TÉCNICO LISBOA

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

Solar-powered vehicles rely on solar energy to charge their batteries and maximize their range, particularly solar-powered boats need an effective energy conversion in rapidly changing environmental conditions. In this context, The Maximum Power Point Tracker (MPPT) plays a critical role in energy conversion, by ensuring that the solar panel operates on their Maximum Power Point (MPP). This work focus on the study, design, simulation and test of a fast response MPPT system for Técnico Solar Boat (TSB).

This document contains the state-of-the-art review covering photovoltaic principles, MPPT algorithms, DC–DC converter topologies, switching devices, sensing techniques, processing units, and commercial MPPT solutions. Special attention is given to the algorithms suitable for dynamic conditions, and DC–DC topologies.

Based on the conduct study and the project requirements, a solution was proposed capable of effective convert energy, operation the solar panel on their MPP, and without compromising battery voltage flexibility. Preliminary simulations were conduct to validate the software tools chosen and gain familiarity with the given tools. The ultimate objective of this project is to develop a reliable, efficient, and customizable MPPT solution that improves energy extraction, enhances system monitoring through CAN communication, and contributes to the overall performance and competitiveness of the TSB.

Keywords:

MPPT, MPPT topology, DC-DC Converter, Solar energy, P&O, Solar Boat

Contents

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

ASIC   Application-Specific Integrated Circuits

R&D   Research and Development

1 Introduction

1.1 Motivation

With environmental pollution intensifying worldwide, the transition to cleaner energy sources such as solar power has become increasingly urgent In 1985 only 20.82% of the energy produced in the world came from renewable energies. These numbers have been rising every year and in 2024 we have reached 31.92% [1]. In 2024, 6.9% of the energy produced in the world come from solar panels, and in Portugal this number rises to 14.5%, demonstrating the importance and the impact of solar energy [1]. Solar energy still plays a miniscule role, and it is listed behind the other sources of energy in terms of the contribution for meeting the world's energy demand. However, solar energy is becoming 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, it is becoming more relevant in the automotive industry, with solar-powered cars, boats and robots [2]. The CO_2 emissions of automotive sector is one of the main contributors to global warming. In 2018, 29% of total CO_2 emissions in the EU came from the transport sector, with 4% coming from the maritime sector alone [3]. These challenges directly motivate the development of the Técnico Solar Boat (TSB) project.

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 grown and several vessels were built. It began with the construction of the first solar prototype, São Rafael 01 which still had a lot of room for improvement, and was followed by São Rafael 02 and 03. The team then 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 was built with the purpose of combining all the technologies used before and was 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 small, and the whole system was built using commercial off the shelf (OTS) components. In 2020 the team stated to built its own solar panels, for São Rafael 02. Many others systems were also designed and built in house, but there is still one system that is yet to be developed, the Maximum Power Point Tracker (MPPT).

The MPPT is a fundamental subsystem in photovoltaic energy systems, responsible for maximizing the power extracted from solar panels by ensuring continuous operation at the Maximum Power Point (MPP). A MPPT controller is typically a power converter, that continuously monitors the voltage and current produced by the photovoltaic modules and adjusts their electrical operating point accordingly. By dynamically regulating these operating parameters, the MPPT compensates for variations in environmental conditions such as solar irradiance and temperature, which cause the MPP to shift over time. As a result, the photovoltaic system is able to operate with improved efficiency and deliver maximum available power under changing conditions [4].

1.2 Objectives

This project aims to design and implement a MPPT controller for the 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.

The main objectives of this project are:

- Study and understand the operation of solar panels and MPPT techniques;

- Choose the most suitable DC–DC topology for the system;

- Implement a fast-response and accurate control algorithm;

- Design and simulate the hardware and software;

- Implement the system in hardware and develop a Printed Circuit Board (PCB);

- Test and validate the performance of the circuit;

- Ensure the safety and reliability of the MPPT for its integration in the TSB project;

- Provide performance data of the solar panel and the MPPT through a Controller Area Network (CAN) communication interface.

By achieving these objectives, the project will contribute for a more effective solar system, maximizing the energy received from the solar panels and increase the available data for performance tracking of the MPPT and solar panel. This data will be used to later improve the energy efficiency of the MPPT and 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. rever o conteudo no futuro

- **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 and methodology is detailed, including converter selection, control strategy, simulation, 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.

- **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 the main state-of-art concepts about the engineering behind a Maximum Power Point Tracker (MPPT) and solar panels are explained. More specifically, it addresses key challenges such as: what is a solar panel, MPPT algorithms, DC-DC converter types and battery charging techniques.
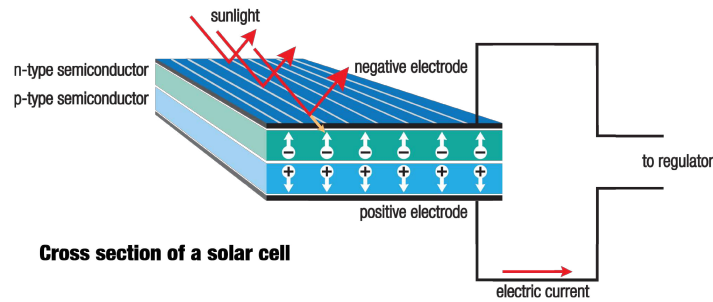
2.1 Solar Panels

Photovoltaic (PV) panels are devices that convert solar irradiance into electrical energy. A PV panel consists of multiple solar cells electrically connected in series and/or parallel to achieve the desired voltage and current levels. As in conventional electrical systems, the interconnection topology directly affects the electrical characteristics of the panel: series connections increase the output voltage, while parallel connections increase the output current [5].

Series connected PV panels operate at higher voltage levels, which reduces conduction losses in interconnecting cables and improves the efficiency of the DC–DC conversion stage. Moreover, power converters designed for high voltage, low current operation are generally less complex and more cost-effective than those operating at low voltage and high current. However, series configurations are more sensitive to partial shading or panel failure, as the output current of the entire string is limited by the weakest module [6]. In contrast, parallel configurations provide improved tolerance to shading and faults but result in higher current levels and increased conduction losses. In this project we will not control the series/parallel configuration of the solar panels, since it is already pre-defined by Técnico Solar Boat (TSB), however it is important to understand the implications of each configuration.

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 [7].

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 [7],

Figure 2.1: Principle of operation of a solar panel. descobrir de onde tirei

Figure 2.1.

The generated energy results in voltage and current outputs that are not constant. Voltage and current are interdependent, therefore, a variation in one parameter leads to a corresponding variation in the other. This relationship is nonlinear and can be characterized by a current-voltage (I–V) curve. Furthermore, the power output also varies with operating conditions and can be represented by a power-voltage (P–V) curve. Both curves are represented in Figure 2.2. In both curves, there is a specific point where the power output is maximized, known as the Maximum Power Point (MPP). This point corresponds to a unique combination of voltage and current, denoted as V_{mpp} and I_{mpp} respectively. Operating the solar panel at this point ensures optimal energy extraction under given conditions.
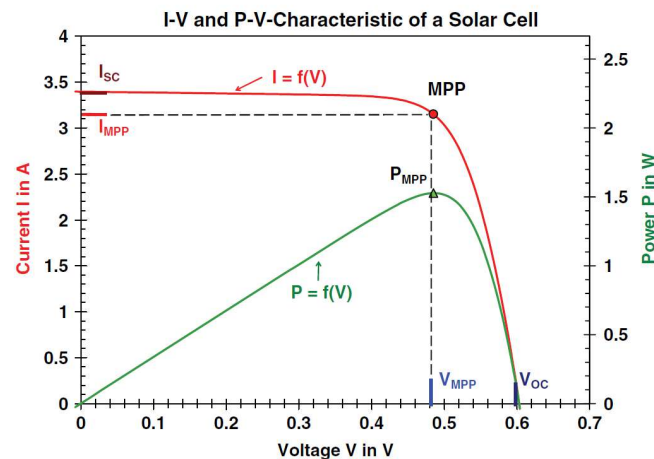
Figure 2.2: I-V and P-V curves of a solar panel [7].

The characteristic curves 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 solar irradiance. It is noted that under partial shading conditions, in some cases it is possible to have multiple local maximum, but overall there is still only one true MPP [8].

As seen in Figure 2.3a, the variation of the solar 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.
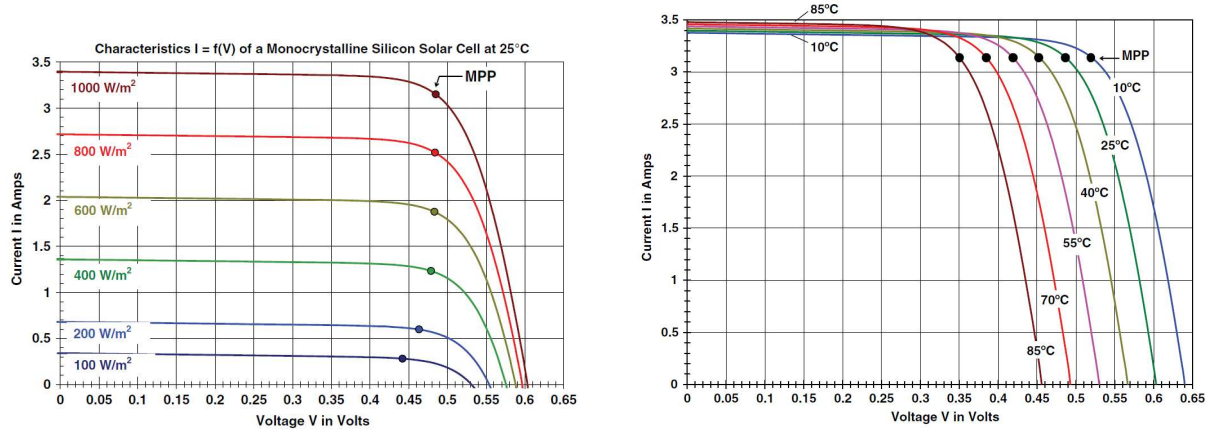
(a) Cell temperature of 25 ºC and variable Irradiance.

(b) Irradiance of $1\ \mathrm{kW/m^2}$ and variable temperature.

Figure 2.3: I-V curves under different conditions. Left: irradiance variation. Right: temperature variation [7].

Both environmental conditions have a meaningful impact on the MPP of the solar panel and therefor on the power output of the system. To maximize the power extracted by the solar panels, a classic power converter like a buck converter, will not get a good result since neither the current nor the voltage are constant. Instead, a MPPT controller is used which will find the MPP and operate the solar panel at that point while sensing the changes caused by the environment.

2.2   Maximum Power Point Tracker (MPPT)

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 a 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 is 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 generates a signal to control the DC-DC converter that will adjust its operation accordingly.

The output can be connected to different types of loads, like batteries, DC loads or inverters.
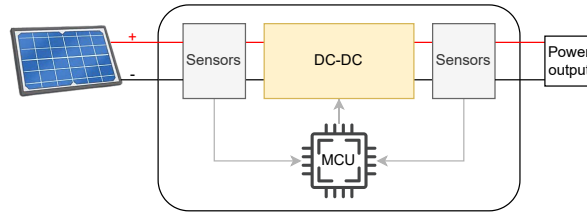
Figure 2.4: Top view of a basic MPPT system.

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 extract the maximum energy 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, orientation and clouds, and also temperature changes due to waves and wind. For these reasons, the tracking speed and accuracy are the most important factors to consider.

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 operating the solar panel at a fixed voltage. This referenced voltage is used to calculate the duty cycle of the DC-DC converter that will maintain the operating point of the solar panel.

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%) [8]. This open circuit voltage can be measured periodically by disconnecting the solar panel from the load for a short period of time. In this way, the reference voltage will be more accurate and the efficiency will increase.

Other variation is based on the short circuit current of the solar panel, setting the reference current to a fraction of this value [9].

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 [8] [10]. Still, the MPP is not always located at the same percentage of the open-circuit voltage or short circuit current, leading to a lack of accuracy

and therefore lower efficiency [4].
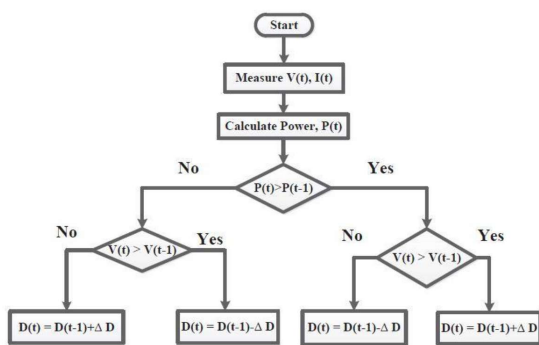
2.3.2 Perturb and Observe (P&O)

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

As its name indicates, it perturbs the voltage of an PV array and observes the resulting effect on the power output [11]. This means that if the voltage was increased and the power output also increased, the algorithm is working in the direction of 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 [12] [13]. Figure 2.5 shows a 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 also reduce the tracking speed of the algorithm. So there is a trade-off between tracking speed and accuracy [9] [8].

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 closer. In 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 value 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 weal-know, 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 [8]. 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 (Figure).

Figure 2.5: Flow chart of the classic version of Perturb and Observe algorithm [13].
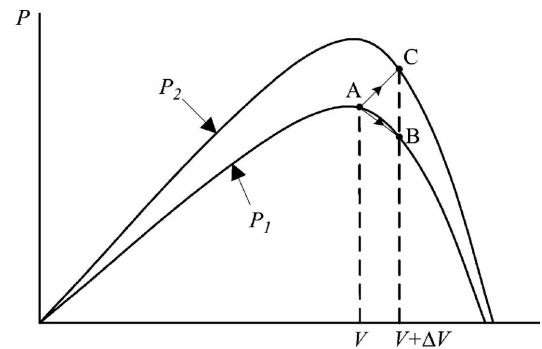
Figure 2.6: Divergence of P&O from MPP as shown in [14]

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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 measurements do not folow the signs of ΔV, 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 [5].

There are other variations of P&O algorithm that improve its performance, like Variable Step Size P&O (VSS-P&O), the three point P&O, a-factor P&O and more. Unfortunately, due to the scope of this work, it is not possible to explain all of them.

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 [15].

The following formulas (Equation 2.2) show the equation which this algorithm is based on.

$$\frac{dP}{dV} = \frac{d(V \cdot I)}{dV} = I + V\frac{dI}{dV} \rightarrow \frac{1}{V} \times \frac{dP}{dV} = \frac{I}{V} + \frac{dI}{dV} \tag{2.1}$$

So at the MPP point, the slope of the P-V curve is zero, which means that the negative of the conductance, $-\frac{I}{V}$, is equal to the incremental conductance, $\frac{dI}{dV}$, (Figure 2.8). 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 [9] [8]:

$$\frac{dP}{dV} = 0 \quad \Longleftrightarrow \quad \frac{dI}{dV} = -\frac{I}{V} \qquad \text{at MPP}$$

$$\frac{dP}{dV} > 0 \quad \Longleftrightarrow \quad \frac{dI}{dV} > -\frac{I}{V} \qquad \text{left of MPP} \tag{2.2}$$

$$\frac{dP}{dV} < 0 \quad \Longleftrightarrow \quad \frac{dI}{dV} < -\frac{I}{V} \qquad \text{right of MPP}$$

Based on these conditions the algorithm adjust it's operating point (increasing or decreasing the voltage) using a variable step size based of the instantaneous conductance relative to the incremental conductance, Figure 2.7. For example, as suggested in [8] the step size can be calculated using a proportional integral (PI) controller with input error defined as:

$$e = \frac{I}{V} + \frac{dI}{dV} \tag{2.3}$$

Comparative analysis demonstrates that the IncCond algorithm exhibits superior performance 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 [15]. For example the IncCond method eliminates the oscillation problem around the MPP that is characteristic of the P&O method. Additionally, IncCond demonstrates superior performance under rapidly changing environmental conditions, such as sudden irradiance variations, since it uses derivative based information that is less sensitive to transient disturbances [5].
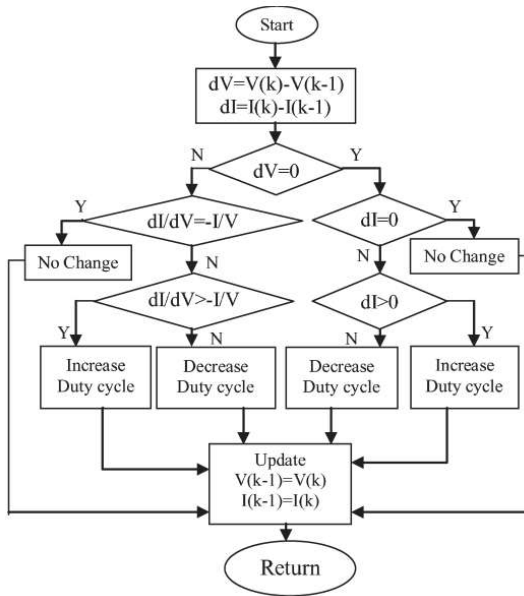
Figure 2.7: Flowchart of the IncCond method with direct control [16].

Figure 2.8: IncCond method principle.
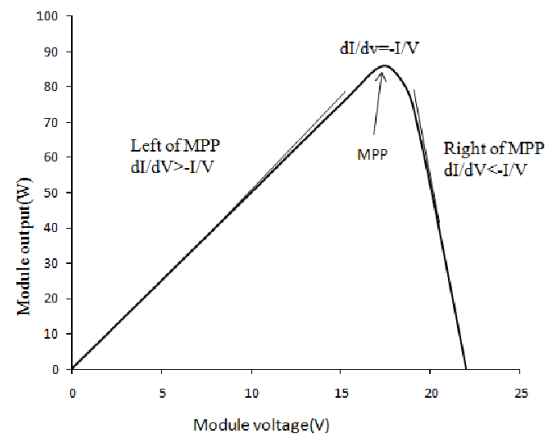
2.3.4 Look Up Table (LUT)

The Look-Up Table (LUT) 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 [9].

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 entries of the table can be calculated truth a mathematical model of the solar panel with different conditions (temperature and irradiance) or measured in laboratory.

Table 2.1 is visual representation of a 2D LUT, only based on current and voltage. Each entry represents the duty cycle used in each case.

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. Also, research

Table 2.1: LUT matrix representation with $m \times n$ elements.

	V_1	$\cdots$	V_k	$\cdots$	V_m
I_1	D_{11}	$\cdots$	D_{1k}	$\cdots$	D_{1m}
$\vdots$	$\vdots$		$\vdots$		$\vdots$
I_j	D_{j1}	$\cdots$	D_{jk}	$\cdots$	D_{jm}
$\vdots$	$\vdots$		$\vdots$		$\vdots$
I_n	D_{n1}	$\cdots$	D_{nk}	$\cdots$	D_{nm}

show less output ripple and higher output power at some levels of irradiance. However, it is not very accurate [13].

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. At extreme cases, the memory requirements became expensive and slow. There is a trade-off between size, speed and accuracy that needs to be considered when using this method.

2.4 Types of DC-DC Converters

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 [17].

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 [18], as they help to protect against voltage spikes and other electrical disturbances or when the solar panels MPP voltage is very 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 lower costs.

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,

Table 2.2: Comparison between Non-isolated Converters and Galvanic Isolated Converters, where red, yellow and green represents bad, medium and good respectively.

Type	Non-isolated 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
Cost	Low	High

non-isolated converters will be considered.

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 [19].

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% [20]. add refs

One downside of this topology is that it can not emulate a 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 with all MPPTalgorithms [21].

2.4.2.B Buck converter

The buck converter is a step-down DC-DC converter also widely use for applications where the solar panel voltage is higher than the battery or load voltage.

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 [21].

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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 [20]. They are used in applications where the solar panel voltage can be both higher or lower than the battery or load voltage.

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

The classic buck-boost and the 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 [21]. 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. The most significant advantages of each topology are highlighted.

Table 2.3: Comparison of non-isolated DC-DC topologies, where green represents good characteristics.

Topology	Boost	Buck	Buck-Boost	Zeta	Cuk	SEPIC
Price	Low	Low	Low	Medium	Medium	Medium
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

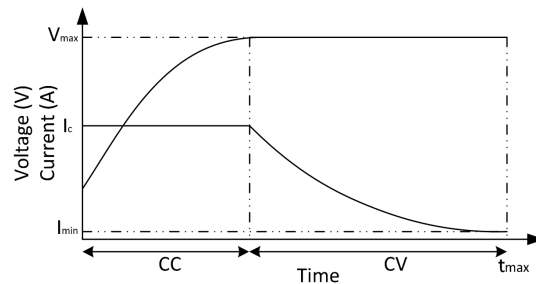# 2.5 Battery charging techniques

As the demand of electronic devices and E-vehicles increased, the need for efficient, compact and lightweight batteries has emerged. Among many exiting technologies, lithium-ion batteries have one of the best energy-to-weight/volume ratios and, at this moment, it is the technology used in TSB batteries.

But, as every other battery technology, they need to be charged properly to ensure their safety and longevity [22].

To charge these batteries properly, the MPPT algorithm can operate 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 algorithm can adjust the operating point of the solar panel to extract the maximum power while the battery charging technique ensures that the battery is charged properly. A proper combination of both algorithms/techniques is essential to ensure both maximum energy extraction and battery safety.

There are several techniques to charge lithium-ion batteries, the most relevant for this use case being the Constant Current-Constant Voltage (CC-CV) method [23]. Also, it is widely used in commercial chargers due to its simplicity and effectiveness [24]. This method consists in two main phases, (Figure 2.9). 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 [24].

When employing the constant current–constant voltage (CC–CV) charging technique with a MPPT controller, the initial constant-current phase is regulated by the MPPT algorithm, which extracts the maximum available current from the solar panel. Once the constant-voltage phase is reached, the MPPT function is disabled, and the power converter increases the solar panel voltage to progressively reduce the charging current while keeping the output voltage constant.

Figure 2.9: Charging profile of CC/CV [22].

More advanced high-performance battery charging techniques have been proposed by the literature to reduce charging time without increasing the charging current, thereby preserving battery lifetime. However, these techniques generally introduce higher switching losses and increased system complexity. In the present application, the current generated by the photovoltaic panels is less than half of the maximum allowable battery charging current, consequently, the charging current is inherently limited

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by the solar panels rather than by the charging strategy. Furthermore, battery lifetime is not a critical concern in this project, as the battery is expected to undergo a limited number of charge cycles, not exceeding 20 cycles per year.

Therefore, the constant-current–constant-voltage (CC-CV) charging method is considered the most suitable technique for this project, owing to its simplicity, effectiveness, and widespread adoption in commercial battery chargers. Although alternative charging strategies may be explored in future work to achieve faster charging or enhanced battery longevity, CC-CV currently represents the most appropriate choice for the proposed system.

Other charging techniques fall outside the scope of this work, however, some methods are briefly discussed in the references provided [23] [22] [24].

2.6   Processing and sensing unit

2.6.1   Types of processing units

Several types of processing units can be considered for this project, including Microcontroller Units (MCUs), Field Programmable Gate Arrayss (FPGAs), and Application-Specific Integrated Circuitss (ASICs).

ASICs are custom-designed integrated circuits optimized for specific applications, offering high efficiency and performance. However, they are typically expensive and time-consuming to design and manufacture. Although commercially available ASICs, commonly referred to as Integrated Circuits (ICs), mitigate these drawbacks, they are usually made for a specific application and therefore not suitable for the flexibility required in this project, as discussed in Section 2.7.1.

FPGAs are reconfigurable devices capable of implementing custom digital circuits through programmable logic blocks based on look-up tables (LUTs) and interconnections [25]. Their main advantage lies in their inherent parallel processing capability, which enables high-performance operation. Nevertheless, FPGAs generally present higher cost, increased design complexity, and volatile configuration memory, requiring reprogramming after power loss [26, 27].

In contrast, MCUs are widely adopted in embedded systems due to their low cost, ease of use, and versatility. They integrate processing, memory, and peripherals in a single non-volatile device, simplifying hardware design and development. Although their sequential execution limits parallel processing performance compared to FPGAs, modern MCUs provide sufficient computational capability for many control and signal-processing tasks [26].

Considering the emphasis on low cost, reduced development time, and implementation simplicity, a MCU is selected for this application. Furthermore, the performance of current microcontrollers is adequate to meet the requirements of the MPPT algorithm and the battery charging strategy.

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2.6.2 Microcontroller

A microcontroller typically consists of three fundamental components: a central processing unit (CPU), memory, and peripheral modules. The CPU executes program instructions and performs arithmetic and logical operations. Memory is generally divided into non-volatile memory (e.g., Flash) for program storage and volatile memory (e.g., SRAM) for data and runtime variables. Peripheral modules provide interfaces to the external environment and may include analog-to-digital converters (ADCs), timers, pulse-width modulation (PWM) units, communication interfaces (such as UART, SPI, and I^{2}C), and general-purpose input/output (GPIO) ports. The integration of these components enables standalone operation without the need for extensive external circuitry [28].

When selecting a microcontroller for a specific application the first factor to consider is to use an 8, 16 or 32 bit MCU. For this application a 16-bit MCU would probably be sufficient, however to ensure future-proof and compatibility with other TSB systems, the choice is for a 32-bit MCU. Besides, nowadays, 32-bit MCUs are considered the industry standard since most embedded system Research and Development (R&D) effort is focused on 32-bit cores, and thus both architectures can achieve similar power consumption [29]. There are two main architectures for 32-bit MCUs: AVR and ARM. Being ARM the most widely used architecture in the industry and the most advanced, it was chosen for this project [26].

Other important characteristics like clock speed, PWM resolution, communication protocols, memory capacity, power consumption, and cost, are not yet well-defined. The choice of microcontroller will be revisited in future stages of the project.

However, the STM32 family of microcontroller was already selected as it is the standard microcontroller used in TSB project and widely used in the industry. The STM32 family offers a wide range of solutions with different characteristics, making it suitable for various applications, including this project.

If there is time, chose a specific STM32 and justify the choice based on some parameters.

2.7 Commercial Options

2.7.1 Specialized ICs

There are a few commercial available ICs that are specialized 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 this ICs already have an integrated DC-DC and input and output protections and on top of the integrated MPPT algorithm.

Table 2.4 showcases 4 of the most used commercial ICs. The characteristic marked in red are no suitable to this project, so the corresponding IC can not be adopted.

The BQ24650RVAT is a IC that with a controller for MPPT algorithm and some current sensors, can

be perfect for cars with 12 V batteries and large panels. However, in our use case we need to charge a 48V battery and panels with at least 12 V 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. Furthermore, 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 and CC-CV charger. 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, where red represents bad characteristics.

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 accuracy	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€

2.7.2 Commercial MPPT controllers

As discussed in the previous section, there are some commercial available solutions for the problem in analysis. This section discusses the available commercial solutions. These products are able to solve the problem without any extra hardware but all of them have specifications that can be improved. Table 2.5 represents a selection of commercial available MPPT controllers and their specifications. Red-marked characteristics are unsuitable for this project.

The first and most important MPPT at the table is the GVB-8-Li-CV(50.4). 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 found except the lack of customization and information. This fact 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, this MPPT is expensive and does not have a programmable output voltage

which makes it only suitable for 50.4 V batteries and is expensive.

Overcoming the problems of the GVB-8-Li-CV will mean success, so it will be used as a reference design to this project.

The Smart Solar MPPT 100/20 is one of Victron Energy solar chargers (MPPT). This brand is well 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 do not suit this project. Additionally, there is only minimal information available.

There is one more converter in Table 2.5, the Reboost V0.2.1. This converter was built 5 years ago by a student team with the automotive sector in mind and is publicly available. Since then, it has been updated over the years. All hardware and software is open sourced and can be modified by any user to achieve the desired performance. The specification of this converter are near what we are looking for, but due to some overpriced components and some discontinued ones this converter is not ideal for project in question. Additionally, the fact of being a boost converter limits 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 rearranged.

Table 2.5: Comparison of commercial MPPT controllers, , where red represents bad characteristics.

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
Programable battery voltage	No	Yes	Yes	Yes (non-lithium batteries)	Yes
Tracking speed	15Hz / 66.6(6)ms	Fast (Unknown value)	Programable	Unknown	Unknown
Tracking efficiency	99%+ typical	Unknown	Programable	99%	Unknown
Electrical efficiency	96-99% typical	98% peak	Unknown	97%	Unknown
Charger profile	CC-CV	Unknown	Programable	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

Proposed Solucion

3.1 System architecture

The solar system is mainly composed by a battery, solar panels and several Maximum Power Point Trackers (MPPTs). Additionally, the Battery Management system (BMS) and sensors are also relevant to the system, Figure 3.1.
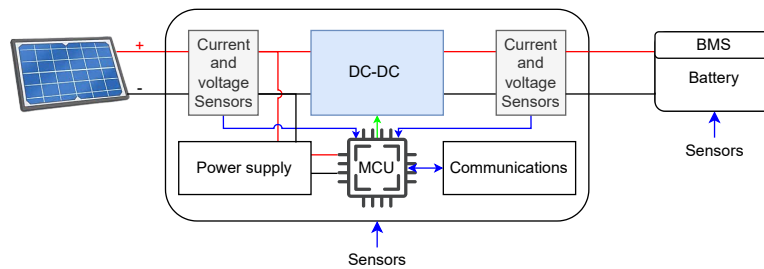
Figure 3.1: Solar system architecture.

This project aims to build a 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 years.

In terms of batteries, 3 different voltages were used in the past: 12V, 24 V and 48 V. 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 the MPPT controller, it is composed by current and voltage sensing elements to feed the MPPT algorithm, a power supply cable to ensure steady DC voltage output in the whole range of input voltages, a DC-DC converter alongside with a MCU which controls the DC-DC converter taking into account the input measures, Figure 3.1.

The proposed system will use a step-down/up DC-DC converter to ensure load voltage and input voltage flexibility. The exact type is still to be decided. As for the MPPT algorithm, a simple P&O will be initial used to simplify the work, however, the prototype needs to support other algorithms for further

improvements.

Thinking on the Look-Up Table (LUT) method, the proposed solution will be able to read both temperature and solar irradiance.

The communication with the system will be made by Controller Area Network (CAN) communication with 1 Mbit/s of bus speed to connect every Printed Circuit Board (PCB) to the same bus. CAN is the standard communication protocol used by TSB, however, when communicating with sensors there is more freedom and every other protocol can be used.

The prototype will send message to CAN bus with the data measured (voltage, current, temperature and irradiance) as weal as calculated data such as power and electrical efficiency. Also, some additional information can be sent such as status (erro codes, charging, not charging, etc.) or warning about solar panels health.

Also connected in the CAN bus is the Battery Management System (BMS). The BMS is the main safety system of the battery. 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 proposed solution in the form of protections against overcurrent, overvoltage and reverse polarity. Also, CC-CV charging mode will be used in order to safely charger lithium-ion batteries.

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 battery voltage: from 12 V to 48 V;

- Input maximum rating: 10 A and 50 V;

- Electrical efficiency: at least 85 %;

- Fast tracking speed: less than 200 ms;

- High track efficiency: close to 100 % (between 95 % and 100 %);

- CAN communication: 1000 Mbit/s and send status, power produced, current, voltage, efficiency and temperature;

- Load limits: overcurrent and overvoltage;

- Charging technique: CC-CV;

- Circuit protection: overcurrent, overvoltage, overtemperature, reverse polarity, ESD, etc.;

- MPPT algorithm: support different algorithms;

- cost less than 150 EUR per unit.

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 voltages, 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 LTspice 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 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. It is expected that by adding temperature and/or irradiance it will get better results.

All the algorithms will 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. A few solutions can be simulated in LTspice for precise tuning.

Finally, before testing the circuit in a proto board or designing the PCB in Altium designer to later be manufactured, the microcontroller and sensors will be chosen accordingly to the specifications.

3.2.2 Experimental results and validation

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

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

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. By applying abrupt variations (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 tests were conducted. In this section, a brief introduction to simulation tools and Hardware tests are presented.

4.1 Simulations

Nowadays, the most used 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 DC-DC converter can be described by connecting electrical components and 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.

Figure 4.1 represents the model build it Matlab Simulink, using a boost converter and the 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.
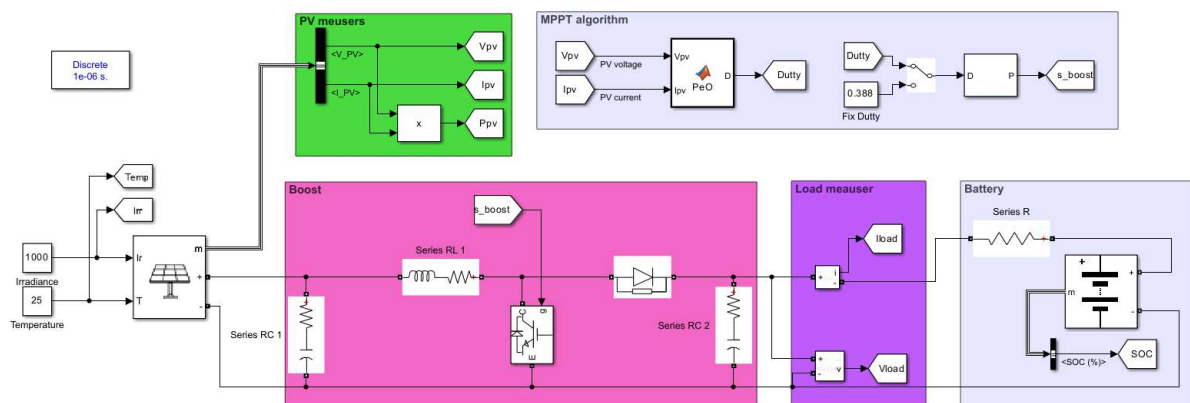
Figure 4.1: Matlab/Simulink system model with Boost Converter and P&O algorithm.

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 ($V_{oc} = 22.33$ V and $I_{SC} = 6.038$ A) 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 the MPP starts tracking. 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.
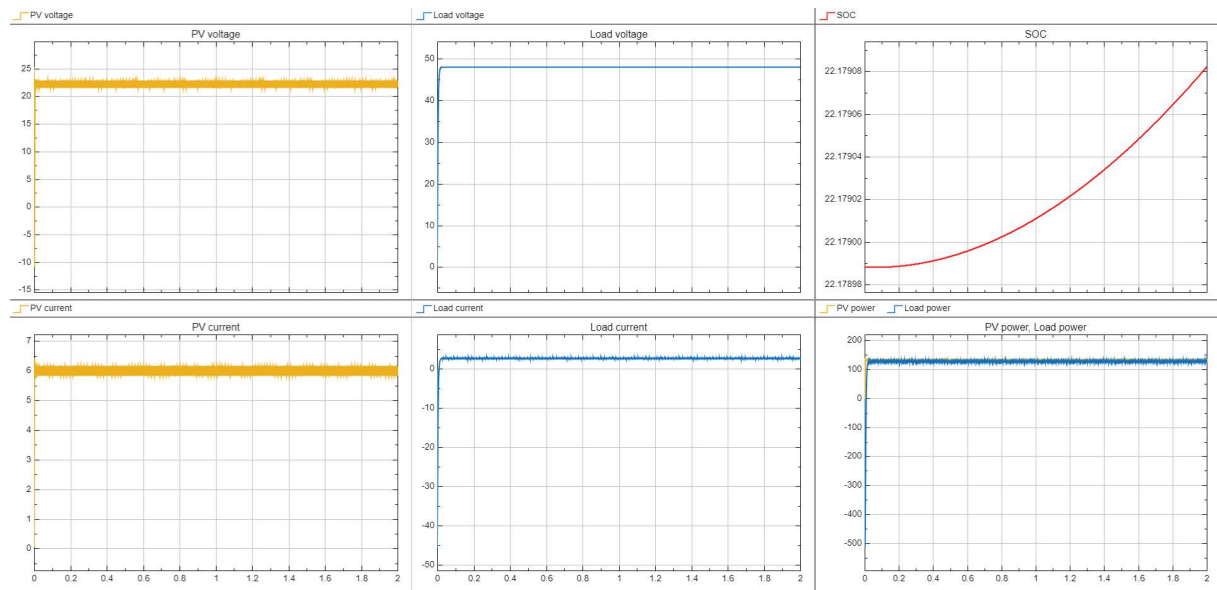

Figure 4.2: Matlab/Simulink results.

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 specifications are not high-end. However, it was suitable for the 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 I^{2}C 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 I^{2}C.
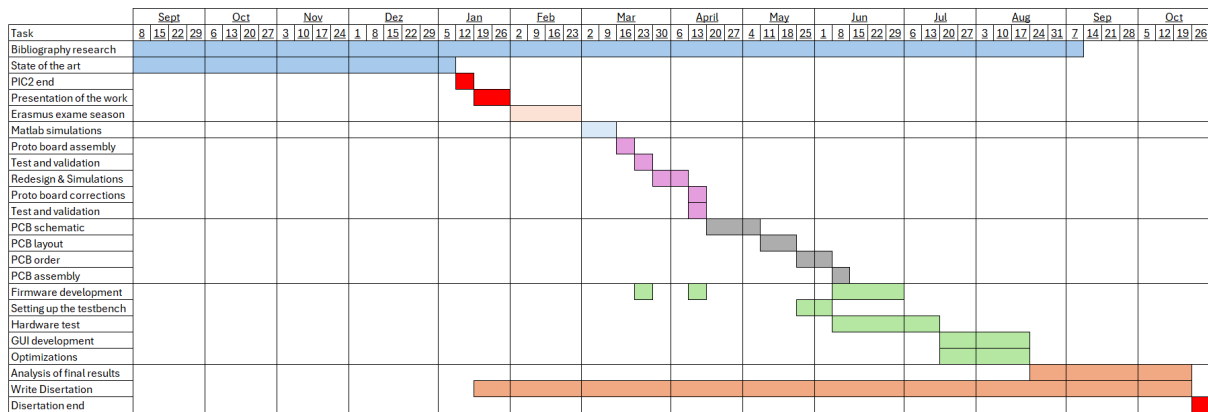
5 Planning and Scheduling

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 further expanded in the dissertation work.

Then, as described in previous sections, some simulations will be developed to evaluate the proposed solution. 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 will be designed, fabricated, assembled and tested.

Finally, firmware specifically made for the Maximum Power Point Tracker (MPPT) controller will be made alongside with hardware test and Graphical User Interface (GUI) development.

After all hardware and software design, the board will be tested alongside with SG01 in real world conditions and the data will be analyzed and documented in the dissertation document.

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