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
Keywords: MPPT, MPPT topology, DC-DC Converter

Contents

Acronyms

IST	Instituto Superior Técnico
TSB	Técnico Solar Boat
MPPT	Maximum Power Point Tracker
MPP	Maximum Power Point
PCB	Printed Circuit Board
CAN	Controller Area Network
USB	Universal Serial Bus
GUI	Graphical User Interface
PV	Photovoltaic

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. But 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 alternate energy, Photovoltaic energy is relevant due to its availability, simplicity, lower maintenance, environmental friendliness, reliability and many other benefits. More recently, is becoming more and 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, 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 begined with the construction of the first prototype, São Rafael 01 wich had a lot of room to improvement and so São Rafael 02 and 03 were built.

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. But 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 but there is still one system that is yet to be developed, the Maximum Power Point Tracker (MPPT).

The MPPT is a fundamental part of any solar energy system. Its main goal is to maximize the energy extracted from the solar panels by operating them at their Maximum Power Point (MPP). This is done by adjusting the electrical operating point of the modules or array.

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 MPPT 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 MPPT system.
- Design and simulate the MPPT system.
- Implement a fast response control algorithm for MPPT.
- Implement the MPPT system in hardware and develop a Printed Circuit Board (PCB).
- Test and validate the performance of the MPPT system.
- Ensure the safety and reliability of the MPPT system for its integration in the TSB project.
- Provide data to the user about the performance of the solar panel and MPPT system 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.

1.3 Outline

Explain how the work is organized by chapters.

2 Background

Before entering into the specific details about the project, in this chapter i will explain some general concepts about solar panels and and how to convert there energy to useful energy. This concepts will help a better understanding of the following chapters.

2.1 Solar Panels

Solar panels, also know 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.

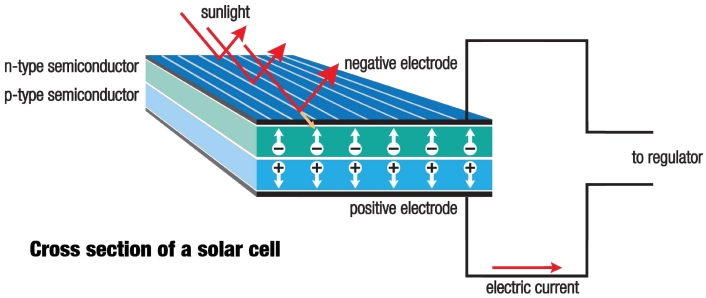


Figure 2.1: Principle of operation of a solar panel

When sunlight hits the solar cell, photons from the light energy are absorbed by the semiconductor material. This energy excites electrons, allowing them to break free from their atoms 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.

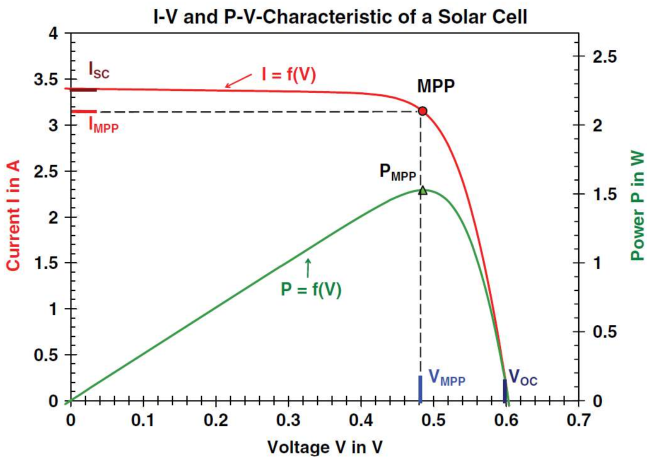
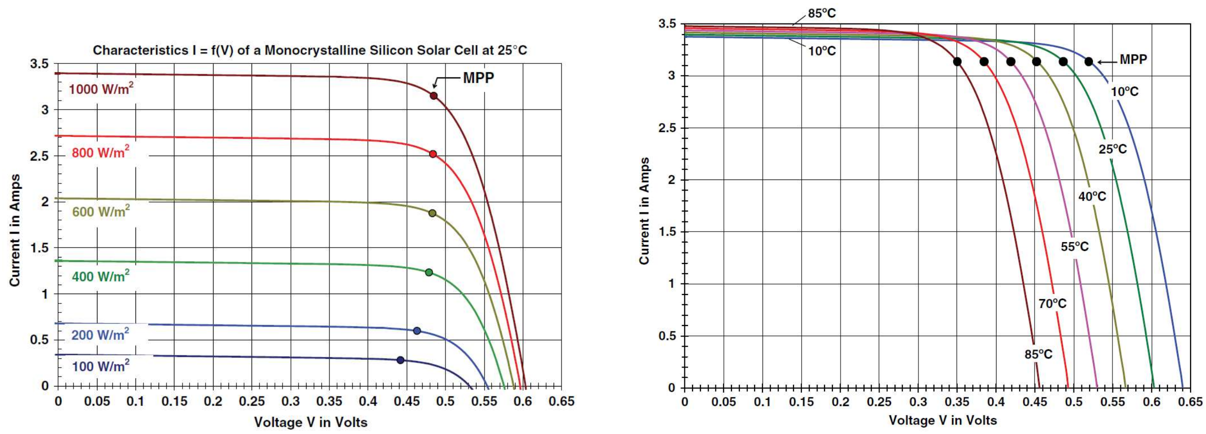


Figure 2.2: I-V and P-V curves of a solar panel [4]

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 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 ºC and variable Irradiance

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

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

substituir pelas i-v, p-v do survey

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 Maximum Power Point Tracker (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 an MPPT are used.

An 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 it's goal, an MPPT is usually composed by an DC-DC converter, an microcontroller and some sensors (Figure 2.4). The sensors are used to measure the input variables of the control system (typically voltage and current). The information acquired by this sensors are processed by the microcontroller, which runs an algorithm to determine if the MPP was reached or what needs to be done to reach it. In the second case, the microcontroller sends control signals to the DC-DC converter to adjust its operation accordingly.

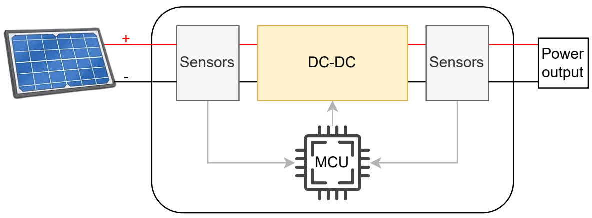


Figure 2.4: Top view of a basic MPPT system

Than, 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 this cases the MPPT is built in with the inverter).

2.3 MPPT Algotithms

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. This method uses a fixed reference voltage to operate the solar panel. This voltage enters in 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 know 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%) [5], Equation 2.1. 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.

$$V_{ref} = k \cdot V_{oc} \tag{2.1}$$

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

Both methods are simple and low cost, but they are inefficient, since they have to stop producing energy to do measurements. But there is also some variations that solve this problem by using a dummy cell to do the measurements or even an diode since its there physical properties are similar to a solar cell [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.

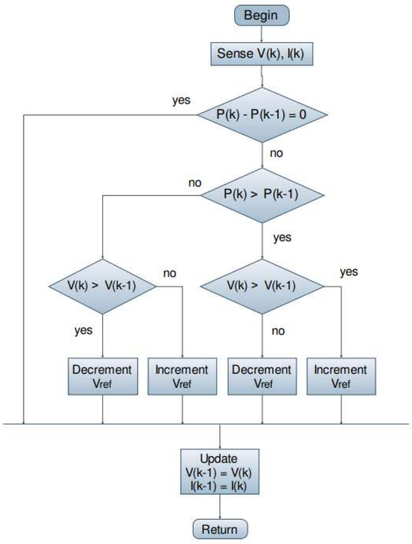


Figure 2.5: Flow chart of the classic version of Perturb and Observe algorithm [9]

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 [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 solve ($\frac{\Delta P}{\Delta V}$). 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 weal know issue of this algorithm 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 conditions must be added to the algorithm to take into account two consecutive musers 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 algorithm” 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)

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:
$-$	$-$	$-$	$-$	$-$	
$-$	$-$	$-$	$+$	$+$	
$-$	$-$	$+$	$-$	$-$	
$-$	$-$	$+$	$+$	$+$	
$-$	$+$	$-$	$-$	$-$	
$-$	$+$	$-$	$+$	$+$	
$-$	$+$	$+$	$-$	$-$	
$-$	$+$	$+$	$+$	$+$	
$+$	$-$	$-$	$-$	$-$	
$+$	$-$	$-$	$+$	$+$	
$+$	$-$	$+$	$-$	$-$	
$+$	$-$	$+$	$+$	$+$	
$+$	$+$	$-$	$-$	$-$	
$+$	$+$	$-$	$+$	$+$	
$+$	$+$	$+$	$-$	$-$	
$+$	$+$	$+$	$+$	$+$	

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.

Note for the future: The pilot could have an automatic mode and a manual mode where it could say the type of weather and the step size could be adjusted accordingly.

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 cundactance and the incremental conductance.

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

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

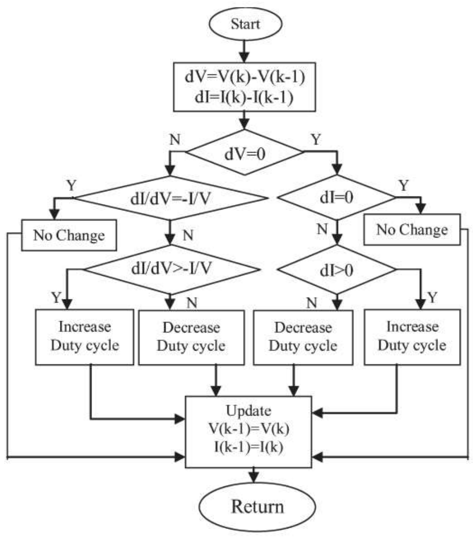
So at the MPP point, the slope of the p-v curve is zero (Figure 2.6b), which means that the negative of the conductance is equal to the incremental conductance. So the algorithm compares these two values to determine if the operating point is at, to the left or to the right of the MPP [6]:

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

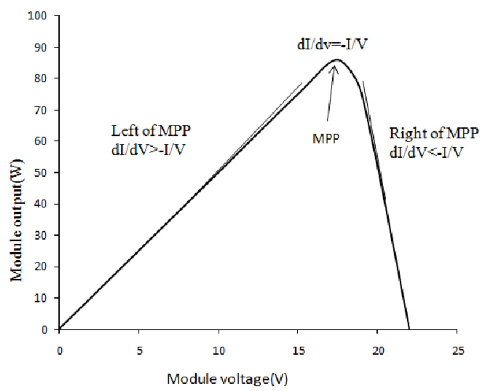
Base on this conditions the algorithm adjust it's operating point (increasing or decreasing the voltage) using a fix step size to track the MPP, as shown in the flow chart of Figure 2.6a.

As in the P&O method, there is a trade off between tracking speed and accuracy when choosing the step size. A larger step size will increase the tracking speed but will also increase the oscillations around the MPP, while a smaller step size will reduce the oscillations but will also reduce the tracking speed. To solve this issue, an variable step size can be used, where the step size is larger when the MPP is far away and smaller when it is close by sizing the step accordingly with the slope derivative [11] [12].

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. Experimental studies conducted in 2006 further corroborate these findings, demonstrating that efficiencies of up to 95% can be achieved when employing a buck converter [13].



(a) Flowchart of the IncCond method with direct control [14].



(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 this 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 acquired.

To improve the accuracy the LUT table needs 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.

2.3.5 Fuzzy logic

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

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

2.4 DCDC types

Não isolados vs isolados

Buck, Boost, Buck-Boost, Cuk, Sepic, Zeta

2.5 Processing unit

Microcontroller vs FPGA vs DSP este paper implementa um MPPT numa FPGA [**?**]

Arduino, STM32, Raspberry Pi, others

3 State-of-the-Art

Intro if needed

3.1 MPPT algorithms

Escolher algumas para falar

3.1.1 Constant Voltage (CV)

3.1.2 Fractional Open Circuit Voltage (FOCV)

3.1.3 Fractional Short Circuit Current (FSCC)

3.1.4 Perturb and Observe (P&O)

3.1.5 Incremental Conductance (IncCond)

3.1.6 Method beta

3.1.7 Method based on temperature

3.2 MPPT converter topology

Intro..

Escolher algumas para falar

3.2.1 Buck Converters

3.2.2 Boost Converters

3.2.3 Buck-Boost Converters

3.2.4 Sepic Converters

3.2.5 Half-Bridge Converters

3.3 Comercial MPPTs

Table with comercial MPPTs and some of their carateristics.

3.4 Battery charging unit

3.5 Protection circuits

4 Solucion Proposal

4.1 Microntroller

Explicar a escolha do microcontrolador, o que ele faz, etc

4.2 Communication

sensors, CAN, USB, GUI

4.3 Current and Voltage Sensing

pq que é necessarion, e o que é que escolhi

4.4 Power electronics

Topologia escolhida, pq, vantagens e componentes

5 Preliminary Work

6 Planning and Scheduling

Fazer um planeamento com um gantt chart e explicar as decisoes

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A Appendix Name