



Fast response MPPT switched charger for the Técnico Solar Boat

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Introduction to the Research in
Electrical and Computer Engineering

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Abstract

Resumo do trabalho

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Acronyms

| | |
|-------------|-----------------------------------|
| TSB | Técnico Solar Boat |
| MPPT | Maximum Power Point Tracker |
| MPP | Maximum Power Point |
| PCB | Printed Circuit Board |
| CAN | Controller Area Network |
| PV | Photovoltaic |
| SG01 | São Guabriel 01 |
| BMS | Battery Management System |
| STC | Standard Testing Conditions |
| FPGA | Field Programmable Gate Arrays |
| MCU | Microcontroller Unit |
| CPLD | Complex Programmable Logic Device |
| DSP | Digital Signal Processor |
| IC | Integrated Circuit |
| HDL | Hardware Description Language |
| GUI | Graphical User Interface |

1 Introduction

1.1 Motivation

As the world is reaching a point where pollution is taking over the news, solar panels are one of the main solutions available. In 2024, 7% of the energy produced in the world comes from solar panels, and in Portugal this number rises to 14.5% [1]. Solar energy still plays a miniscule role that it is listed behind the other sources of energy in terms of the contribution for meeting the world's energy demand. However as the years go by, solar energy is becoming more and more relevant, with the cost of solar panels dropping significantly in the last decade.

In comparison to other forms of green energy, Photovoltaic energy is relevant due to its availability, simplicity, lower maintenance, environmental friendliness, reliability and many other benefits. More recently, is becoming more relevant in the automotive industry, with solar-powered cars, boats and robots. The CO₂ emissions of automotive sector is one of the main contributors to global warming. More than 30% of total CO₂ emissions in the EU in 2018 came from transport sector, with 3% of global pollution coming from the maritime sector alone [2] [3]. And that is where the Técnico Solar Boat (TSB) project fits in.

In 2015, TSB was created with the goal of designing and building a solar-powered boat to compete in international competitions. Since then, the project has growth and built several vessels. It begins with the construction of the first solar prototype, São Rafael 01 which had a lot of room to improvement and so São Rafael 02 and 03 were built. Then the team decided to approach the hydrogen energy and autonomous driving, and therefore São Miguel 01 and 02 and São Pedro 01 were built. More recently, a vessel were built with the purpose of combing all the technologies used before and were named São Guabriel 01 (SG01).

All of these prototypes used solar energy to maximize their range and efficiency. In the first years the energy produced was not much and the all system were commercial available. However, as a team of students that want to push the limits of solar power boats and the overall technology, the "built your self" philosophy was presented all over the years. And that is why we started building our own solar panels in 2020 for São Rafael 03. As the years went by, a lot of other systems were designed and built in house however there is still one system that is yet to be developed, the Maximum Power Point Tracker (MPPT).

The MPPT constitutes an essential subsystem of photovoltaic energy systems, designed to optimize

energy extraction from solar panels by maintaining continuous operation at the Maximum Power Point (MPP). This optimization is achieved through dynamic adjustment of the electrical operating parameters of the photovoltaic modules or arrays.

1.2 Objectives

This project aims to design and implement a MPPT system for solar panels used in the TSB project. The MPPT will convert the energy produced by the solar panel as efficiently as possible with the use of a quality DC-DC converter and the implementation of MPP tracking algorithms.

So the main objectives of this project are:

- Study and understand the operation of solar panels and MPPT techniques;
- Chose the most suitable DC-DC topology for the system;
- Design and simulation of the hardware and software.
- Implement a fast response and efficient control algorithm;
- Implement the system in hardware and develop a Printed Circuit Board (PCB).
- Test and validate the performance of the PCB.
- Ensure the safety and reliability of the MPPT for its integration in the TSB project.
- Provide data to the user about the performance of the solar panel and of MPPT through a Controller Area Network (CAN) communication interface.

By achieving these objectives, the project will contribute for a better control of the system, maximizing the data received from the solar panels to later improve the energy efficiency of the MPPT or even take conclusions about the manufacture quality of the solar panels build by TSB project. A cheap, efficient and versatile MPPT will also mean future savings to the team, since it could be used in a variety of vessels.

1.3 Outline

This document is organized into five main chapters.

Chapter 1 introduces the context of the work, presenting the motivation behind the development of a Maximum Power Point Tracker for the Técnico Solar Boat project. The objectives of the project are defined, and the scope of the proposed solution is established.

Chapter 2 presents the state-of-the-art related to photovoltaic energy systems and MPPT technology. It reviews the operating principles of solar panels, solar energy production, and the most relevant MPPT algorithms. Additionally, different DC–DC converter topologies, switching circuits, battery charging techniques, processing units, sensing methods, and both commercial and integrated MPPT solutions are analyzed and compared.

Chapter 3 describes the proposed solution for the MPPT system. The overall system architecture is presented, followed by a summary of the technical requirements. The adopted design approach is detailed, including converter selection, control strategy, simulation methodology, and experimental validation plan.

Chapter 4 presents the preliminary work developed so far, including initial simulations and early design results that support the feasibility of the proposed solution.

Finally, Chapter 5 outlines the planning and scheduling of the project, presenting the development timeline and key milestones required to achieve the defined objectives.

2

State-of-the-Art

In this chapter is explained the main state-of-art concepts about the engineering behind a Maximum Power Point Tracker (MPPT). More specifically explains this key concepts: what is a solar panel, how to convert there energy to useful energy, MPPT algorithms, dc-dc types and battery charging techniques.

2.1 Solar Panels

Solar panels, also known as Photovoltaic (PV) panels are devices that convert sunlight into electrical energy. Each solar panel is made of multiple solar cells connected in series and/or parallel. As in electrical circuits, the connection type will affect the voltage and current output of the panel. More specifically, series increases voltage and parallel increases current.

Each cell is made of semiconductor materials, usually silicon. This semiconductor is doped with phosphorus, a group V element, to create a negative type layer. On the other side, a layer is doped with boron, a group III element, to create a positive type layer. This creates a p-n junction, which is essential for the photovoltaic effect.



Figure 2.1: Principle of operation of a solar panel

When sunlight hits the solar cell, photons energy are absorbed by the semiconductor material. This energy excites electrons, allowing them to escape their atomic bonds and create electron hole pairs. The electric field at the p-n junction drives these free electrons towards the n-type layer and holes towards the p-type layer, generating a flow of electric current when the cell is connected to an external circuit [4].

This energy produces a direct current (DC) voltage and current output, which are not constant. Both voltage and current are codependent, so if one suffers variation the other will too. This variation is not

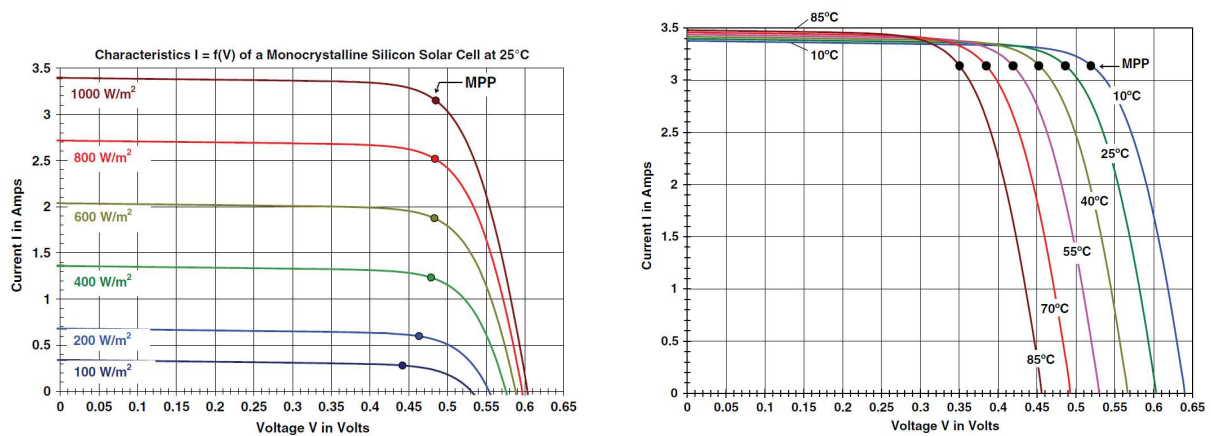
linear and can be represented in an I-V curve, as in Figure 2.2. Also, the power output suffers variations, which can be represented in a P-V curve.



Figure 2.2: I-V and P-V curves of a solar panel [4]

The efficiency of a solar panel depends on various factors, including the quality of the materials used, the design of the cells, and environmental conditions such as temperature and irradiance.

As you can see in Figure 2.3a, the variation of the irradiance change the I-V and P-V curve of the solar panel. The increase of irradiance produces more power by mainly increasing the current output of the panel. On the other hand, the temperature has an opposite effect, Figure 2.3b. The increase of temperature produces a decrease in power output, mainly by decreasing the voltage output of the panel.



(a) I-V curves of a solar panel with cell temperature of 25 °C and variable Irradiance

(b) I-V curves of a solar panel with $1\text{ KW}/\text{m}^2$ of irradiance and variable temperature

Figure 2.3: I-V curves under different conditions. Left: irradiance variation. Right: temperature variation [4].

Both environmental conditions have a meaningful impact on the Maximum Power Point (MPP) of the solar panel and there for on the power output of the system. So, if we want to maximize the power

extracted by the solar panels, we can not use a classic power converter like a buck converter since neither the current nor the voltage are constant. Instead, we need to use a MPPT.

2.2 Solar energy production

As discussed in the previous section, solar panels produce a variable DC voltage and current output which depends on environmental conditions. To extract as much energy as possible, commonly a MPPT are used.

A Maximum Power Point Tracker (MPPT) is a device that is used to optimize the power output from solar panels by continuously tracking and adjusting the operation point of the panels to ensure they operate at their MPP.

To achieve its goal, a MPPT is usually composed by an DC-DC converter, a microcontroller and some sensors (Figure 2.4). The sensors are used to measure the input/output variables of the control system (typically voltage and current). The information acquired by these sensors are processed by the microcontroller, which runs an algorithm to determine if the MPP was reached or how to act on the system towards the MPP. In the second case, the microcontroller sends control signals to the DC-DC converter to adjust its operation accordingly. Usually a PWM signal to control transistors.

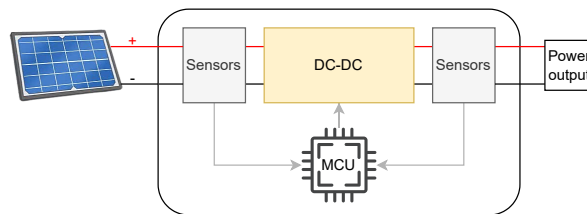


Figure 2.4: Top view of a basic MPPT system

Then, the output can be connected to different types of loads, like batteries, DC loads or inverters to convert the energy to alternative current and inject it in the grid (usually in these cases the MPPT is built-in with the inverter).

2.3 MPPT Algorithms

There are plenty of MPPT algorithms, each one with its own advantages and disadvantages. The choice of the algorithm will depend on the specific application, the desired performance, and the available resources.

In this work the aim is to achieve the max efficiency possible of a solar panel installed in a moving boat, which will produce an i-v curve variation due to the quick changes in irradiance caused by changes

of inclination and clouds, and also temperature changes due to waves and wind. So the tracking speed and accuracy are the most important factors to consider to be able to follow the MPP in these conditions.

With that in mind, some of the most relevant algorithms will be briefly explained, so we can choose the most suitable one for this project.

2.3.1 Constant Voltage

This is the simplest and the most inefficient method. It works by fixing a reference voltage to operate the solar panel. The reference voltage is the input of a PID controller that will adjust the duty cycle of the DC-DC converter to maintain the solar panel voltage at this reference value.

There are some well known variations of this method that improve the performance by adjusting the reference voltage to a fraction of the open circuit voltage of the solar panel (usually between 71% and 78%), equation 2.1 [5], . This open circuit voltage can be measured periodically by disconnecting the solar panel from the load for a short period of time. This way, the reference voltage will be more accurate and the efficiency will increase.

$$V_{ref} = k \cdot V_{oc} \quad (2.1)$$

Other variation is based on the short circuit current of the solar panel, setting the reference voltage to a fraction of this value [6].

Although both methods are simple and cost-effective, they are inherently inefficient due to the necessity of interrupting energy production during measurement phases. However, alternative implementations address this limitation through proxy measurement techniques employing dummy cells or diodes, whose physical properties closely approximate those of standard solar cells, thereby enabling continuous power generation during measurement acquisition [5] [7].

2.3.2 Perturb and Observe (P&O)

The Perturb and observe method is widely used in commercial products and is the basics of many advanced algorithms. Its popularity lies on its simplicity, low cost and ease of implementation.

Its name says exactly what it does, it perturbs the voltage of an PV array and observes the resulting effect on the power output. This means that if the voltage was increased and the power output also increased, the algorithm is working in the direction to the MPP, so it will continue increasing the voltage. In the opposite case, if the power output decreased, the algorithm is working away from the MPP, so it will reverse the direction of the perturbation [8]. Figure 2.5 shows an flow chart of the algorithm.

The biggest drawback of this algorithm is that it oscillates around the MPP, which produces power losses. This oscillation can be reduced by decreasing the step size of the perturbation, but this will

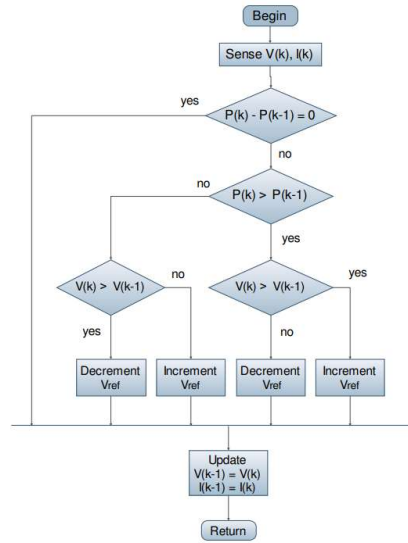


Figure 2.5: Flow chart of the classic version of Perturb and Observe algorithm [9]

also reduce the tracking speed of the algorithm. So there is a trade-off between tracking speed and accuracy [6].

To mitigate this issue an adaptive step size can be used, where the step size is larger when the MPP is far away and smaller when it is close. This way, the tracking speed is maximized while minimizing the oscillations around the MPP. This can be achieved by measuring the power and voltage and calculating the p-v curve slope ($\frac{\Delta P}{\Delta V}$). In the MPP this values must be zero, so the step size can be reduced. This variation of the algorithm is called "differential power-perturb and Observe (dP-P&O)".

Another well known issue of P&O is that it can get confused in rapidly changing environmental conditions, like fast irradiance changes caused by clouds. In this case, the algorithm can misinterpret the power change caused by the environmental variation as a result of its own perturbation, leading it to move away from the MPP instead of towards it. For example, if the perturbation was in the wrong direction but the irradiance increased, the power output would increase and the algorithm would continue perturbing in the wrong direction.

To solve this issue, a new condition must be added to the algorithm to take into account two consecutive measures of ΔP and ΔV . This way, if the sign of both ΔP are different, it means that the power change was caused by an environmental variation and not by the perturbation, so the algorithm must not change the voltage. This variation is called "two point algorithms" or "improved P&O" [10]. Table 2.1 shows the 16 possible cases of the truth table of this algorithm with an extra column showing the changes caused by the perturbation or by the environment. **Por acabar e rever (não sei se gosto muito desta tabela e explicação)**

To address this limitation, an additional condition is incorporated into the algorithm that evaluates two consecutive measurements of ΔP and ΔV . Specifically, when the signs of consecutive ΔP measure-

ments differ, this indicates that the observed power variation results from environmental disturbances rather than the algorithm's perturbation; consequently, the voltage adjustment is suppressed. This refined variant is designated the two-point algorithm or improved P&O method [10]. Table 2.1 presents the sixteen distinct operational states encompassed by this algorithm's truth table, with an additional column delineating whether observed changes originate from algorithm perturbation or environmental variation.

Table 2.1: Truth table for the Improved P&O algorithm (extended with one extra column) [10].

| $\Delta V(k-1)$ | $\Delta P(k-1)$ | $\Delta V(k)$ | $\Delta P(k)$ | $\Delta V(k+1)$ | Changes caused by: |
|-----------------|-----------------|---------------|---------------|-----------------|--------------------|
| — | — | — | — | — | |
| — | — | — | + | + | |
| — | — | + | — | — | |
| — | — | + | + | + | |
| — | + | — | — | — | |
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| + | + | + | + | + | |

There are some more relevant variations of this algorithm that will not be explained here, like the Variable Step Size P&O (VSS-P&O), the three point P&O, a-factor P&O and others.

Posso explicar o three point algorithm e o a-factor aqui no futuro se achar relevante.

2.3.3 Incremental Conductance (IncCond)

The Incremental Conductance algorithm is another widely used MPPT method due to its accuracy and ability to track the MPP under rapidly changing environmental conditions.

This algorithm lies on the fact that at the MPP the derivative of power with respect to voltage is zero. By knowing the output voltage and current of the solar panel, the algorithm can calculate the conductance and the incremental conductance.

The following formulas (Equation 2.3) show the equation which this algorithm is based on.

$$\frac{dP}{dV} = \frac{d(V \cdot I)}{dV} = I + V \frac{dI}{dV} \rightarrow \frac{1}{V} \times \frac{dP}{dV} = \frac{I}{V} + \frac{dI}{dV} \quad (2.2)$$

So at the MPP point, the slope of the p-v curve is zero, which means that the negative of the conductance is equal to the incremental conductance (Figure 2.6b). So the algorithm compares these two

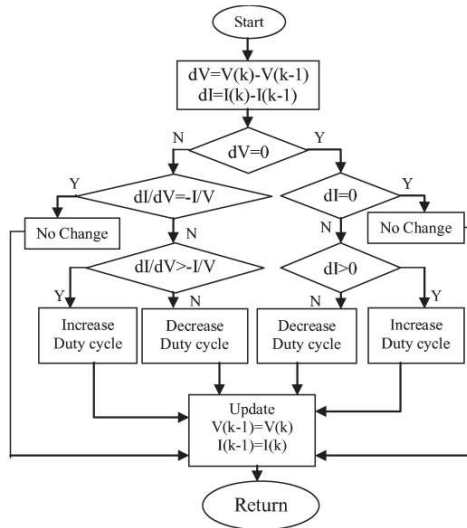
values to determine if the operating point is at, to the left or to the right of the MPP [6]:

$$\left. \begin{aligned} \frac{dP}{dV} = 0 &\iff \frac{dI}{dV} = -\frac{I}{V} && \text{at MPP} \\ \frac{dP}{dV} > 0 &\iff \frac{dI}{dV} > -\frac{I}{V} && \text{(left of MPP)} \\ \frac{dP}{dV} < 0 &\iff \frac{dI}{dV} < -\frac{I}{V} && \text{(right of MPP)} \end{aligned} \right\} \quad (2.3)$$

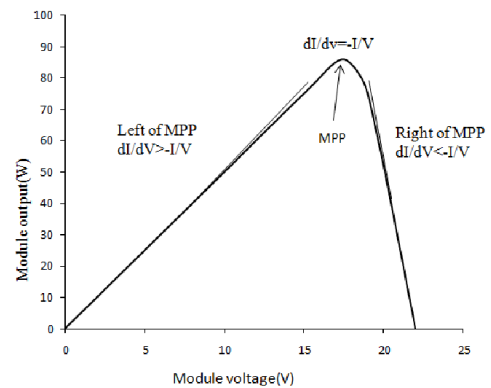
Base on this conditions the algorithm adjust it's operating point (increasing or decreasing the voltage) using a variable step size based of the deviation of the current and voltage ($\frac{dI}{dV}$) and the measured current divided by voltage ($\frac{I}{V}$), Figure 2.6a.

Comparative analysis demonstrates that the IncCond algorithm exhibits superior efficiency relative to the Perturb and Observe method. This outcome is expected, as the Incremental Conductance technique was developed specifically to address the limitations inherent in the P&O approach. For example the IncCond method eliminates the oscillation problem around the MPP that is characteristic of P&O by directly comparing the instantaneous conductance (I/V) with the incremental conductance (dI/dV), rather than relying on power changes alone. Additionally, IncCond demonstrates superior performance under rapidly changing environmental conditions, such as sudden irradiance variations caused by cloud cover, since it uses derivative-based information that is less sensitive to transient disturbances.

Experimental studies conducted in 2006 further corroborate these findings, demonstrating that efficiencies of up to 95% can be achieved when employing a buck converter [11].



(a) Flowchart of the IncCond method with direct control [12].



(b) IncCond method principle.

Figure 2.6

2.3.4 Look Up Table (LUT)

The Look Up Table method is a simple and fast MPPT algorithm that relies on pre-calculated/measured data to determine the optimal operating point of a solar panel.

The LUT table contains several entries organized by voltage and current. Each of these entries contains the optimal duty cycle of the DC-DC converter, that are pre-calculated or measured for a specific voltage and current. This way, the algorithm can reach the MPP in one clock cycle by measuring the voltage and current of the solar panel, looking for the closest entry in the LUT table and applying the corresponding duty cycle to the converter.

The main advantage of this method is its speed since it can reach the MPP in one clock cycle. This makes it suitable for applications where fast tracking is required, like in this project. But the main drawback is that it is not very accurate.

To improve the accuracy the LUT table needs to be larger, which increases the required memory resources. Also, by adding the temperature and/or irradiance to the table would increase the accuracy, making it almost 100% accurate, but this would increase the size of the table exponentially, making it unfeasible for most applications.

referir a tese do Antonio

2.3.5 Fuzzy logic

tenho de ler melhor sobre este algoritmo antes de escrever algo. Não sei se é assim tão relevante e também não sei como funciona. Li num survey que foram obtidos bons resultados com ele.

<https://ieeexplore.ieee.org/document/349703>

2.4 DC-DC types

2.4.1 Non-isolated versus isolated DC-DC converters

DC-DC converters can be classified into two main categories: isolated and non-isolated converters. The main difference between these two types of converters is the presence or absence of galvanic isolation between the input and output circuits [13].

This galvanic isolation is usually achieved by using a transformer which provides electrical separation between the input and output sides of the converter. This isolation is important in applications where safety is a concern, such as in medical devices or industrial equipment, as it helps to prevent electrical shock and damage to sensitive components. In the context of solar energy systems and E-mobility, isolated converters are often used when the solar panel is connected to the grid [14], as they help to

protect against voltage spikes and other electrical disturbances or when the solar panels MPP voltage is a lot different from the battery or load voltage (typically medium voltages).

On the other hand non-isolated converters do not provide isolation between the input and the output circuits but they are generally more efficient and at lower costs.

Table 2.2: Comparison between Switching Converters and Galvanic Isolated Converters.

| Type | Switching Converters | Galvanic Isolated Converters |
|------------------------------------|----------------------|------------------------------|
| Price | Cheaper | Expensive |
| Isolation | No | Yes |
| Circuit Complexity | Low | High |
| Efficiency | High | Medium |
| Size | Compact | Large |
| Electromagnetic Interference (EMI) | High | Medium/High |
| Switching Frequency | Low/Medium | Medium |
| Thermal Management | Easier | Moderate |
| Control Complexity | Simple | Complex |

In summary, the choice between isolated and non-isolated DC-DC converters depends on the specific requirements of the application, including safety, efficiency, cost, and complexity. In many solar energy applications where the solar panel voltage is not too different from the battery or load voltage, non-isolated converters are preferred due to their higher efficiency and lower cost. So in this project, non-isolated converters will be considered. Nenhum paper que eu li fala diretamente dum caso como este. Em que os painéis são usados para alimentar uma bat de baixa tensão e que fale da opção de ser isolado ou não. Encontrei sim para veiculos de baterias de media tensão e ai já faz sentido ser isolado.

pesquisar e falar sobre Synchronous Buck, aqui fala um bocado sobre isso: <https://www.instructables.com/DIY-1kW-MPPT-Solar-Charge-Controller/>

2.4.2 Non-isolated DC-DC converters

Modern non-isolated conversion circuits generally use one of three basic topologies: buck, boost or buck-boost converters. They are 'basic' in the sense that only one switching element needed and there is no isolation between the input and output circuits. A given topology is used to obtain a specific result, such as voltage step-down, voltage step-up, or hybrid mode [15].

2.4.2.A Boost converter

The boost converter is a step-up DC-DC converter widely employed in MPPT systems, as photovoltaic panels typically operate at voltages substantially lower than the target battery or load. This topology has been extensively documented in the literature and is distinguished by its inherent simplicity, cost-effectiveness, and superior efficiency characteristics, frequently achieving conversion efficiencies exceeding 98% [16].

One downside of this topology is that it can not emulate smaller impedance than the load impedance, and therefore, it does not reach values near the short circuit current of the PV module, so it can not be used for all algorithms [17].

2.4.2.B Buck converter

The buck converter is a step-down DC-DC converter also widely used for applications where the solar panel voltage is higher than the battery or load voltage. However, in most automotive applications the area of the solar panel is limited, so the voltage is usually lower than the battery voltage, making the boost converter a more suitable choice.

Similar with the boost converter, the buck converter can not emulate smaller impedance than the load impedance, and therefore, it can not reach values near the open circuit voltage of the PV module [17].

2.4.2.C Buck-Boost converter

Buck-Boost converters are step-up and step-down DC-DC converters that can operate in both modes. This makes them more versatile than the previous two topologies, but also more complex and less efficient [16].

They are used in applications where the solar panel voltage can be both higher or lower than the battery or load voltage, also certain MPPT use it to have a wider range of operation or add versatility of the used batteries.

This type of converter has some variations. The most common variations are called the Zeta, Cuk and SEPIC converters.

The classic buck-boost and Zeta topologies have an input current always working in discontinuous conduction mode, which produces high ripple current and harmonic distortion. To solve this issue, the Cuk and SEPIC topologies are used, which have an input current working in continuous conduction mode (CCM), reducing the ripple current and harmonic distortion [17]. Also, the classic buck-boost and Zeta have an inverted output voltage referred to the input voltage. Which in most cases is undesired.

2.4.3 Comparison between Non-isolated DC-DC converters

All the non-isolated DC-DC topologies explained before have their own advantages and disadvantages. The choice of the topology will depend on the specific application, the desired performance, and the available resources. To help with this choice, Table 2.3 shows a comparison between the most relevant characteristics of each topology. In green the best advantages of each topology are highlighted.

Table 2.3: Comparison of non-isolated DC-DC topologies.

| Topology | Boost | Buck | Buck-Boost | Zeta | Cuk | SEPIC |
|--------------------------|------------|------------|--------------|---------------------|---------------------|---------------------|
| Price | Low | Low | Low | Medium | Medium | Medium |
| Isolation | No | No | No | No | No | No |
| Circuit complexity | Low | Low | Low | Medium | High | Medium |
| Efficiency | High | High | Medium | Medium | High | Medium |
| Size | Low | Low | Low | Medium | Medium | Medium |
| Type | Step-Up | Step-Down | Step-Down/Up | Step-Down/Up | Step-Down/Up | Step-Down/Up |
| Versatility | Low | Low | Medium | High | High | High |
| Inverted output | No | No | Yes | Yes | No | No |
| Input current ripple | High | Low | High | Low | Very low | Low |
| Output current ripple | Low | High | High | Very low | Low | Low |
| Energy-storage elements | 1 inductor | 1 inductor | 1 inductor | 2 inductors, 2 caps | 2 inductors, 2 caps | 2 inductors, 2 caps |
| Switch stress | No | Yes | No | Yes | Yes | Yes |
| Continuous input current | No | Yes | No | Yes | Yes | Yes |
| EMI | Low | Low | High | Medium | Medium | Medium |

2.5 Switching circuit

2.5.1 Types of transistors

falar dos tipos de transistores e como dar drive deles. BJT, Mosfet, GaN FETs, IGBT, ...

2.5.2 Switching problems

diode voltage drop (sync FETs)

Body diode current leakage.

Caso se use um transistor em vez de um diodo tem de se ter cuidado para não provocar curto circuito

2.5.3 Protection circuits

Ways to solve the problem

2.6 Battery charging techniques

Needs to be summarized. Only CC-CV is relevant.

As the demand of electronic devices and E-vehicles increased, emerge the need for efficient, compact and lightweight batteries. Among the exiting technologies lithium-ion batteries have one of the best energy-to-weight/volume ratios and, at this moment, it is the technology use in Técnico Solar Boat (TSB) batteries. But, as every other battery technology, they need to be charged properly to ensure their safety and longevity [18].

To charge these batteries properly, the MPPT algorithm can stand alone if an additional converter is

used in series. But in most cases, the MPPT and the battery charging unit are integrated in the same converter. This way, the MPPT can adjust the operating point of the solar panel to extract the maximum power while the battery charging unit ensures that the battery is charged properly.

There several Algorithms to charge lithium-ion batteries being the most relevant for this use case the Constant Current-Constant Voltage (CC-CV) method [19]. This method consists in two main phases, (Figure 2.7). In the first phase, the battery is charged with a constant current until it reaches a predefined voltage limit (usually 4.2V per cell). In the second phase, the voltage is held constant at this limit while the current gradually decreases as the battery approaches full charge. Once the current drops below a certain threshold, the charging process is terminated to prevent overcharging.

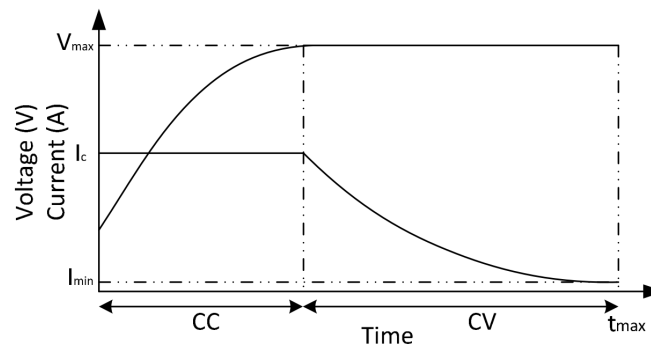


Figure 2.7: Charging profile of CC/CV [18]

Some variations of this method are relevant for other types of charges.

There is also some more advanced and high performance techniques. For example, DL-CC/CV eliminates the need for a current sensor with a positive and negative feedback loop, the BC-CC/CV adds efficiency by charging faster at the first 30% of the battery capacity and then switching to CC-CV.

There are two more complex methods that use advanced control techniques to implement CC-CV, mainly the fuzzy logic and gray predict (FL-CC/CV and GP-CC/CV). These methods can adapt the charging process based on the battery's state of charge, temperature, and other factors, potentially improving charging efficiency and battery lifespan. As downside, they required computational power.

In cases that the digital resources are limited, analog methods such as PLL-CC/CV and IPLL-CC/CV can be used. These methods use phase-locked loop (PLL) circuits to regulate the charging current and voltage, providing a simpler and more cost-effective solution compared to digital control methods.

There is also Multistage current charging (MSCC) method that divides the charging process into multiple stages with different current levels.

Finally, the pulse charging method uses short bursts of high current to charge the battery, which can

help reduce heat generation and improve charging efficiency.

2.7 Processing unit

2.7.1 FPGA

NOTE: This is just a draft made with knowledge base on a "Hardware programming" course and an internship in Synopsys. This text needs to be verified with the state of the art, and make some meaningful references.

The digital circuit of a MPPT have 4 main functions, implementation of a MPPT Algorithm, sensor acquisition mainly done by ADCs, generate PWM signal to drive the converter circuit and, in some cases, communication.

All of these functions can be implemented in a variety of ways. The most professional way is to use an Integrated Circuit (IC). These chips are usually designed and manufactured by a team of professional engineers that dedicated their time and knowledge to develop an efficient product. But as we will discuss later in section 2.9, these ICs are designed and produced with a specific application in mind and depending on the application, they can be useful or not.

Assuming that there is no IC perfect for this application, what are the options? The main options are Microcontroller Units (MCUs) or Field Programmable Gate Arrays (FPGAs). There are also some less powerful options like Complex Programmable Logic Devices (CPLDs) and Digital Signal Processor (DSP) however usually they are too complex to work with and not powerful enough. Let's focus on FPGA for now.

In an industrial design, if a company needs an IC with specific specs that there isn't in the market, they can design one.

The design of an IC starts with the constraints, then a design is made in a Hardware Description Language (HDL) and after software test bench and verifications, the design needs to be tested in real hardware. To test this new IC in hardware there are two main options, ask a manufacturer to produce a prototype or test the circuit in an FPGA. In most real world cases, a prototype is produced since the circuits are too complex and the timing constraints can't be validated in an FPGA however an IC prototype costs thousands of euros. So every time that an FPGA can be used, they use it.

An FPGA is a powerful design tool that implements HDL code in real hardware, offering the possibility of cheap prototyping.

Comparing with MCUs, FPGAs can be beneficial in terms of energy efficiency and speed, however it is expensive, requires a lot of knowledge in HDL and time to design. If the design will not be mass-produced in the form of an IC, it is not worth the time and money spent.

On the other hand MCUs are easily programmed, versatile, cheap, fast and reliable. Since this

project is for a team of students, it needs to be easily changed for the future needs and understandable without having depth knowledge in MCUs or FPGAs. With that in mind, FPGAs will not be use in this project despite its advantages.

este paper implementa um MPPT numa FPGA [20]

2.7.2 Microcontrollers

Arduino, STM32, Raspberry Pi, others

tentar justificar o uso do STM32 (speed, resolution of ADC/DAC, standardization)

2.8 Voltage and current sensing

This is just a draft based on my research writen in OneNote and converted to latex with the help of chatGPT. (It needs some work and references). The text is written as I have already decided a solution, but I did not. IT's JUST A DRAFT!!

Accurate voltage and current measurements are essential for MPPT operation, since tracking algorithms directly rely on these quantities to estimate power and adjust the operating point of the photo-voltaic (PV) array. Measurement noise or inaccuracies directly impact tracking efficiency, especially in high frequency switching DC–DC converters.

Voltage sensing is generally straightforward and can be implemented using resistive voltage dividers followed by ADC sampling. Current sensing, however, is more critical and requires careful consideration of the available measurement techniques.

2.8.1 Overview of current sensing options

Several approaches can be used to measure current in power electronics applications:

- Shunt-based sensing with operational amplifiers
- Differential amplifiers;
- Instrumentation amplifiers;
- Dedicated current-sense amplifiers;
- Hall effect current sensor.

Instrumentation amplifiers offer very high accuracy and excellent common-mode rejection, but they are typically more complex, consume more power and are unnecessary for the current and voltage levels involved in this application. Dedicated current-sense amplifiers integrate many features and simplify the design, but they increase cost, reduce flexibility and may impose voltage or interface constraints.

In contrast, shunt-based sensing combined with discrete amplifiers provides a good balance between accuracy, simplicity, power consumption and design flexibility, making it well suited for a custom MPPT implementation.

2.8.2 Shunt-based sensing with operational and differential amplifiers

The adopted approach is based on a low-value shunt resistor placed on the low side of the power path, converting the load current into a small differential voltage. This voltage is then amplified using a differential amplifier built from a precision operational amplifier.

Low-side shunt sensing results in a low common-mode voltage and a ground-referenced output signal, simplifying the analog front-end and easing direct interfacing with the microcontroller ADC. Compared to high-side sensing, it also improves noise immunity in a switching environment, which is particularly relevant in DC–DC converters.

The differential amplifier ensures that only the voltage drop across the shunt resistor is amplified, rejecting common-mode noise generated by switching activity. Operational amplifiers are especially attractive in this role due to their low power consumption, flexibility in gain selection, price and availability in precision, low-noise variants suitable for power electronics applications.

In a switching MPPT environment, the chosen amplifier must exhibit high common-mode rejection, low offset voltage and low noise to ensure accurate current measurement. The shunt resistor should have a very low resistance to minimize conduction losses, while maintaining high precision and a low temperature coefficient to reduce measurement error.

2.9 ICs specialized in MPPT

There are a few commercial available ICs that are specialized specifically on Solar battery chargers or MPPT. These ICs are worth mentioning since, if they are suitable for our application, they can save a lot of time on the design thinking of most of the previously discussed sections. Some of these ICs already have an integrated DC-DC, input and output protections and even an integrated MPPT algorithm.

In table 2.4 is represented 4 of the most used commercial ICs, with marked in red the specs that make them not perfect or not suitable for our use case.

The BQ24650RVAT is a IC that with a controller for MPPT algorithm and some current sensors, can be perfect for cars with 12V batteries and large panels. But in our use case we need to charge a 48V battery and panels with at least 12V in open circuit.

The MAX20801TPBA+ and SPV1040TTR are designed for IoT applications characterized by low-power systems with miniaturized batteries and solar panels. However, these devices are unsuitable for the present application, as neither can accommodate the required 48V output specification. Further-

more, the lack of publicly available information regarding their tracking speed characteristics presents an additional limitation for performance evaluation.

The last one in the table, LT8491IUKJ#PBF, is almost perfect. It has an wide input and output range, can do both step up and step down, it has a good efficiency, communication, CC-CV, etc. However digging in the data sheet, there is an image showing a tracking speed of 2 seconds, which is not fast enough for this application. Additionally, it uses I2C communication that would require an additional microcontroller to convert the telemetry to CAN.

Table 2.4: Comparison of commercial MPPT controllers and specialized ICs.

| Model | BQ24650RVAT | MAX20801TPBA+ | SPV1040TTR | LT8491IUKJ#PBF |
|-----------------------|------------------|------------------|-------------------|----------------|
| Input Voltage | 5 to 28V | 1.5 to 18V | 0.3 to 5.5V | 6 to 80V |
| Output Voltage (BAT) | 12 to 24V | 12.4V | -0.3 to 5.5V | 1.3 to 80V |
| Max Output Current | - | 12A | 1.8A | 10A |
| Topology | Synchronous Buck | Synchronous Buck | Synchronous Boost | Buck-Boost |
| Electrical Efficiency | 95% | 99.1% (max) | 80 to 95% | 95 to 99% |
| Tracking Efficiency | User dependent | 99.9% (max) | Unknown | Unknown |
| Tracking Speed | User dependent | Unknown | Unknown | 1 to 2 seconds |
| Algorithm | User input | Unknown | Unknown | P&O |
| Switching Frequency | 600kHz | Unknown | 100kHz | 100 to 400 kHz |
| Communication | No | No | No | I2C |
| Configurability | No | No | No | Yes |
| Charge Profile | CC-CV | Unknown | Unknown | CC-CV |
| Price | 5.25€ | 4.50€ | 3.02€ | 15-20€ |

There is more ICs but not a lot usually they have low input and output voltage.

2.10 Commercial MPPTs

As discussed in the previous section, there are some commercial available solutions for the problem in analysis. In this section is discussed the commercial solutions on layer above. These products are able to solve the problem without any extra hardware but all of them have a spec that can be improved. In table 2.5 is represented a selection of MPPT commercial available with some important specs and marked in red the worst specs.

The first and most important MPPT at the table is the GVB-8-Li-CV. This converter is extremely efficient and fast, making it one of the best MPPTs in the market for moving vehicles like a boat. For the past years TSB have been using this converter in all of their boats and no problems have been encountering except the lack of customization and information. Fact that lead to this project because TSB is a competitive team and every information about the boat is an advantage during competition and for future improvements. Additionally, it does not have a programmable output voltage which make it only suitable for 48V batteries and is expensive.

Overcome the problems of the GVB-8-Li-CV will mean success, so it will use as a reference to this project.

The Smart Solar MPPT 100/20 is one of Victron Energy solar chargers (MPPT). This brand is weal

known in the caravan community for its high efficiency, fast MPP tracking and low cost. Their MPPTs have CAN and Bluetooth communication with a mobile app for data visualization. The only downside of this converter is the need of a relative large solar panel since it uses a buck converter. In TSB application the solar panels are small and organized in groups of 2 to 3 solar panels in the same array to minimize the effects of clouds, defective solar panels or shadings. Therefore, we conclude that although this converter is excellent, it is not suitable for the application in question.

There are some other companies in the market but not so relevant as the two previous ones. For example the Rover Lite and MS4840N are reasonable converters but use communication protocols that not suit this project. Additionally, there is only minimal information about them public available.

There is one more converter in table 2.5, the Reboost V0.2.1. This converter was built 5 years ago by student team with the automotive sector in mind and is public available. Since then, it has been updated over the years. All hardware and software is open sourced and can be modified by every user to achieve the desired. The specs of this converter are near what we are looking for, but due to some overprice components and some discontinued ones this converter is not ideal for project in question. Additionally, the fact of being a boost converter limit the voltage of solar panels relative to the batteries, since boost converters always have the output higher than the input. So if in the future TSB decides to change from a 48V batteries to a 24V batteries, the arrays above 24V would need be rearrange.

Table 2.5: Comparison of commercial MPPT controllers.

| Model | GVB-8-Li-CV (50.4V) | Smart Solar MPPT 100/20 | Reboost V0.2.1 | Rover Lite | MS4840N |
|-----------------------------|---|-------------------------|--|-----------------------------|-----------|
| Brand | Gensun | Victron Energy | TPEE | Renogy | BougeRV |
| Type | Boost | Buck | Synchronous Boost | Boost | Boost |
| Communication | No | Yes (VE.can/ Bluetooth) | Yes | Bluetooth and RS485 | Bluetooth |
| Configurable | No | Yes | Yes | Yes | Yes |
| Commutation frequency | ?? | Unknown | Programmable | Unknown | Unknown |
| Programable battery voltage | No | Yes | Yes | Yes (non-lithium batteries) | Yes |
| Tracking speed | 15Hz / 66.6(6)ms | Fast (Unknown value) | Programmable | Unknown | Unknown |
| Tracking efficiency | 99%+ typical | Unknown | Programmable | 99% | Unknown |
| Electrical efficiency | 96-99% typical | 98% peak | Unknown | 97% | Unknown |
| Charger profile | CC-CV | Unknown | Programmable | Unknown | CC-CV |
| GUI | No | Yes | Yes | Yes | Yes |
| MCU | ATtiny461A-U | Unknown | STM32G474 | Unknown | Unknown |
| Details | High Performance, Low Power AVR® 8-Bit Microcontroller (RISC) | - | 32-bit, Mainstream Arm Cortex-M4 MCU 170 MHz with Math Accelerator | - | - |
| Transistor | FZT951 (BJT PNP 60V 5A) | Unknown | GS61008T (GaN FETs 100V 90A) | Unknown | Unknown |
| Price | 240€ | 100-200€ | Components: 250-280€ PCB:20-100€ Total:270-380€ | 300-350€ | 120-160€ |

3

Solucion Proposal

3.1 System architecture

The system is mainly composed by a battery, solar panels and several Maximum Power Point Tracker (MPPT). Additionally, the Battery Management system (BMS) and sensors are also relevant to the system.

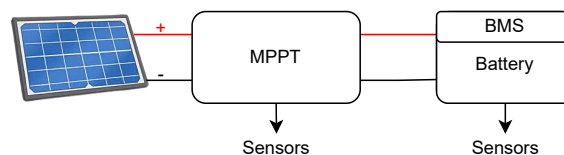


Figure 3.1: System architecture

This project aims to build an MPPT for São Guabriel 01 (SG01), which is one of the vessels built by Técnico Solar Boat (TSB), but TSB is continuously developing new boats with different batteries and different configurations of solar panels. With that in mind, the final solution needs to be versatile in terms of battery voltage and maximum ratings which will provide savings over the future years.

In terms of batteries, 3 different voltages were used in the past years, the 12V, 24V and 48V. As for solar panels, the biggest solar panel array that TSB have ever built had 56 solar cells in series, which in total give a 40.94 V in open circuit and 6.382 A in short circuit (with Maxeon Gen 5 solar cells from SunPower). This will be considered as the limit size of the solar panel and some margin will be added.

As for communication with the system, TSB uses Controller Area Network (CAN) with 1Mbit/s of bus speed to connect every Printed Circuit Board (PCB) to the same bus. However, when communicating with sensors there is more freedom and every other protocol can be use.

Also connected in the CAN bus is the Battery Management System (BMS). The BMS is the main safety system of the batter. It measures input and output currents, cells temperatures and voltages and decides if the battery is safe to use or not. So the final product does not need to provide these features. However, the safety of the battery is always a priority, so it will be taken into consideration in the purpose solution.

3.1.1 Requirements summary

Taking into account all user requirements and adding some margin, the summary of the requirements is:

- Work with a wide range of batteries: from 12V to 48V;
- Minimum input max rating: 10A and 50V;
- Electrical efficiency: at least 85%;
- Fast tracking speed: less than 200ms;
- High track efficiency: close to 100% (between 95% and 100%);
- CAN communication: 1000 Mbit/s and send status, power produced, current, voltage, efficiency, temperature, etc;
- Battery protection: overcurrent, overvoltage and charging techniques;
- Circuit protection: overcurrent, overvoltage, overtemperature, reverse polarity, ESD, etc.;
- MPPT algorithm: support different algorithms for future prove;

To successfully complete this project, all the above requirements must be achieved in the final prototype.

3.2 Methodology

3.2.1 Simulations and design

To achieve the requirements, a step-down/up converter needs to be used for versatility. The main purpose is to both convert from low input to high outputs or high inputs and low outputs. Even when the solar panels and battery have similar voltage, the step-down/up converter will be able to achieve the Maximum Power Point (MPP).

After choosing one of the DC-DC converter types, calculations and simulation in Matlab/simulink and LT-spice will be conducted to achieve a high efficient converter.

As for the algorithm, the final prototype needs to be able to use different algorithms to be future prove and to provide their comparison. Additionally, one new algorithm can be implemented based on a previous study by António Miguel Soares de Matos Neves in his master thesis. In this thesis he proposed an algorithm which combines LUT and P&O but this LUT table only uses voltage and current. Maybe if we add temperature or irradiance we will get better results. **Not sure if i like this paragraph.**

All the algorithms can be implemented and tested in Matlab/simulink.

Also, research about how to implement low power consumption voltage and current sensors will be conducted to find a cheap and accrued solution. Some available solution can be simulated in LTspice for precise tuning.

Finally, before designing the PCB in Altium designer to latter be manufactured, the microcontroller and sensors will be chosen accordantly with the specs.

3.2.2 Experimental results

To test the circuit in lab, a control environment needs to be built with a close box and a light emitter device (for example an LED light). Inside this box the irradiance emitted by external sources, like lab lights or sun, will be reduced. The light emitter device should achieve irradiance close to the Standard Testing Conditions (STC), which is $1000w/m^2$,

The same can be done with the temperature using a simple thermostat to maintain the system at the same temperature or at STC conditions, which is 25°C.

This setup provides constant irradiance and temperature but can also provide variations to the environment variables, by changing the irradiance of LEDs with PWM or changing the reference signal of the thermostat. So by applying abrupt variants (steps), to one of the variables, the speed of the response and accuracy can be analyzed.

To eliminate setup errors, an irradiance sensor and a temperature sensor should be installed inside the box for better analyses of the results.

Add: efficiency tests and robustness tests

4 Preliminary Work

In order to get familiar with the tools needed for the development of the project, some basic test was conduct. In this section, a brief introduction to simulation tools and Hardware tests are presented.

4.1 Simulations

Nowadays, the most use tool to simulate the behavior of a MPPT is Matlab Simulink. With this software a solar panel can be simulated by providing the environmental conditions (temperature and irradiance) at every simulation instance. This block can be set with the exact parameters of the real system (open circuit voltage, short circuit current, temperature coefficient, etc.). Then, using Simscape electrical library, the electronics of the converter can describe by connecting specific blocks configured with the parameters needed (resistance, capacities, inductance, forward voltage, etc.). For the battery, the same procedure was executed. Like the others blocks the battery can be configured with the exact same parameters as the real battery (nominal voltage, discharge current, battery type, capacity, etc.).

By providing the correct parameters to every block, the system behaves has the actual circuit. However, it is just a simulation tool, and by doing some approximations, simulation errors will be found. Therefore, the simulations need to be analyzed carefully.

In figure 4.1 is represented the model build it Matlab Simulink, using a boost converter and P&O method. As previously said, this model was built to understand how to use this simulation tool and how to overcome the problems that show up in the process. Therefore, everything can be changed later.

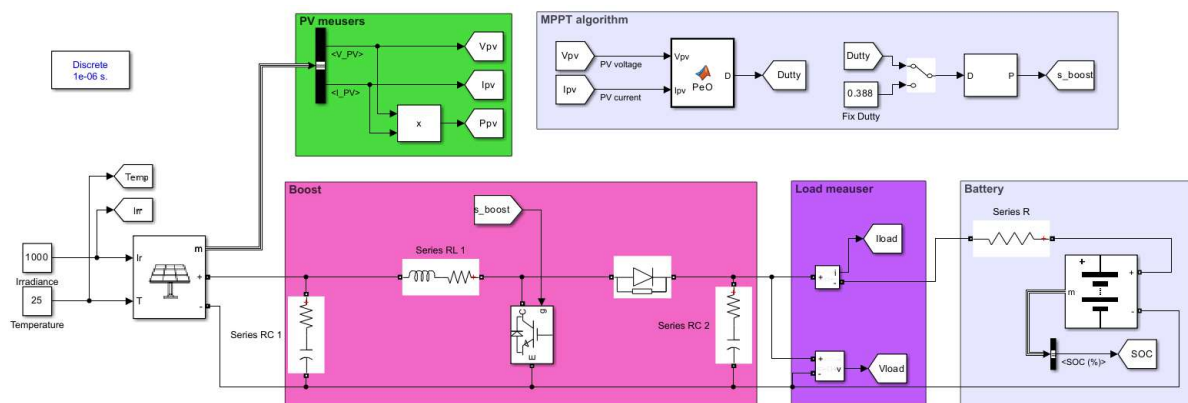


Figure 4.1: Matlab/Simulink system model with Boost Converter and P&O.

The objective was successfully accomplished, with good results. Figure 4.2 shows the results of the presented model.

The Maximum Power Point (MPP) of the given solar panel ($V_{oc} = 22.33V$ and $I_{SC} = 6.038A$) was successfully tracked with a simple algorithm. The results show some noise at the input which can be improved in future work. Also, a strange behavior was found at the beginning of the simulation. The load current goes to negative before starts tracking the MPP. This behavior is introduced by the resistance in series with the battery, which drains the battery when the converter is disconnected. This problem is not alarming since this resistance is only placed for simulation.

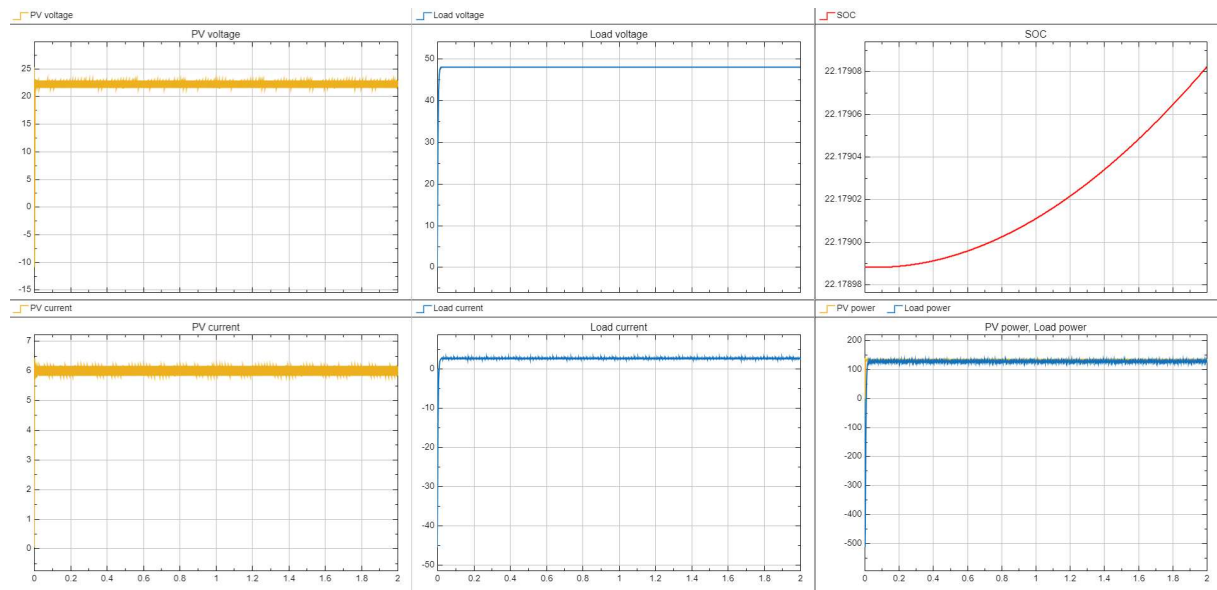


Figure 4.2: Matlab/Simulink results

4.2 Hardware tests

Since the use of an STM32 is one of the requirements of TSB to comply their standards, some research and tests were also performed to get familiar with the software tools and the requirements of the MCU.

The test were carried out with a cheap development board called Blue Pill witch accommodates a STM32F103C8T6. As this is one of the cheapest boards on the marked, the specs are not perfect. However, it was suitable for aim of these tests.

The STM32F103C8T6 has an ARM Cortex-M3 32-bit core running at up to 72 MHz, providing sufficient processing performance for real-time control and signal-processing tasks. It integrates two 12-bit ADCs with a maximum sampling rate of approximately 1 million samples per second and up to 16 multiplexed analog input channels, while no internal DAC is available. The device includes several general-

purpose and advanced timers capable of generating PWM signals, with maximum PWM frequencies limited by the 72 MHz timer clock and the selected resolution. Housed in a 48-pin package, it offers up to around 37 configurable GPIO pins. In terms of communication interfaces, the MCU supports multiple USARTs, SPI and I²C peripherals, as well as a Full-Speed USB 2.0 device interface, making it suitable for a wide range of embedded communication requirements.

The tests conducted were based on online examples, which allowed the evaluation of several functionalities of this MCU, including timers, interrupts, basic GPIO operations, PWM generation, ADC usage, and communication interfaces such as USB, CAN, serial and I²C.

5

Planning and Scheduling

The establishment of deadlines, and work organization is important to evaluate the work progress and ensure better performance at all tasks.

A Gantt Chart, was built and presented in figure 5.1 where the work was divided into tasks and stages spread throughout the year.

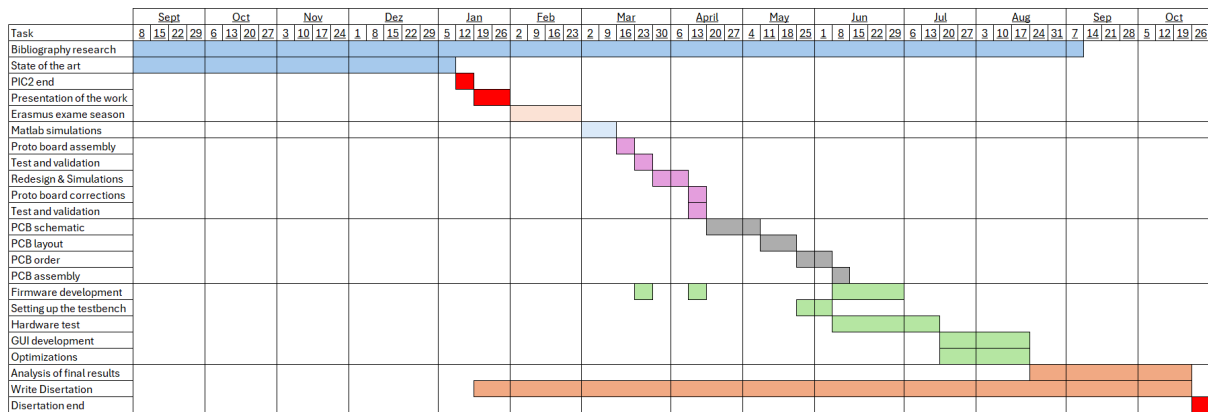


Figure 5.1: Gantt Chart of the work to be performed

The work started with the state-of-the-art research, presented in this document that will be furthered devolved deeper.

Then, as described in previous sections, some simulations will be developed to evaluate the solution proposal. After a reliable and robust solution is achieved, a prototype will be built in a proto board to validate the simulations without spending a lot of money and time.

When a successful prototype is achieved, the PCB designed will start and ordered in the end of the process.

Finally, firmware specifically made for the designed PCB will be made alongside with hardware test and Graphical User Interface (GUI) development.

After all hardware and software design, the board will be tested in real world conditions and the data will be analyzed and documented in the dissertation document.

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