Development of a Maximum Power Point Tracker system for the project Técnico Solar Boat

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Abstract—The use of renewable energy sources has been growing considerably through the last years, with solar energy being one of the protagonists of this growth. Solar energy’s road has been promising, reaching a point where it’s possible to power almost any type of load, from industrial and domestic installations to electric vehicles.

Given solar cells’ low efficiency, it’s crucial to maximize the energy produced by photovoltaic systems. In order to achieve this goal, the Maximum Power Point Tracker is created. The MPPT is a device that seeks to ensure that a solar panel is always working at its maximum power point, thus maximizing the produced energy.

This paper consists of the design and development of an MPPT prototype, developed for one of Tecnico Solar Boat’s vessels. The goal is to perform a complete study going through the stages of investigation, design and finally, prototyping.

This document begins with the theoretical component, analyzing the boat’s electrical system which contains 5 solar modules with a total peak power of 1.2kW and a Li-Po battery of 1.5kWh. After, the design of the DC-DC converter is done, which is the fundamental block of the MPPT. The DC-DC converter allows rising the solar panels’ voltage to match the battery’s value, working as connection between both components.

After, an introduction is made about MPPT algorithms explaining how they work. Several algorithms such as Perturb & Observe and Fuzzy Logic are explained, discussing their respective advantages and disadvantages.

After concluding the theoretical stage, the prototyping phase begins. During this phase, the circuit and PCB are designed, and after, all the components are soldered. With the prototype finalized, several tests are performed to confirm the correct behaviour of the MPPT.

Index Terms—Maximum Power Point Tracker, DC-DC Converter, Photovoltaic Panels, Solar Energy, Solar Boat

I. INTRODUCTION

Nowadays, the world is experiencing an authentic energetic revolution which has been driven by several aspects such as economy, environment and technology. This has led to the growth of renewable sources producing in 2020 almost 29% of the energy worldwide, with solar energy corresponding to 11.5% of the renewable energy sources [1].

Solar energy has assumed a fundamental role in the energetic industry growing exponentially during the last few years. It is expected for it to reach an installed capacity of over 1250 GW in the year 2030 [2]. This growth also leads to an increase in demand and in the importance of photovoltaic integration circuits, which are essential for the production of solar energy. One of the most important of these components is the Maximum Power Tracker. This component seeks to ensure the photovoltaic panels are extracting the maximum possible power at any moment and at any conditions.

This paper addresses the dimensioning, design and prototyping of an MPPT with the objective to be used in Tecnico Solar Boat’s competition vessels. This will give TSB the flexibility of a custom made product that may be improved and adjusted to the vessel’s needs.

II. STATE OF THE ART

The relationship between humanity and the sun remotes to ancient times, the idea of using solar energy has been around for 2000 years. However, it was only in 1883 that the inventor Charles Fritts developed the first solar cell using selenium as main material and goal coating, this cell had an overall efficiency of around 1% [3]. One year later the first solar panel was installed in a rooftop in New York, marking an important milestone for solar energy. Since the decade of 1950 solar cells’ efficiency has had a considerable evolution going from a 6% efficiency to values over 47%. However, the current efficiency values are still not high enough to make solar power completely affordable for everyone, which is why it’s essential that the panels are able to perform as efficiently as possible at all time.

From this need, the Maximum Power Point Tracker concept appears, a device meant to maximize the energy produced by a solar array. Two types of trackers arise, mechanical, which consists of structures that allow the solar panels to physically accompany the sun’s movement, and electrical tracking which involved the use of MPPT algorithms to keep the panels working at their most efficient operating point, the MPP. Due to the complexity and low efficiency of mechanical trackers, most of the research was directed to MPPT algorithms for electrical tracking [4].

The first MPPT charger was born in 1985 when Australian electrical engineer Stuart Watkinson developed a device to power an electric bicycle through a solar panel. This device was called “power optimizer” [5].

Technological advances during recent years in semiconductor devices development have helped to achieve considerable improvements in power electronics components, micro-controllers, and consequently in MPPT. These have become much more efficient reaching values above 95% efficiency in the search for the maximum power point. Furthermore, MPPT have become increasingly compact and inexpensive. For these
reasons, the use of MPPT has become a standard practice for photovoltaic systems.

III. GENERATION AND STORAGE SYSTEMS

The system where the MPPT will be inserted is the solar powered boat SR02, built by the team of Técnico Solar Boat. The boat’s system is complex, but for the development of the MPPT it’s only necessary to analyze the generation and storage systems. These systems consist in two main components, the solar panels and the battery, with the MPPT working as the link between the two components.

A. Photovoltaic Panels

The vessel SR02 has a total solar of 384 monocrystalline cells distributed in 9 different panels as shown in figure 1. The panels are divided into 5 ensembles (four ensembles of 80 cells and one individual panel with 64 cells) connected in parallel and have a total peak power of 1.2kW.

Solar cells present a characteristic I/V curve that begins with a maximum current value $I_{SC}$ when the voltage is zero, and that gradually drops as the voltage increases. The curve eventually reaches the "knee" zone where the current drops rapidly until going to 0 at the maximum voltage value, $V_{OC}$. Multiplying the each current value by its corresponding voltage, one obtains the panel’s P/V curve, as seen in figure 2.

The P/V curve presents a unique maximum power point where the power that can be extracted from the panel is maximum. The I/V and P/V curves for a solar array present the same shape as a single cell’s curves. These curves depend heavily on the environmental conditions to which the panel is subject, especially irradiance and temperature, which means the MPP may be continuously changing. The objective of the MPPT is to induce the panel to operate at the MPP, trying to track it under any conditions.

B. Current MPPT

Currently 5 Genasun MPPT are used in the SR02’s system, having one MPPT for each panel ensemble and being all of them connected in parallel to the battery. Figure 3 shows the current MPPT with the arrangement used on the boat.

These MPPT have a good performance, but the objective is to replace them for several reasons, the first being that these MPPT don’t have any communication system to enable data storage and analysis. This is an obstacle since data analysis is essential to study the system’s performance and to evaluate possible changes that could be done to improve it.

Another disadvantage is that the MPPT have fixed parameters, which means they can only be used with batteries that share the same parameters as the current one. This makes it difficult to re-use the devices for systems that may be different, and gives no possibility of improving the algorithm used.

Finally, the price of each MPPT is nearly 150€, which makes purchasing more devices for future vessels an unfeasible option.

C. Battery

The battery used in the boat is a custom made Li-Po cells battery. It’s formed by two series of 12 cells, each one with capacity of 16.8Ah, a nominal voltage of 3.7V and a maximum voltage of 4.2V. With these specifications, the resulting battery presents a total capacity of 33.6Ah, nominal voltage of 44.4V and a maximum voltage of 50.4V.

The standard charging method for lithium ion batteries presents a process made by two phases, Constant Current (C.C) and Constant Voltage (C.V). The first phase occurs when the battery voltage is below its maximum value, during C.C the battery’s charging current is maintained constant while the voltage increases. When the voltage reaches its maximum value C.V phase begins keeping the battery voltage constant and gradually reducing the current. Once the current value drops to 5% (sometimes 10%) of the battery’s capacity value, the charging process ends and the battery is considered charged. For the SR02’s battery, the charging will be finished once its
charging current reaches 1.68A. Figure 4 shows the typical charging process for a lithium-ion battery.

![Graph](image)

Fig. 4. Typical charging curve for lithium-ion batteries [7]

IV. DC-DC CONVERTER

Switching converters are a part of today’s everyday, they can be found in almost any electrical device. This type of converters are specially important in energy systems which require integration between different voltage levels. With the evolution of semi-conductors it is possible to develop very high efficiency converters nowadays. For the MPPT, a boost converter type was chosen, in order to step-up the voltage from the solar panels to match the battery voltage. A generic circuit for a boost converter may be seen in figure 5.

![Diagram](image)

Fig. 5. Boost converter schematic

A. Boost converter operation

As seen in the figure, the boost converter presents a simple structure with 4 fundamental components: inductor, capacitor, MOSFET (or TBJ, IGBT, etc), and diode.

The MOSFET operates as a switch that is turned ON and OFF by a control signal, given this it’s possible to conclude that this circuit has two possible states, ON and OFF. The circuit operates switching periodically between the two states, hence the name switching converter. Both states are shown in 6.

During the ON state, the MOSFET is conducting, so it behaves as a short circuit. This means the inductor is directly connected to ground and the input voltage is applied to it. This leads to a current flow through the inductor which charges it. At the same time since the diode is also connected to ground, it becomes reverse polarized and acts as an open circuit.

When the circuit switches to the OFF state, the MOSFET stops conducting, behaving like an open circuit. The inductor’s current must maintain its continuity, this polarizes the diode, becoming a short circuit as shown in figure 6(b). The current is transferred to the capacitor which charges and increases its voltage value.

![Diagram](image)

Fig. 6. Switching states of boost converter

The switching between these two states is done through a control signal, a PWM wave with a fixed frequency and a variable duty cycle. The duty cycle defines the time percentage from each period, where the converter is in the ON state. Being duty cycle represented with the variable $\delta$ and the signal period with the variable $T$, we obtain the following expression

$$\begin{cases}
[nT : nT + \delta] \rightarrow S_1 \text{ ON} & \text{& D OFF} \\
[nT + \delta (n+1)T] \rightarrow S_1 \text{ OFF} & \text{& D ON}
\end{cases}$$

(1)

Duty cycle is described by a value between 0 and 1, the closest this value is to 1, the more time the converter will spend on state 1. The longer the converter stays in this state, the more time the inductor will have to charge and hence, the output voltage will be higher. Once in stationary mode, the rate at which the inductor charges and discharges stabilizes, keeping the output voltage’s average value constant.

Studying one time period $T$ in stationary mode, it is possible to obtain the following expressions:

$$\begin{cases}
[0 : n\delta T] \rightarrow v_L = V_{in} \\
[n\delta T : (n+1)T] \rightarrow v_L = V_{in} - V_o
\end{cases}$$

(2)

Since the inductor charges and discharges completely in one period, it’s possible to conclude that the average current value in one period is equal to zero

$$v_{L_{avg}} = \frac{1}{T} \left( \int_0^T v_L \, dt \right) = 0$$

(3)

Using (2) and (3), it is possible to obtain the relationship of the input and output voltages with the duty cycle

$$\frac{V_o}{V_{in}} = \frac{1}{1 - \delta}$$

(4)

From this equation it’s possible to conclude that in stationary mode the output and input voltage ratio depends exclusively on the control signal’s duty cycle. This is an ideal expression that suggests that the input voltage could be increased infinitely by regulating the duty cycle, but this is not possible considering the losses in each component.

B. Sychronous boost converter

The conventional boost converter shown in figure 5 corresponds to an asynchronous boost converter. In this type of converter there is no need for synchronization between the MOSFET and the diode, since the diode is in free wheeling
mode (driven by the MOSFET). This diode can be substituted by another MOSFET as shown in 7.

This update brings a main advantage to the circuit, given that MOSFETs often present less losses than diodes. This way the converters efficiency can be increased, but this also creates the necessity to ensure that both MOSFETs are never turned on at the same time. If both MOSFETs turn on at the same time a short-circuit will happen, damaging the circuit and its components. To ensure this doesn’t happen, an adequate gate driver should be used.

C. Dimensioning

To design the boost converter, several parameters must be analyzed in order to choose the most adequate values for each component. The correct dimensioning of these components is essential for the converter to achieve high-efficiency and reliability.

The main parameters to be defined are the following:

- Switching frequency ($f$): An important parameter since it will directly affect the dimensions of the inductor and the capacitors. The MOSFETs’ switching losses also depend on this parameter. The frequency chosen is 80kHz.
- Input voltage ($V_{in}$): The possible interval of voltages measured at the solar panel’s terminals. This parameter is important to determine the duty cycle ranges at which the converter will operate. The minimum value chosen corresponds to 15V, with the maximum voltage being the battery’s maximum voltage, 50.4V.
- Input current ($I_{in}$): The input current values are especially important for the inductor’s rating. The maximum average value defined for this parameter is 7A, and a 10A as total maximum value including the current ripple.
- Duty cycle ($\delta$): The range of possible duty cycles will affect the dimensioning of some of the components and will also have an impact on the overall efficiency of the circuit. The operating duty cycle is determined to be able to rise up to 70%.

With these parameters defined, it’s possible to begin dimensioning all the boost converter’s components.

1) Inductor: To dimension the inductor the inductor’s equations are analyzed, obtaining:

$$v_L = L \frac{di_L}{dt} = L \frac{\Delta i_L}{\Delta t}$$

were $\Delta i_L$ corresponds to the inductor’s current ripple. Through (3) and (5) it’s possible to obtain the inductor’s value expression

$$L = \frac{V_o(1-\delta)\delta T}{\Delta i_L}$$

The circuit must be designed to work in the Continuous Conduction Mode, which means that inductor’s current value never reaches 0. Considering the frontier case between Continuous Conduction Mode and Discontinuous Conduction Mode we obtain

$$I_{L_{avg}} = \frac{\Delta i_L}{2} \iff \Delta i_L = 2 \left( \frac{I_o}{(1-\delta)} \right)$$

Using the expression obtained in (7) with equation (6) and maximizing its result through $\delta$ it is possible to obtain the expression for the critical inductance value

$$L_{crit} = \frac{2V_oT}{2T_{io}}$$

In order for the circuit to work in CCM, the inductor value must be greater than the critical value. The expression is maximized with an output voltage of 50.4V and an output current of 1.68A, calculating the critical inductance value.

$$L_{crit} = 28 \mu H$$

This way, it’s concluded that the inductor needs to fulfill the following conditions:

$$\begin{cases}
L \geq 28 \mu H \\
I_{L_{rated}} \geq 10A
\end{cases}$$

A 68$\mu H$ inductor is chosen, which respects the critical induction value condition. For the second condition, the maximum current ripple value is calculated through (6) and added to the maximum average PV current value (7A). This way we obtain

$$i_{PV_{max}} = 7 + 2.32 = 9.32 A$$

thus respecting the second condition.

2) Output capacitor: The output capacitor value is essential to limit the output voltage ripple. The dimensioning begins with the capacitor’s equation

$$i_C = C_o \frac{dV_o}{dt} = -C_o \frac{\Delta V_o}{\Delta t} = -C_o \frac{\delta V_o}{\delta T}$$

Knowing that $i_C = -I_o$ the equation is modified resulting in

$$C_o = \frac{I_o \delta T}{\Delta V_o}$$

Relating $I_o$ and $I_L$ it’s possible to obtain

$$C_o = \frac{I_L(1-\delta)\delta T}{\Delta V_o}$$
Choosing a voltage ripple value and replacing the remaining variables in order to maximize the equation, a critical value for the output capacitance is calculated

\[ C_{o_{\text{min}}} = 625 \mu F \]  \hspace{1cm} (15)

Given this value, an 820\( \mu \)F capacitor is chosen.

3) Input capacitor: The process for selecting the input capacitor is similar to the output capacitor process. A value for the voltage ripple \( \Delta V_{in} \) is chosen, and for \( \Delta t \) the value of half a period \( T \) is considered. Given this the critical value for the input capacitance is the following:

\[ C_{in} = \frac{\Delta t \times I_{in}}{\Delta V_{in}} = \frac{T \times I_{in}}{2 \times 0.01 \times V_{th_{\text{min}}}} = 417 \mu F \]  \hspace{1cm} (16)

In order to give a considerable margin, an 820\( \mu \)F capacitor is chosen.

4) MOSFETs: The MOSFETs for the DC-DC converter must be able to withstand all the voltage and current values. Besides this, the MOSFETs should have low internal resistance and low switching times in order to minimize the power losses.

Having these aspects in consideration the MOSFETs chosen are Infineon’s BSC070N10NS5, with the characteristics presented in Table I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_{ds} )</td>
<td>10.3 m( \Omega )</td>
</tr>
<tr>
<td>( V_{ds_{\text{adh}}} )</td>
<td>100 V</td>
</tr>
<tr>
<td>( I_{\text{rated}} )</td>
<td>80 A</td>
</tr>
<tr>
<td>( t_{\text{rise}} )</td>
<td>18 ns</td>
</tr>
<tr>
<td>( t_{\text{fall}} )</td>
<td>30 ns</td>
</tr>
</tbody>
</table>

D. Efficiency

Since none of the electrical components are ideal, power dissipation exists in the circuit. Given this, the input and output power are related through an efficiency \( \eta \). The expression to calculate this efficiency is the following,

\[ \eta = \frac{P_o}{P_o + P_{\text{loss}}} = \frac{1}{1 + \frac{P_{\text{loss}}}{P_o}} \]  \hspace{1cm} (17)

where \( P_{\text{loss}} \) corresponds to the sum of all the losses in the different components. Separating by terms the different types of losses, the following expression is obtained:

\[ \eta = \frac{1}{1 + \frac{r_L}{L_o (1-\delta)^2} + \frac{r_C}{C_o (1-\delta)} + \frac{(t_{\text{rise}} + t_{\text{fall}})}{V_o (1-\delta)^2} + \frac{r_{ds} I_o}{V_o (1-\delta)^2}} \]  \hspace{1cm} (18)

Using the real component’s values and assuming the highest values for output voltage and current, it’s possible to obtain a function with \( \delta \) as its only variable. Figure 8 shows the obtained curves for efficiency and power losses.

Through the figure it’s concluded that the estimated efficiency of the circuit is above 95% for duty cycle values under 70%. It can be observed that the most significant losses correspond to inductor’s losses and the MOSFET’s conduction losses. In order to increase the circuits efficiency even more, components with less internal resistance should be used.

V. MAXIMUM POWER POINT TRACKING

The main objective of an MPPT is to voltage point where a solar panel produces the most energy and induce it to operate in it. An I/V curve always has a value that allows a maximum power to be extracted from the panel, this value changes easily due to environmental conditions. Since the panel’s operating point depends exclusively of the impedance of the load connected to its terminals, it’s necessary to be able to control this impedance in order to induce the panel to work on the MPP. This is done by the DC-DC converter, working as a bridge. While keeping the output voltage approximately constant due to the battery, changes in the converter’s duty cycle will force the impedance at the solar panel’s terminals to change as well. This will induce changes in the panel’s voltage, thus modifying its operating point.

This means the duty cycle is used as a control variable in order to regulate the panels operating point. As it can be observed in figure 9, an MPPT algorithm is used to control the value of the duty cycle in order to find the MPP.

MPPT algorithms are used to estimate the MPP value in a given instant, and control the duty cycle in order to search for it. Nowadays, there are several kinds of MPPT algorithms developed [8]. Each algorithm has with its own advantages.
and disadvantages in several aspects such as speed, robustness and complexity. Some of the most popular algorithms will be addressed in this paper.

A. Fractional open-circuit voltage

A very simple algorithm that uses the knowledge of the \(I/V\) and \(P/V\) curves’ form. It is known that the ratio between \(V_{MPP}\) and \(V_{OC}\) normally corresponds to a value between 0.78 and 0.92 for any value of irradiance and temperature. This way it’s possible to assign a constant value \(K_{OC}\) that allows to assume

\[
V_{MPP} \simeq K_{OC} \times V_{oc}
\]  

(19)

Through tests with the solar panels, a value is chosen for \(K_{OC}\). At the beginning of the algorithm, the panel is forced into its \(V_{OC}\) and the value is measured, and then with the defined constant, the estimated \(V_{MPP}\) is calculated. This process must be repeated periodically, since the weather conditions may be constantly changing. Since this requires the panel to be forced into its \(V_{OC}\) periodically, considerable energy is “wasted” during this process. The main advantage of this algorithm is its simplicity, since it may be implemented in almost any micro-controller, and it only needs to measure the panel’s voltage. The main disadvantage is its low efficiency.

B. Perturb & Observe

One of the most popular MPPT algorithms, for its simplicity and excellent efficiency [8]. This algorithm presents a hill-climber operating principle which means the algorithm changes periodically its operating point based on the \(P/V\) curve’s slope trying to climb it to reach the top. Hill-climber algorithms are interesting because they are able to adapt to almost any environmental condition change.

P&O bases its decision on the variation of the power produced by the panel \(\Delta P\) and the variation of its voltage \(\Delta V\) between two iterations. The algorithm “perturbs” the panel’s operating point by increasing or reducing the voltage, then it observes the power variation caused by that change in voltage. Through this process, the algorithm estimates if the panel is operating in the "left" or "right" side of the MPP, as shown in 10. If the power variation was positive, the algorithm concludes it’s getting closer to the MPP and therefore it continues, if not, it begins to make an opposite perturbation.

The panel’s voltage increases and decreases are done through duty cycle steps of the converter. The size of these steps is essential for the overall efficiency of the algorithm, since it affects the time to converge and precision of the algorithm. A larger step will converge faster, but will be less accurate finding the MPP.

Since this algorithm depends on variation measurements to decide its next step, it’s possible to conclude that this algorithm will have a static error associated to it. The P&O algorithm is not able to reach a single MPP value, it will always be oscillating. This problem can be fixed by defining a stop criterion when the power variation reaches a value that is small enough.

C. Incremental Conductance

A similar algorithm to P&O, given that it’s also a hill-climber algorithm. Given this, its efficiency is approximately equal to the P&O algorithm [8]. The main difference from these two algorithms consists in the parameters that are analyzed in each iteration for the decision-making. Incremental Conductance analyzes the value of the conductance (reverse resistance) at the panel’s terminals. This term appears analyzing the \(P/V\) curve’s derivative equation

\[
\frac{dP_{pv}}{dV} = \frac{d(V \times I)}{dV} = I + V \frac{dI}{dV} = I + V \frac{\Delta I}{\Delta V}
\]

(20)

Through this equation it’s possible to conclude that the derivative of power to voltage is equal to the current added to the product between the voltage and the slope of the conductance (incremental conductance). Since it’s known that at the MPP, the derivative of power to voltage is equal to 0, using (20) it’s possible to obtain a new condition for the MPP

\[
\frac{I}{V} = \frac{\Delta I}{\Delta V}
\]

(21)

This means, the solar panel is operating at its MPP when the instantaneous conductance matches the incremental conductance. Given this it’s possible to obtain 3 different conditions that are able to describe a \(P/V\) curve

\[
\begin{align*}
-\frac{1}{V} < \frac{\Delta I}{\Delta V} & \quad \text{Operating point at left side of MPP} \\
-\frac{1}{V} > \frac{\Delta I}{\Delta V} & \quad \text{Operating point at right side of MPP} \\
-\frac{1}{V} = \frac{\Delta I}{\Delta V} & \quad \text{Operating point at MPP}
\end{align*}
\]

(22)

As the P&O algorithm did, IC applies a perturbation in the panel’s voltage and registers the different variation values between iterations. After measuring, the algorithm validates which one of the three conditions is met, and concludes if it should increase or decrease the panel’s voltage in the next iteration.
The IC algorithm bases its decisions from both current and voltage measurements allowing it to react better in fast changing conditions. However, since this algorithm is also based on variations of values it presents a static error which may be solved through a stop criterion.

D. Fuzzy Logic

With the rise of computing power during last years, soft computing algorithms have been popularized for implementing MPPT systems. The term soft computing represents the use of intelligence and computational capacity to solve uncertain or inaccurate problems, which would take too long to solve through conventional algorithms. Soft computing techniques allow obtaining the best results in systems with non-linear behavior [10].

Fuzzy logic is one of the most used methods of soft computing. It’s an extension of the boolean logic that allows representing intermediate values between true or false using linguistic variables.

As it can be observed in 11, the iteration of a fuzzy logic algorithm consists in 3 phases: fuzzyfication, inference and de-fuzzyfication.

![Fig. 11. Phases of a fuzzy logic iteration for a PV system [10]](image)

The fuzzyfication consists in the conversion of the numerical input values \( \Delta V \) and \( \Delta P \) into linguistic values, fuzzy values. This step is done through categorization using a set of predefined membership values for each variable.

The inference phase consists on the application of a rulebase to the fuzzy values, allowing to obtain output values. The rulebase is designed according to the system with one rule assigned to each membership value.

After the output values are obtained they require to be de-fuzzified again into a numerical value. These values are translated into a real output value that is applied to the system, updating the converter’s duty cycle.

Fuzzy logic presents several advantages, one being its adaptability to a given system through calibration, the fuzzy logic algorithm can be as exact as needed by the user. This can also be a downsize, since its efficiency depends exclusively of quality of the defined rulebase and membership values. This leads to a considerable effort in the calibration of the algorithm through simulation and experimentation.

E. Partial shading conditions

Most algorithms work with the a priori estimative of the I/V and P/V curves’ shapes, assuming the existence of only one MPP. This assumption is true in ideal conditions, when all solar cells are uniformly irradiated, in case of partial shading, due to the use of bypass diodes the curves’ shape changes with multiple MPP appearing, as shown in 12.

![Fig. 12. P/V curve in partial shading conditions [11]](image)

In this cases, the MPPT algorithm will not be able to distinguish if the estimated MPP actually corresponds to the global MPP. There are algorithms that attempt to tackle this situation, but there is currently no algorithm that presents a 100% convergence in the global MPP, and all the advantages from conventional algorithms. One of the most popular solutions is to use a conventional MPPT algorithm and to periodically make a voltage sweep in the panel measuring the power for each point, verifying if the calculated MPP corresponds to the global value. This process leads to some loss in efficiency, but it helps guarantee the solar panel is working at the global MPP almost all the time.

VI. IMPLEMENTATION

The MPPT implementation phase can be divided into 2 steps: simulations, and prototyping.

A. Simulations

Simulation is a fundamental step for any project, since it allows to predict the circuit’s behaviour and detect possible errors before beginning the prototyping stage. It also allows to design different features that are needed for the MPPT system.

The boost converter circuit is simulated with the software LTspice, allowing to validate its correct dimensioning and also to design protection systems, obtaining the circuit seen in 13.

![Fig. 13. LTspice schematic of boost converter](image)

For shoot-through protection two small value resistors were connected to the gate-driver’s output, being the smaller one in series with a Schottky diode. With this connection the current is blocked on its way through the lower resistor to the MOSFET’s gates, forcing the current through the higher resistor and thus causing a higher rise time for the MOSFET.
When the MOSFET is pulled down, the current is able to flow through the diode and the smaller resistor, causing a considerably lower fall time. This way it’s guaranteed that both MOSFETs will take longer turning on, helping not to have both MOSFETs on under any circumstances.

Reverse polarity, overvoltage and overcurrent protection is done with the same chip, the LTC4359. This chip is connected to 2 MOSFETs in the output of the circuit, one to block current flowing from the load to the converter, being this for the reverse polarity protection. The second MOSFET is used to disconnect the load when needed, an enable flag is connected to the micro-controller and de-activated in case either overvoltage or overcurrent is detected.

After simulating the boost converter, the complete system circuit including a solar panel and a battery was modeled using Simulink as shown in 14. Through this model, an operating MPPT was simulated which allowed analyzing the behaviour of some MPPT algorithms: Fuzzy Logic, Incremental Conductance and Perturb & Observe.

Several variations in irradiance and temperature are done during the simulations in order to evaluate each algorithm’s capacity to adapt to these variations. All algorithms are tested under the same conditions defined in II in order to have an even comparison between them, obtaining the results shown in 15.

<table>
<thead>
<tr>
<th>Testing Parameters for MPPT Simulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>time (s)</td>
</tr>
<tr>
<td>Irradiance (W/m²)</td>
</tr>
<tr>
<td>Power at MPP (W)</td>
</tr>
<tr>
<td>Temperature (°C)</td>
</tr>
</tbody>
</table>

As it can be seen in both figures, all algorithms are able to follow the MPP changes successfully during the entire simulation. The hill-climber algorithms show a ripple when converging at the MPP, due to their static error. Fuzzy Logic on the other hand shows an almost constant estimate for the MPP, but fails to converge accurately in one of the cases, which means that the rulebase and membership values should be better calibrated.

B. Prototyping

The prototyping begins with the development of a schematic of the complete circuit with all its components, including measuring components, micro-controller and additional logic. After finalizing the schematic and choosing all the components, the PCB for the prototype is designed. Figure 16 presents the completed PCB with all its components and ready for testing.

VII. Results

With the prototype ready, several tests are performed to validate the correct operation of the circuit and also the MPPT algorithms. Separated tests are done first to evaluate each component individually before testing the entire circuit. After validating every component the final tests are performed using a complete setup including a solar panel and a 48V Li-Po battery.
A. MPPT algorithms

Three algorithms are tested in order to validate their correct implementation and reliability tracking the MPP under several environmental condition changes. The results obtained for each algorithm can be observed in 17.

(a) Perturb & Observe

(b) Incremental Conductance

(c) Fuzzy Logic

Fig. 17. MPPT algorithm testing results

From the results obtained it is possible to conclude that all of the algorithms are able to successfully react to sudden environmental changes. For the hill-climber algorithms it’s possible to observe that the $V_{MPP}$ value is never constant, but it presents a small oscillation around its real value. The oscillation is caused by the static error inherent to both algorithms. This isn’t verified in the case of Fuzzy Logic, as it may be seen that the algorithm tracks a constant $V_{MPP}$ value, this is an advantage since it increases the algorithm’s efficiency. However, it was verified that in some cases the estimate of MPP calculated by the Fuzzy Logic algorithm would be less accurate that the one obtained through Perturb & Observe or Incremental Conductance. This means that the algorithm is still in need of some calibration at the rulebase and membership values levels in order to be optimized.

B. MPPT’s electrical efficiency

During the algorithms’ testing it’s also possible to analyze the electrical efficiency of the circuit. For this purpose, input and output powers are calculated and represented in figure 18. The results of the tests show that the converter presents an efficiency above 88% for any duty cycle between 0 and 90%. This is a very positive result given that the converter is expected to work at lower duty cycle values, and thus at a higher efficiency.

C. Full battery charging

The final tests consist of performing full battery charges with the prototype using DC supply capable of simulating a solar panel in order to obtain uniform results. Figure 19 shows the process of a complete charging cycle, both C.C and C.V phases can be clearly observed. The battery begins with 45V voltage and it charges with the panel working at its MPP, thus supplying its maximum power. The battery voltage rises during this phase, while the current reduces since the solar panel is already supplying the maximum power available. When the battery voltage reaches its maximum value, 50.4V, the charging mode switches to C.V, and the current flowing to the battery starts reducing gradually while the voltage is kept constant. Once the current reaches the value of 5% of the batterie’s capacity the process ends and the battery is considered fully charged.

Having finalized this test, it’s possible to conclude that the prototype is ready to be included in the system of SR02.

VIII. CONCLUSIONS

In this paper an MPPT prototype for a solar powered boat was designed, developed and tested successfully.

The electrical system of the SR02 was studied in order to better understand the role the MPPT would play, and
the conditions it should satisfy for a correct implementation. Having these conditions defined, a boost converter type was selected and designed according to the system’s requirements. With a study of the functioning of Maximum Power Point Tracking several algorithms were analyzed.

For the implementation of the MPPT simulations were made in order to validate the circuit’s design and the algorithms to be used in the prototype. Finally the prototype PCB was designed and soldered in order to perform the tests.

With the prototype finalized the MPPT tests are done implementing the algorithms: Perturb & Observe, Incremental Conductance and Fuzzy Logic. With the tests it’s possible to conclude that all algorithms are implemented correctly and are able to react robustly to environmental conditions changes. It’s also possible to conclude that the hill-climber algorithms showed the most robust results, being able to always track the MPP and keeping a relatively small oscillation around it. In order to avoid tracking the wrong MPP in partially shaded conditions, a voltage sweep can be programmed to be triggered once periodically to verify the MPP, this way an overall robust algorithm is obtained. Through the tests it’s also possible to confirm the MPPT’s high electrical efficiency. Finally a test of a full battery charge process was performed successfully which indicated the readiness of the prototype to go into production.

A major improvement to be made is the design of a final PCB prototype could be done including several MPPT channels in the same board, making the system more compact and economic. Another possibility is to make a more efficiency focused design for the MPPT taking into consideration the capability of developing the system’s solar panels, this way the result would be an even more optimized ensemble. It’s also possible to further study more complex MPPT algorithms using tools such as machine learning, and also focus on addressing the multiple MPPs problem. Finally, battery charging algorithms could be investigated to search for a faster alternative to the C.C/C.V method.

References