gained a good knowledge of the solar energy and its components.

Not only was knowledge gained about solar energy, but also in programming skills through the use of MATLAB/SIMULINK. At first, it's a complex program due to the programming skills required, but then it is a really useful and powerful tool for engineers to simulate all kinds of systems.

The difficult phases of the project have made me work harder to ultimately get a SIMULINK working model. There were difficult parts of the process that were not easy to solve. For example, there was a problem with the solar cell loop that was generated by the solar cell characteristics. With this problem that the cell has, there was not much practical information about how to solve it.

The solar energy is relatively new and there is just general information about it. It is a really good energy with a lot of areas where it can be improved. This could be the energy of the future and can be installed everywhere. For that, many studies have to be carried out to improve this energy that will be needed in the future.

Future work

6.1 Future work

Due to the time constraints, a few parts of the project couldn't be finished. The model needs small parts to be improved.

The solar panel can be modified to improve its behavior. After spending a lot of time doing and designing the solar cell, at the end the cell only depends on the irradiance, cell temperature, and the characteristics of the cell. There are not many projects where that can be seen. The only improvement in this part would be to add a block to remove the loop. The loop can be solved too by modeling a cell with MATLAB code so the Newton-Raphson method can be implemented easier.

Focusing on the boost converter, another control can be implemented so the voltage at the output of the boost can be fixed like the photovoltaic systems have.

The next part of the project was to feed the current converter on the inverter to the grid. To carry this out, a block in Simulink can be implemented to act like an inverter. That block is called Universal Bridge. With this block, a buck-boost converter can be made. Apart from the inverter, the synchronization control to be able to feed the system to the grid had to be designed

References

7.1 References

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Annexes

Shell Solar

Shell PowerMax™ solar modules for grid-connected markets*

1st edition 2004

General

Shell PowerMax™ is a new range of dependable, high performance solar products – with designs created specifically for grid-connected applications.

Shell PowerMax™ Ultra 175-PC and 165-PC products contain 72 series connected 125mm x 125mm mono-crystalline solar cells, which can generate a peak power of 175 and 165 watts at 35.4 and 35V respectively.

Qualifications and Certificates

The Shell PowerMax™ Ultra 175-PC and 165-PC products meet the following requirements:

- **IEC 61215**
- **UL - Listing 1703**

All Shell Solar modules are produced in ISO 9001 certified factories.

Limited Warranties

- **Peak Power for 25 years**
- **Product workmanship 2 years**

***See Shell Solar Limited Warranty for PV-Modules**

*North America only

Shell PowerMax™ Ultra 175-PC/165-PC

ELECTRICAL EQUIPMENT,
CHECK WITH YOUR INSTALLER

Due to continuous research and product improvement, the specifications in this Product Brochure are subject to change without notice. Specifications can vary slightly. For installation and operation instructions, please see the applicable manuals. No rights can be derived from this Product Brochure and Shell Solar assumes no liability whatsoever connected to or resulting from the use of any information contained herein.

References in this Product Brochure to 'Shell Solar' are to companies and other organizational entities within the Royal Dutch/Shell Group of Companies that are engaged in the photovoltaic solar energy business. Shell Solar has its principal office in Amsterdam, The Netherlands.

The Shell PowerMax™ advantage

Exceptional Performance

- **High efficiency crystalline silicon cell technology; enhanced by TOPS™ and new silicon nitride anti-reflection coatings.**
- **One of the industry's leading energy yields in a wide variety of climates.**
- **Improved performance coefficients result in higher PTC ratings.**
- **Products rated on fully stabilized initial power so you get the power you pay for.**

Proven Reliability

- **Module design proven over 30 years of field operations with field failure rates less than 0.1%.**
- **Extended limited power warranties backed by a company you can trust.**
- **IEC 61215 and UL 1703 certifications.**

Safety by Design

- **Suitable for high snow and wind loads.**
- **UL fire safety class C.**

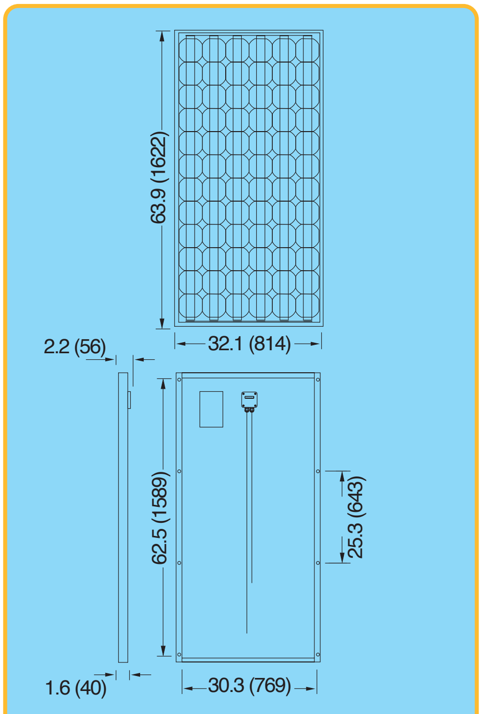
Easy to Install

- **Pre-assembled cables and Multi-Contact® plugs.**
- **12 mounting holes per product; 4 grounding holes.**
- **20A series fuse rating**

Shell PowerMax™ Ultra 175-PC/165-PC

Mechanical Specifications

A torsion and corrosion-resistant anodized aluminum frame ensures dependable performance, even under harsh weather conditions. Pre-drilled mounting holes are provided for ease of installation.



Outside dimensions (in)	63.9 x 32.1
Thickness (inc. junction box) (in)	2.2
Thickness (exc. junction box) (in)	1.6
Weight (lbs)	40
Junction box type	ProCharger™ IP54
Cable length – male /+ female (in)	51/39
Cable cross-section (AWG)	12

For ease of installation the junction box includes pre-mounted male and female cables and Multi-Contact® plugs. The junction box allows for easy field replacement of diodes and cable assemblies.

Electrical Characteristics

Data at Standard Test Conditions (STC)

STC: irradiance level 1000W/m², spectrum AM 1.5 and cell temperature 25°C

	Shell PowerMax™	Ultra165-PC	Ultra 175-PC
Rated power	P_r	165W	175W
Peak power	P_{mpp}*	165W	175W
Module efficiency	η	12.5%	13.3%
Maximum system voltage	V_{sys}	600V	600V
Peak power voltage	V_{mpp}	35.0V	35.4V
Peak power current	I_{mpp}	4.72A	4.95A
Open circuit voltage	V_{oc}	44.5V	44.6V
Short circuit current	I_{sc}	5.40A	5.43A
Series fuse rating	I_{fuse}	20A	20A
Minimum peak power	$P_{mpp\ min}$	156.75W	166.25W
Tolerance on peak power	%	+/- 5	+/- 5

*The abbreviation 'mpp' stands for Maximum Power Point.

Typical data at Nominal Operating Cell Temperature (NOCT) conditions

NOCT: irradiance level 800W/m², spectrum AM 1.5 , wind velocity 1m/s, T_{amb} 20°C

Temperature	T_{noct}	45.5°C	45.5°C
Peak power	P_{mpp}	120W	127W
Peak power voltage	V_{mpp}	31.6V	32.2V
Open circuit voltage	V_{oc}	40.0V	40.4V
Short circuit current	I_{sc}	4.20A	4.25A

Temperature coefficients

$\alpha\ P_{mpp}$	%/°C	-0.43	-0.43
$\alpha\ V_{mpp}$	mV/°C	-145	-145
$\alpha\ I_{sc}$	mA/°C	0.8	0.8
$\alpha\ V_{oc}$	mV/°C	-145	-145

Typical data at low irradiance

The relative reduction of module efficiency at an irradiance of 200W/m² in relation to 1000W/m² both at 25°C cell temperature and AM 1.5 spectrum is 8%.

For further information on all Shell Solar products contact:

Shell Solar
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805•482•6800 Fax 805•388•6395
www.shell.com/solar

V2/Power-Max/Grid-Connected/US/07/04