Optimised Photovoltaic Solar Charger With Voltage Maximum Power Point Tracking

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ABSTRACT

The main goal of this thesis is to use the solar power to charge Lithium-ion (Li-ion) batteries. It is implemented a conventional Pulse Width Modulator (PWM) duty cycle ratio control method to design and build a solar battery charger prototype. Maximum power point tracking (MPPT) is used in the photovoltaic (PV) system to maximise the PV output power, irrespective of the temperature and irradiation conditions. It has been implemented a MPPT system, consisting of a buck-type Direct Current (DC)/DC converter, which is controlled by a microcontroller unit. The microcontroller is programmed with a simple and reliable MPPT technique: the voltage MPPT (VMPPT). It is presented a model for the lithium-ion battery (Li-Ion) that is suitable for computer simulation. The used model can be easily modified to fit data from different batteries.

The simulation results achieved by using Pspice and Simulink programs are in good agreement with the experimental results. These results allowed demonstrating the reliability and validity of the proposed MPPT technique. The battery charger prototype was tested and the results obtained allowed to conclude about the conditions of permanent control on the battery charger.

KEYWORDS

Solar battery charger, photovoltaic systems, DC/DC converter, maximum power point tracking, duty cycle ratio control, microcontroller.
RESUMO

O principal objectivo desta tese é utilizar a energia solar para carregar baterias de Ion Lítio (Li-ion). É implementado um Modulador por Largura de Impulso (PWM) que utiliza um controle através de duty cycle de modo a controlar todo o processo de carga. Desta forma foi possível projectar e construir um protótipo para o carregador solar. De forma a maximizar a potência extraída do painel fotovoltaico foi utilizado um algoritmo que procura constantemente extrair o máximo ponto de potência (MPPT) do sistema fotovoltaico independentemente das condições de temperatura e níveis de irradiação existente. O sistema de MPPT implementado consiste num conversor de corrente contínua associado a uma topologia do tipo buck (DC/DC buck converter) que é controlado por um microcontrolador. O microcontrolador é programado com um algoritmo simples e eficaz de procura do ponto máximo de potência designado por voltage MPPT (VMPPT). É também apresentado um modelo elétrico para a bateria de Li-ion adequado para realizar a simulação em computador. O modelo utilizado pode ser facilmente modificado para permitir a simulação de diferentes tipos de baterias.

Os resultados obtidos experimentalmente estão de acordo com os resultados obtidos através de simulação utilizando as ferramentas do Pspice e Simulink. Estes resultados permitem demonstrar a fiabilidade e a validade da técnica de MPPT proposta. O protótipo do carregador solar foi testado e permitiu concluir acerca das condições de permanente controlo existentes no sistema.

PALAVRAS CHAVE

Carregador solar, sistema fotovoltaico, conversor DC/DC, ponto máximo de potência, controle por duty cycle, microcontrolador.
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<th>Description</th>
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<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>Li-ion</td>
<td>Lithium-ion</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracking</td>
</tr>
<tr>
<td>VMPPT</td>
<td>Voltage Maximum Power Point</td>
</tr>
<tr>
<td>DC/DC</td>
<td>Direct Current/Direct Current</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
</tr>
<tr>
<td>PIC</td>
<td>Programmable Interface Circuit</td>
</tr>
<tr>
<td>IC</td>
<td>Integrated Circuit</td>
</tr>
<tr>
<td>KCL</td>
<td>Kirchoffs Current Law</td>
</tr>
<tr>
<td>PCB</td>
<td>Print Circuit Board</td>
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</table>
1. INTRODUCTION

As people are much concerned with the fossil fuel exhaustion and the environmental problems caused by the conventional power generation, renewable energy sources and among them photovoltaic panels and wind-generators are now widely used. Photovoltaic sources are used today in many applications such as battery charging [1], light sources [2], water pumping [3], satellite power systems [4], etc. They have the advantage of being maintenance and pollution free but their main drawbacks are high fabrication cost, low energy conversion efficiency, and nonlinear characteristics. Since PV modules still have relatively low conversion efficiency, the overall system cost can be reduced using high efficiency power trackers which are designed to extract the maximum possible power from the PV module (maximum power point tracking, MPPT) [5].

The main goal of this thesis is to study the use of solar power to charge lithium-ion batteries (Li-ion). In the literature, many battery charging techniques are investigated and proposed [6]-[7]. These methods use a variety of battery characteristics (voltage and temperature) to achieve a safe and fast charging process. However, in this thesis a simple maximum power point tracking technique, known as Voltage MPPT (VMPPT) [8], is simulated and constructed. The implementation and simulation of the proposed method uses a low-cost, low-power consumption microcontroller, which controls a buck type Direct Current (DC)/DC converter and performs all control functions required by the MPPT process and battery charging.

Due to their high energy densities and long life times, Li-Ion batteries are increasingly used in systems such as portable electronics [9], electric vehicles [10], among others. The optimisation designs of these batteries have been built [11]-[12] in order to study its internal dynamics. In this thesis it is implemented a simple dynamic model based on capacitor/resistor networks [13]-[14] in order to predict the charging time and optimise the use of the battery.

In short, real time measurements of panel open circuit voltage are used to detect the maximum power point of the solar panel. Battery charge rate is continuously adjusted in a way that the system operating point is forced near the detected maximum power point of the solar panel. Theoretical and experimental analyses are used to demonstrate the reliability and validity of the proposed technique.
1.1 PROPOSED OBJECTIVES AND CONTENTS OF THE REMAINING CHAPTERS

With traditional energy sources running low and prices raising each time people must take advantage of renewable energy sources. With more and more portable devices coming out all the time the need to use renewable energy is ever increasing. The development of this thesis is very important because nowadays there is a current need in the market for an alternative energy device that can charge different types of batteries efficiently. The developed charging process is not very fast but can ensure an efficient loading and without any additional cost for the final user.

We all have been in situations where our batteries have run out. We then had to make the choice to stop what we were doing to go get batteries or we could stay and “suffer” through the silence. This was a huge waste of time when all we needed was to have a solar charger sitting around nearby with a backup set of batteries ready and waiting to be used.

Below, are presented some benefits and features for the developing of the presented solar charger:

**Benefits:**
- Eliminates need for multiple chargers (for the same battery type);
- Solar powered;
- Does not pollute;
- Reduces the environmental impact of our fuel consumption;
- Convenient – can be used whenever adequate light is present.

**Features:**
- Can charge any lithium-ion battery (with same specifications);
- Easy to operate.

This thesis is organised as follows: the solar charger system description is presented in Section 2; the simulation of the system is analysed in Section 3 and 4 for Pspice and Simulink environment, respectively; Section 5 presents the design process for the charger and a summary of the achieved results and future scope of the work is presented in Section 6.
2. SYSTEM DESCRIPTION

The photovoltaic charger system consists of four subsystems, each with its own function. These four subsystems are connected in accordance with the block diagram presented in Figure 1.

The first subsystem (Solar Panel) consists of one polycrystalline PV module from Solarex. This PV module has a rated power of 1.2 Watt and is formed by 18 photovoltaic cells connected in series (more technical specifications may be consulted in ANNEX 1).

The Charger Unit (second subsystem) includes a DC/DC converter controlled by a PWM signal. DC/DC converter is formed by two switches and an input and output filter. PWM signal is computed from the Control Unit (more technical specification on DC/DC converter components may be consulted in ANNEX 2).

The Control Unit (third subsystem) consists of one Programmable Interface Circuit (PIC) microcontroller, model PIC18F4585, and an Integrated Circuit (IC), SG3524. PIC microcontroller is a high performance 8-bit Reduced Instruction Set Code (RISC) architecture, operates from 2V to 5.5V belonging to 40 pins family and IC is a 16 pin PWM switching regulator circuit (more technical specification on PIC18F4585 and IC SG3524 may be consulted in ANNEX 3).

The fourth subsystem consists of a rechargeable Lithium-ion (Li-ion) battery from Varta supplier. This battery has an output voltage of 3.7V and an energy storage capacity of 1230mAh (more technical specification on battery may be consulted in ANNEX 4)

![Figure 1- Global Block Diagram – Solar Charger.](image-url)
2.1 SOLAR PANEL (PV)

On this thesis the solar panel serves as a power supply to the circuit. It receives light from the sun and converts this to energy. The photovoltaic cell is an unusual power source whereas most sources of electrical power are constant voltage sources, such as a battery, a PV cell is a constant current source. The PV cell only displays this constant current characteristic up to a limiting voltage where the current collapses. For an ideal PV module the voltage where the current collapses would be at the open circuit voltage, $V_{oc}$.

![Ideal I-V Curve for a PV cell.](image)

In reality the I-V characteristics for a PV cell do not look like Figure 2 but exhibit the following characteristics.

![Typical current-voltage I-V curve.](image)

The slight current drop between points M and A is a result of some of the current passing through the internal resistance of the PV cell. Between points A and S the load resistance increases forcing some of the current to flow through the diode resulting in the fast drop in current to the load. This continues until point S where all the current flows through the diode and the internal resistance.
Where the PV operates on this I-V curve is greatly determined by the insolation, array voltage, cell temperature and the load connected to the array. According to [15] by altering the amount of sunlight that is available to the PV module the current that the module can produce is also altered. The current and power output of the used solar panel is approximately proportional to illumination intensity (irradiance). At a given intensity, the module voltage is determined by the characteristics of the load.

According to the conclusions achieved in [16] the effect of temperature on the current of a PV cell is only small. By increasing the temperature a slightly higher current is produced, however this increase in temperature has a negative effect on the cell voltage. Increasing the temperature forces the diode in Figure 4 to conduct at a lower voltage therefore reducing the PV voltage where the curve collapses and greatly reducing the output power.

The effect of varying the load on the PV operating point can be explained using ohms law:

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

(1)

Figure 3 shows the load lines for different load resistances. The slopes of these load lines are given by $1/R$. So, lower resistances result in steeper load lines and higher resistances result in flatter load lines. The operating point of the PV connected to these loads is restricted to the intersection of the load line and I-V curve. Therefore for a given irradiance there is only one load resistance that will produce maximum power and if the irradiance changes then the resistance required for operation at MPP also changes. The irradiance is not constant and will change throughout the day therefore maximum power point trackers are needed to match the operating point to the load resistance.

### 2.1.1 Electric Model of Photovoltaic Cell

During darkness, the solar cell is not an active device: it works like a normal diode, i.e. a p-n junction. It produces neither a current nor a voltage. However, if it is connected to an external supply a current $i_D$, called diode current, will be present.

A solar cell is usually represented by an electrical equivalent one-diode model [3] with a series resistance, as shown in Figure 4.
Figure 4- Electrical equivalent model – Solar Cell.

The model contains a current source $I_S$, one diode and a resistor $R_S$. The net current is the difference between the photocurrent $I_S$ and the normal diode current $i_D$. The diode current is given by (2).

$$i_D = I_0 \left( e^{\frac{(v_{sa}+R_{sa})}{mV_T}} - 1 \right)$$  \hspace{1cm} (2)

where:
- $I_0$ - diode current (strongly dependent on temperature);
- $v_{sa}$ - voltage imposed across the cell;
- $m$ - ideal factor (ideal: $m=1$; real: $m > 1$);
- $V_T$ - Thermal potential given by (3);
- $R_S$ - Series cell resistance.

$$V_T = \frac{KT}{q}$$  \hspace{1cm} (3)

where:
- $K$ : Boltzmann constant, $K = 1.38 \times 10^{-23} \text{ J/K}$ ;
- $T$ : cell temperature in K, $0^\circ \text{C} = 273.16 \text{ K}$ ;
- $q$ : electric charge of electron, $q = 1.6 \times 10^{-19} \text{ C}$ .

The net current, $i_{sa}$, is given by (4):

$$i_{sa} = I_s - I_0 \left( e^{\frac{(v_{sa}+R_{sa})}{mV_T}} - 1 \right)$$  \hspace{1cm} (4)

Taking into account the model for a single solar cell, it is possible to determine the $I-V$ characteristic of $M$ cells in parallel and $N$ cells in series:
\[
V_{sa} = \gamma \times V_T \times \ln \left( \frac{I_S - i_{sa}}{M \times I_0} + 1 \right) - R_i i_{sa}
\]  

(5)

where \( \gamma = m \times N \). For the used solar panel \( M = 1, N = 18 \) and it is assumed \( m = 1 \).

In short, a real solar cell can be characterised by the following fundamental parameters:

- **Short circuit current**, \( I_{sc} \) is the greatest value of the current generated by a cell. It is produced under short circuit conditions: \( V_{sa} = 0 \);

- **Open Circuit Voltage** – Corresponds to the voltage drop across the diode (p-n junction) when it is traversed by the photocurrent \( I_S \), namely when the generated current is \( i_{sa} = 0 \). It can be mathematically expressed as:

\[
V_{OC} = \gamma \times V_T \times \ln \left( \frac{I_S}{M \times I_0} + 1 \right)
\]  

(6)

**Maximum Power Point** – is the operating point A in Figure 3, at which the power dissipated in the resistive load is maximum. Therefore for a given irradiance there is only one load resistance that will produce maximum power.

For the used solar panel, Solarex NEGA Series Module Products MSX-01, the following main characteristics were withdrawn from the datasheet:

<table>
<thead>
<tr>
<th>Table 1-PV, Electrical Specifications.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrical Specifications MSX-01</strong></td>
</tr>
<tr>
<td><strong>Specified Load Voltage (Vld)</strong></td>
</tr>
<tr>
<td><strong>Typical Current at Vld (Ild)</strong></td>
</tr>
<tr>
<td><strong>Open Circuit Voltage (Voc)</strong></td>
</tr>
<tr>
<td><strong>Short Circuit Current (Isc)</strong></td>
</tr>
</tbody>
</table>
2.2 CHARGER UNIT

The charger unit is a global block that includes the Maximum Power Point Tracking allied to a DC/DC converter with buck topology. Figure 5 gives a general description of the charging unit block.

![Figure 5-Block Diagram of the charging unit.](image)

2.2.1 DC/DC Converter

A DC/DC converter consists of a number of storage elements and switches that are connected in a topology such that the periodic switching controls the dynamic transfer of power from the input to the output, in order to produce the desired DC conversion. The storage elements are connected in such a way that they form a low pass filter to yield low output ripple voltage (less than 3%). In the designed system, there is also an input storage element that will allow the input ripple voltage to be less than 3%.

The two fundamental topologies of DC/DC converters are the buck and the boost converter as described in [17]. There are many other topologies, most of which are derived from either the buck or the boost. The purpose of the DC/DC converter is to transform a DC voltage from one level to another. This is done by varying the duty cycle, $\delta$. The duty cycle is defined as the ratio of the “on” duration to the switching time period. By varying $\delta$ the width of the pulses is varied and the concept of pulse width modulation, PWM is realised.

DC/DC converters have two distinct operating modes [18]: Continuous Conduction Mode (CCM) and Discontinuous Conduction Mode (DCM). The converter can operate in either of these modes and each mode has significantly different characteristics. The DC/DC converter serves the purpose of transferring power from the solar PV module to the load and acts as an interface between the load and the module. On this thesis the DC/DC converter is always working in CCM, as described on the next chapters.
2.2.2 Buck Converter Topology

The ideal buck converter has the basic five components, namely a power semiconductor switch, a diode, an inductor, a capacitor and a PWM controller. The topology of the buck converter is shown in Figure 6.

![Figure 6–Electrical Model – DC/DC converter (buck topology).](image)

2.2.2.1 Theory of Operation

The DC/DC converter will connect / disconnect conveniently the solar panel from the battery based on PWM signals. Taking in account the idealised buck converter shown in Figure 6 and in order to simplify the results shown bellow, it is assumed that input voltage \( v_{\text{in}} \) is ripple free (on Pspice simulation subchapter and in the practical work it was included a capacitor on the left side of the converter in order to minimise the input voltage ripple – less then 3%).

The capacitor C is assumed to be large enough such that \( v_{\text{out}} \) has a ripple of less than 3% and is therefore, essentially ripple free. Current \( i_{\text{out}} \) is also assumed to be ripple free. Assuming continuous conduction (e.g. \( i_L \) is always greater than zero), the circuit has two topologies – switch \( M_1 \) closed and switch \( M_1 \) open. These steady states are shown in Figure 7.

When switch \( M_1 \) is closed, the power of the voltage source \( v_{\text{in}} \) is delivered to the load through inductor \( L_1 \). The diode is reverse biased and opens, and the current \( i_L \) increases at the rate of:
In this case the inductor $L_1$ is charging. When the switch is open, current $i_L$ continues to circulate through the diode, and this component is forward biased, and $i_L$ decreases at the rate of:

$$\frac{di_L}{dt} = \frac{v_L}{L_1} = \frac{-v_{out}}{L_1}, \delta T \leq t \leq T$$

and the inductor $L_4$ is discharging. If the parameters of the circuit are well dimensioned such that the current $i_L$ does not go to complete zero (in this case the circuit is in continuous conduction), the diode remains in conduction until the switch closes and the diode is reverse biased and opens.

Due to the steady-state inductor principle, the average voltage $v_L$ across $L_1$ is zero. Since $v_L$ have two states, both having constant voltage, the average value is given by (9).

$$v_{out} = \frac{1}{T} \int v_{out}(t)dt = \frac{1}{T} \int_0^{\delta T} v_{sa}(t) = v_{sa} \delta$$

Therefore,

$$v_{out} = v_{sa} \delta$$

This relationship is very important because describes the operation of the buck converter. $\delta$, is the duty cycle and varies between 1 and 0. Therefore the output voltage will always be less then the input voltage.

### 2.2.2.2 Sizing of the output filter

Expressions (7) and (8) give the rate of rise and fall for current $i_L$. The average value of $i_L$ is found by examining the node at the top of capacitor in Figure 6. Applying Kirchoffs Current Law (KCL) in the average sense, and recognising that the average current through a capacitor operating state is zero, it is obvious that:

$$i_{Lav} = i_{out}$$
Expressions (7), (8) and (11) provide the necessary information to draw a graph of current $i_L$, as shown in Figure 8.

\[
L_{i_{\text{avg}}} = \frac{i_{L_{\text{avg}}} + \Delta i_L}{2}
\]

\[
L_{i_{\text{out}}} = \frac{i_{L_{\text{out}}}}{2}
\]

\[
i_{L_{\text{avg}}} = i_{L_{\text{out}}}
\]

\[
i_{L_{\text{min}}} = i_{L_{\text{avg}}} - \frac{\Delta i_L}{2}
\]

Figure 8–Inductor Current Waveform – Output Filter.

**Value of the inductor $L$**

Since the inductor current consists of straight line segments, it is possible to write the following expression:

\[
i_{L_{\text{avg}}} = i_{L_{\text{ averaged}}} + \frac{i_{L_{\text{max}}} + i_{L_{\text{min}}}}{2}, i_{L_{\text{max}}} = i_{L_{\text{avg}}} + \frac{\Delta i_L}{2}, i_{L_{\text{min}}} = i_{L_{\text{avg}}} - \frac{\Delta i_L}{2}
\]

(12)

From (7),

\[
\frac{di_L}{dt} = \frac{v_{in} - v_{out}}{L_1} = \Delta i_L
\]

(13)

So that,

\[
\Delta i_L = \frac{v_{in} - v_{out}}{L_1} \times \Delta T = \frac{v_{in} - v_{out}}{L_1} \times \Delta T = \frac{v_{in} \delta (1 - \delta)}{L_1 f_{PWM}}
\]

(14)

Where $f_{PWM}$ is the commutation frequency. In the limit of the CCM, $\Delta i_L = 2i_{L_{\text{out}}} = 2i_{L_{\text{out}}}$, such:

\[
\frac{v_{out}}{L_{\text{max}}} (1 - \delta)T = 2i_{L_{\text{out}}} \Leftrightarrow L_{\text{max}} = \frac{v_{out} (1 - \delta)}{2i_{L_{\text{out}}} f_{PWM}}
\]

(15)

The maximum value occurs when $\delta \to 0$. Therefore,

\[
L_{\text{max}} > \frac{v_{out}}{2i_{L_{\text{out}}} f_{PWM}}
\]

(16)
which guarantees a continuous conduction for any value of duty cycle. \( v_{out} \) and \( i_{out} \) are the converter output voltage and current at the maximum input power and \( f_{PWM} \) is the switching frequency.

**Value of the capacitor, \( C \)**

The capacitor current, \( i_c \), is given by the difference between the current in the inductor and the load current \( i_{out} \) as follows:

\[
i_c = i_L - i_{out}
\]

(17)

Looking at Figure 9, it can be seen that each charging and discharging process is given by an equal area where it spends half of the period value \( \frac{T}{2} \), and where each area represents a charge increment \( \Delta Q \) of the capacitor.

![Inductor Current Waveform used to Illustrate Capacitor Charging](image)

Using relation (18) from [17]:

\[
\Delta V = \frac{\Delta Q}{C}
\]

(18)

where \( \Delta V \) is the output ripple voltage.

and Figure 9, we have:

\[
\Delta V = \frac{\Delta Q}{C} = \frac{1}{C} \times \frac{1}{2} \times \frac{T}{2} \times \frac{\Delta i_L}{2} = \frac{T \times \Delta i_L}{8 \times C}
\]

(19)
In the worst case, $\Delta i_L = 2i_{out}$ and therefore,

$$C_2 = \frac{i_{out}}{4\times\Delta V \times f_{PWM}}$$

(20)

where $i_{out}$ is the converter output current at maximum input power, $\Delta V$ is the voltage ripple and $f_{PWM}$ is the switching frequency.

### 2.2.2.3 Maximum voltage output for duty cycle ratio control

Less usual in the literature is the buck topology on Figure 10. It is intended to minimise the voltage ripple $v_{in}$, similar to voltage $v_{C1}$, since voltage $v_{out}$ is supposed to be constant. Figure 10 presents the case where the load is a battery or a resistor-capacitor (R-C) network with ripple-free.

![Figure 10-Switch operation – DC/DC converter.](image)

When switch $M_1$ is closed, the diode is reverse biased and opens, and it is possible to write:

$$\frac{di_L}{dt} = \frac{v_L}{L} = \frac{v_{in} - v_{out}}{L}, \quad 0 \leq t \leq \delta T$$

(21)

$$\frac{dv_{C1}}{dt} = \frac{i_{in} - i_L}{C_1}, \quad 0 \leq t \leq \delta T$$

(22)

When switch $M_1$ is open, current $i_L$ continues to circulate through the diode and capacitor $C_1$ is being charged by current $i_{in}$ allowing rewriting (21) and (22):

$$\frac{di_L}{dt} = \frac{v_L}{L} = -\frac{v_{out}}{L}, \quad \delta T \leq t \leq T$$

(23)

$$\frac{dv_{C1}}{dt} = \frac{i_{in}}{C_1}, \quad \delta T \leq t \leq T$$

(24)
Assuming that all currents and voltages across the circuit are ripple free, when compared to the respective average values and due to the condition of permanent state applied to inductor $L_1$ and capacitor $C_1$, it is possible to conclude after the integration of (21) and (31) that:

$$\left( v_{in} - v_{out} \right) \delta T - v_{out} \left( 1 - \delta \right) T = 0 \rightarrow v_{outavg} = \delta v_{inavg} \quad (25)$$

$$\left( i_{in} - i_L \right) \delta T + i_{in} \left( 1 - \delta \right) T = 0 \rightarrow i_{Lavg} = \frac{i_{inavg}}{\delta} \quad (26)$$

In the same conditions it is possible to see that the ripple voltage for capacitor $C_1$, when it is being charging by the current $i_{in}$, is given by:

$$\Delta v_{C1} = C_i \cdot i_{in} \left( 1 - \delta \right) T \quad (27)$$

The previous deductions keep their validity even for cases where less restrictive conditions are stated. Figure 11 presents the inductor current waveform where is represented the current ripple.

![Figure 11-Inductor Current Waveform.](image)

Current $i_{in}$ is presented in two different situations. In the first situation $i_{in}$ (full line) is always lower than $i_L$ and secondly (dash line), although is average value is still lower than the average value of $i_L$, this behaviour is not constantly identified for all the period of time $\delta T$. In the first case condition (26) is still valid. In the second case the process is not equal. On the last situation, the capacitor charging process happens not only on the period of time $(1 - \delta) T$ but also partially in $\delta T$. This behaviour is not compatible with the duty cycle ratio control that is implemented. In the limit, for the duty cycle control:
Replacing (28) in (21) and taking into account (25) and (26) it is possible to write the maximum value for voltage $v_{out}$ that allows the circuit to be in permanent control:

$$v_{out} = \sqrt{2 \times i_{m} \times v_{oc} \times L \times f_{PWM}}$$  \hspace{1cm} (29)$$

### 2.2.3 Maximum Power Point Tracking

A Maximum Power Point Tracker is an electronic DC/DC converter that optimises the match between the PV module and the load: Maximum Power Point trackers maximise the PV module output power despite of the ambient temperature and insulation levels.

As seen in the I-V curve of typical PV modules (Figure 3) there is a single maximum of power. This means that there is a peak power corresponding to a particular voltage and current. Knowing that efficiency of the solar panel is low it is desirable to operate the module at the peak power point so that the maximum power can be delivered to the load.

There are several studies of MPPT techniques [18] and [19], such as the perturbation and observation, the constant current method, the constant voltage method and the incremental conductance method. The next subchapter will focus on the constant voltage method (algorithm implemented to track MPPT).

### 2.2.4 Maximum Power Point Method

Due to the non-linear I-V characteristics of a PV cell, a different maximum power point can be found for each irradiance condition on the solar cell. To fit the demand of a low power algorithm, a simplified 75% constant voltage method was used to deduce the maximum power point [20]. Instead of finding the maximum via derivative, and employ numerical methods to show a linear dependency between “cell voltages correspond to maximum power” and “cell open circuit voltages” it is assumed that a maximum power point of the used solar PV module lies at about 0.75 times ($M_v$ value – voltage factor) the open circuit voltage of the module: the MPPT can be found at 75% of the open circuit voltage, according to (30).
Therefore, by measuring the open circuit voltage of the solar panel, $V_{oc}$, a reference voltage can be generated ($V_{MP}$) and a duty cycle control scheme can be implemented in order to bring the solar PV module voltage to the point of maximum power.

$$V_{MP} = M_V \times V_{OC}$$  \hspace{1cm} (30)

Can the result achieved by [20] be applied to the used solar panel on this thesis? In order to use this voltage factor value an analysis to the solar panel main characteristics was done. With the help of the solar panel datasheet (Annex1) and looking at the maximum voltage under load (reported by $V_{Id} = 7.5V$ value on page 2) it is possible to state that the chosen value for the voltage factor, $M_V = 0.75$ characterises the main idea of the Voltage-Based Maximum Power Point Tracking technique.

Although very simple this method has a low efficiency compared to other MPPT methods: in reality $M_V$ is not constant and is affected by temperature and irradiance levels as already said above. Another limitation of this technique is the open circuit voltage of the module: it varies with the temperature. Therefore, as the temperature increases the module open circuit voltage changes and it is required to measure the open circuit voltage of the module very often.
2.3 CONTROL UNIT

As stated above, the control unit is composed by a microcontroller and an integrated circuit as shown in Figure 12. The microcontroller is used to process measured voltage (from the solar panel output) and to compute the required signal for control of the system (VMPPT algorithm). IC is employed to generate the required PWM command that will control the switch gate of the DC/DC converter.

2.3.1 Microcontroller PIC18F4585

A microcontroller is a type of microprocessor furnished in a single integrated circuit [21]. Its principal nature is self-sufficiency and low cost. This microcontroller includes a central processor, input and output doors, memory for program and data storage. It also has an internal clock and more than one peripheral device such as: timers, counters, analog-to-digital converters and serial communication facilities.

PIC18F4585 belongs to the high-performance group. This PIC has 16-bit program words, flash program memory, a linear memory space of up to two Mbytes, and protocol-based communications facilities.

These PIC microcontrollers can be programmed in high-level languages or in their native machine language (Assembly). In this thesis the C language was chosen, using the software MPLAB and C18 libraries (included with MPLAB). The advantages of C language consist of better control and greater efficiency. Another reason for using C language is that the interface with the programmer is quite simple and easy to understand.
The use of the microprocessor allows capturing the voltage value from the solar panel output. In order to reach the VMPPT algorithm the PIC18F4585 will:

- Capture analog voltage value from the solar panel output;
- Proceed to an Analog / Digital (A/D) conversion;
- Apply the VMPPT algorithm;
- Send to the Integrated Circuit the correspondent voltage signal ($V_{ref}$) in a way to allow the control of the PWM duty cycle (this signal is sent by a PWM signal).

After the PWM signal has been generated from the microcontroller there is a need to “transform” it into an average value. An easy and inexpensive way to implement this functionality is by passing the signal into a low pass filter. This PWM signal is fixed, but the pulse width is variable, depending on the operation point of the solar panel. Figure 13 will allow clarifying the description:

![Figure 13–PWM signal – Average Value.](image)

2.3.1.1 Low Pass Filter
The low pass filter (LPF) mentioned above is a simple RC filter where the capacitor is in parallel with the load. The capacitor exhibits reactance, and blocks low frequency signals, causing them to go through the load instead. At higher frequencies the reactance drops, and the capacitor functions as a short circuit. The combination of resistance and capacitance gives the time constant of the filter:

$$\tau = RC$$  \hspace{1cm} (31)

The cut off frequency is given by (32).

$$f_c = \frac{1}{2\pi RC}$$  \hspace{1cm} (32)
2.3.2 Integrated Circuit SG3524

IC SG3524 is an improved version of a PWM controller [22] that was used in this thesis to set switch M1 (see Figure 6). IC SG3524 is responsible for the generation of an appropriate PWM signal, according to the values received from the microcontroller, in a way to correctly control the switch gate from the DC/DC converter. Looking at the block diagram (Figure 14) of the IC it is possible to explain its functionality.

The work process of the integrated circuit is as follows:

- It receives at the input from pin1 and pin2 two voltages;
- In pin1 it receives voltage $V_{set}$ proceeding from the PV solar panel;
- In pin 2 it receives voltage $V_{ref}$ that simulates the maximum point of power for the chosen solar panel, proceeding from the microcontroller;
- Then a comparison is performed and a logical value: 0 or 1 (0 or 5V) is generated;
- This value is again submitted to a comparison with a slope generated with constant frequency and a maximum amplitude of 5V;
- Depending on the exiting value from the first comparator, a new logical value is generated, 0 or 1 (or 0 or 5V respectively) that, in turn, will affect the final state of the bipolar transistors responsible for controlling the switch M1 gate;
- This final value is a PWM control with determined duty cycle that can vary depending on the voltage value of $V_{set}$. If $V_{set}$ is greater than $V_{ref}$ transistor M1 is ON. Otherwise if $V_{set}$ is lower than $V_{ref}$, transistor M1 is OFF.

![Figure 14–Block Diagram – IC SG3524.](image-url)
2.4 BATTERY

Driven by integrated functionality and shrinking form factors, the demand for portable devices such as cellular phones, PDAs, portable DVD players, etc has grown significantly during the last few years. Of all rechargeable batteries, Lithium-ion (Li-ion) battery has been widely adopted [23].

Li-ion batteries have several advantages compared to other rechargeable batteries, such as:

- Present a higher energy density than most other types of rechargeables. This means that for their size or weight they can store more energy than other rechargeable batteries;
- Operate at higher voltages than other rechargeables, typically about 3.7V for lithium-ion vs. 1.2V for NiMH or NiCd. This means a single cell can often be used rather than multiple NiMH or NiCd cells;
- Li-ion batteries also have a lower self discharge rate than other types of rechargeable batteries. This means that once they are charged they will retain their charge for a longer time than other types of rechargeable batteries.

Nevertheless Li-ion batteries have some disadvantages compared to others, such as:

- Li-ion batteries are more expensive than similar capacity NiMH or NiCd batteries. This is because they are much more complex to manufacture. Li-ion batteries actually include special circuitry to protect the battery from damage due to overcharging or undercharging;
- Li-ion batteries also require sophisticated chargers that can carefully monitor the charge process.

In summary, Li-ion batteries can be smaller or lighter, have a higher voltage and hold a charge much longer than other types of batteries. For these main reasons, the Li-ion battery was chosen for the proposed solar charger.

With accurate and efficient circuit and battery model, it is possible to predict an intuitive and comprehensive electrical battery model. In the next subchapter it is presented a model of a Li-ion battery that is suitable to test the behaviour of portable battery powered systems. The electric model is built by a combination of voltage sources, resistances and conductors.
2.4.1 Electrical Model for Li-ion Battery

Before describing the used model to simulate the Li-ion battery it is worth reviewing some parameters that characterises it such as:

- **Life Cycle:**
  The duration of the battery cycle is the total amount of discharge-charge cycles (see Figure 15) that a battery relieves before more power can not be hold. The useful life of a reloadable Lithium battery is difficult to predict because it is affected by the average operational temperature and energy discharge rate.

- **Capacity:**
  The battery capacity is expressed in ampere-hour, Ah. The energy of the battery, expressed in Watt-hour, Wh, is the product of the capacity and the voltage of the battery, V. The operational tension of a Lithium battery remains relatively constant during its useful life; however, its capacity starts to decrease in practical linear way as soon as it starts to be used.

A practical way to express the real capacity of a battery throughout the time is called State of Charge (SOC). The SOC is express as a percentage of the initial nominal capacity of the battery.
In general, the battery models view the battery as a voltage source $E$ in series with an internal resistance. Figure 16 represents an intuitive and comprehensive electrical battery model.

![Figure 16–Equivalent Model – Li-Ion Battery.](image_url)

Where,

- $E =$ Internal voltage, $V$
- $E_o =$ Constant voltage, $V$
- $K =$ Polarization voltage, $V$
- $Q =$ Battery capacity, Ah
- $A =$ Exponential Voltage, $V$
- $B =$ Exponential Capacity, Ah$^{-1}$

The terminal voltage $V_{batt}$ is given by (33).

$$V_{batt} = E - I_{batt}R_0$$  \hspace{1cm} (33)

All the parameters described above represent the equivalent circuit of the Li-ion battery used to simulate the charge and discharge characteristics. A typical discharge curve is composed of three sections as shown in Figure 17.
The first section represents the exponential voltage drop when the battery is fully charged. The second section represents the charge that can be extracted from the battery until the voltage drops below the battery nominal voltage. Finally, the third section represents the total discharge of the battery, when the voltage drops rapidly.

When the battery current is negative, the battery will recharge following a charge characteristic as shown in Figure 18.
3. IMPLEMENTATION IN PSIPCE

_Pspice_ is a powerful general purpose analog and mixed-mode circuit simulator that is used to verify circuit designs and to predict the circuit behaviour. This is of particular importance for the print circuit board (PCB) design as well for the study of integrated circuits.

The use of _Pspice_ is very useful in cases where there is the need to determine the values of voltage and current circulating in the circuit, in order to investigate the range of values of some components, or even just to make changes in topology. This is the main reason why _Pspice_ was used in this thesis.

With the help of this simulation program it was possible to build a basic circuit of a step-down switching regulator with duty cycle ratio control. The circuit is depicted in Figure 19 and allows the modulation of the DC/DC converter. It also allowed predicting the system behavior for different resistive values on the terminal load (estimation for current and voltage values).

An ideal voltage source, $V_i$ in series with a resistance, $R_{pv}$ was considered in substitution of the solar panel. This model admits that the solar panel characteristic of Figure 3 can be linearised between points A and S and it is also considered that the working point of the system in centered around point A of maximum power. The _Pspice_ model of the IC SG3524 regulates the PWM pulse width. In turn, the duty cycle controls the switch gate ($M_i$) allowing the control of the buck converter and as a consequence, the control of the output voltage and current in the load (represented by resistance $R_{load}$). Specification of the used components may be consulted in Table 2.
Figure 19–Step-down switching regulator circuit.

Table 2-Specifications of components used for simulation.

<table>
<thead>
<tr>
<th>Voltage source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{P}=V_{I}=V_{O}=10V_{dc}$</td>
</tr>
</tbody>
</table>

**Resistances**

<table>
<thead>
<tr>
<th>R$_1$</th>
<th>R$_4$</th>
<th>R$_2$</th>
<th>R$_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>4kΩ</td>
<td>5kΩ</td>
<td>4kΩ</td>
<td>5kΩ</td>
</tr>
</tbody>
</table>

**DC-DC Converter components**

<table>
<thead>
<tr>
<th>C$_1$</th>
<th>L$_1$</th>
<th>C$_2$</th>
<th>Q$_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10µF</td>
<td>300µH</td>
<td>100µF</td>
<td>Mosfet 2N6660</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>D1N5817</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Diode</th>
</tr>
</thead>
<tbody>
<tr>
<td>D1N5817</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IC SG3524 components</th>
</tr>
</thead>
<tbody>
<tr>
<td>C$_3$=5nF</td>
</tr>
<tr>
<td>C$_4$=100nF</td>
</tr>
</tbody>
</table>
3.1 DESCRIPTION OF THE REGULATOR CIRCUIT

The regulator circuit shown in Figure 19 was built based on of four main blocks:

1. PV, solar panel is represented by a voltage source of 10V (simulates the maximum voltage output) and an internal resistance, $R_{PV} = 15\Omega$ (allows the output voltage of the solar panel to be near $7.5\text{V}$ at a average source current $i_s = 0.15\text{A}$) which allows to simulate the maximum power point for the chosen solar panel;

2. The buck converter: a DC/DC converter circuit that converts a dc input, $7.5\text{V}$ (output of the solar panel) to a lower dc output voltage. For different values on the resistive load are achieved different values for voltage and current. Due to project characteristics the ideal voltage across the load should be near $4.2\text{V}$ in order to properly simulate the ideal battery charging process (according to the information given by the battery datasheet for ideal charging);

3. IC SG3524, responsible for the PWM pulse that controls the switch $M_1$;

4. The load, represented by resistance $R_{load}$. The resistor simulates the following battery conditions: energy dissipation, voltage and current levels supported in order to maintain the circuit working in CCM and to predict ideal conditions for the charging process.

In order to explain the functioning of the system it is important to look at the block diagram of the IC SG3524 (see Figure 14). Pin 2 receives $V_{ref} = 3.75\text{V}$ (voltage reference value). The MPPT is given by (30) and leaves to $V_{MPPT} = 7.5\text{V}$. Therefore, and considering that IC SG3524 is powered by a $5\text{V}$ voltage supply (scaled operating point is $3.75\text{V}$ instead of the proposed $7.5\text{V}$). To achieve this value $R_1$ and $R_4$ are used to properly scale $V_{ref}$. This voltage works as a “guide line” to the input voltage in Pin 1. Pin 1 receives $V_{set}$ (voltage set). This voltage represents the output voltage of the solar panel. The goal here is verify $V_{set}$ tending to $V_{ref}$ (optimal operational power point).

To complement the above stated please focus on point A from the I-V characteristic from Figure 3, which represents the maximum power point. Reaching this point the following may happen:

- If the load curve is at the right of the MPPT, the system will present an increase of voltage and a decrease of current on the load;
- If the load curve is at the left of the MPPT, the system will present a decrease of voltage and an increase of current on the load.
The previous paragraph represents the system dynamics: the main goal is to give a reference point \( V_{\text{ref}} \) and to make the system converge dynamically into it \( V_{\text{set}} \). This allows IC SG3524 to control the duty cycle conveniently in order to reach the optimal voltage and current in the load.

Another important aspect is the power conservation: if the system is always “looking” for the maximum power point, it must also ensure energy or power conservation, for which the system does not need to charge the battery at a voltage or constant current. This process ensures the maximum power point operation and the delivery of the maximum power to the load.

3.1.1 Circuit Scaling

**DC/DC Converter:**

- **Input Filter:** Dimensioned by capacitor \( C_1 = 10 \mu F \) using (34), according to [24] with a maximum voltage ripple of 3%. This capacitor allows minimising the voltage ripple of \( v_{\text{sa}} \). Considering the worst case when \( \delta \to 0 \):

  \[
  C_1 \geq \frac{i_{\text{out}}(1-\delta)}{\Delta v_{\text{sa}} f_{\text{PWM}}} \geq \frac{0.15}{0.03 \times 7.5 \times 40k} \geq 17 \mu F \to 10 \mu F
  \]

  \[
  (34)
  \]

- **Power semiconductor switch:** It is used the transistor 2N6660 and diode D1N5817 (internal library of Pspice). In ANNEX 2 it is possible to consult the general description of these components;

**Output Filter:** designed as deducted from (16), \( L_1 = 300 \mu H \) :

\[
L_1 = \frac{V_{\text{out}}}{2 \times i_{\text{out}} \times f_{\text{PWM}}} = \frac{4.2}{2 \times 0.15 \times 40k} = 350 \mu H \to 300 \mu H
\]

\[
(35)
\]

and (20), \( C_2 = 100 \mu F \) :

\[
C_2 = \frac{i_{\text{out}}}{4 \times \Delta V \times f} = \frac{0.15}{4 \times 0.01 \times 40k} = 94 \mu F \to 100 \mu F
\]

\[
(36)
\]

The existing inductance of \( 300 \mu H \) and capacitance of \( 100 \mu F \) were chosen for the simulation in order to facilitate the design project.
**IC SG3524:**
- In order to simulate the functioning of the IC an existing library in Pspice was used;

**Load:**
- The load is simulated by a resistance $R_{\text{load}}$. The Pspice simulation program allowed identifying the limit for the duty cycle ratio control sized by (29). The maximum value for the output voltage is:

$$V_{out\_max} = \sqrt{2 \times 0.15 \times 7.5 \times 300 \times 10^{-6} \times 40 \times 10^3} = 5.2V$$  \hspace{1cm} (37)
3.2 SIMULATION RESULTS

Two schemes were simulated for both $R_{\text{load}} = 20\Omega$ and $R_{\text{load}} = 40\Omega$. It is assumed that the circuit is working on the MPPT point and that all the results obtained depend on it. These two schemes will allow to better understand the system behaviour for different conditions on the load and to characterise the system duty cycle ratio control. It is also presented a power transfer study from the solar panel to the load.

3.2.1 Load Variation Influence

Figure 20 presents the simulation results for the system with the load resistance equal to $R_{\text{load}} = 20\Omega$. In the curves obtained, $V_{\text{ref}} = 3.75V$ and the circuit is stabilised in the Maximum Operating Point. The value of $V_{\text{set}}$ (output voltage of the solar panel) is tending to this operation point which allows predicting that the circuit is being controlled: without knowing the value of the output voltage and current the system evolves to the maximum power rate that the PV model allows (VMPPT algorithm). There is a permanent control of the system (duty cycle ratio control).

Another important aspect worth to look at is the ripple value of the $V_{\text{set}}$ voltage (corresponds to the solar panel output voltage). In Figure 20 the maximum ripple obtained is nearly 3% of the voltage value ($\Delta V_{\text{set}} = 0.1V$), which means that capacitor, $C_1$ is well dimensioned.

Figure 20-$V_{\text{set}}$ and $V_{\text{ref}}$ - $R_{\text{load}} = 20\Omega$. 
Figure 21 presents the PWM signal ($V_{gate}$) that controls the transistor gate. It is possible to see that the duty cycle value is not constant: depends on the result of the difference between $V_{ref}$ and $V_{act}$. The PWM signal gives us the final idea that the system is, in fact, being controlled. Figure 22 is a zoom in of this process, and exemplifies the methodology described in Section 3.1.

![Figure 21-PWM control - $R_{load} = 20\Omega$.](image)

![Figure 22-$V_{act}, V_{ref}$ and $V_{gate}$.](image)

Figure 23 presents the voltage and current that is present in the load ($R_{load} = 20\Omega$). This resistive load reflects the ideal conditions for the charging process, taking into account the technical specifications of the chosen battery, presenting very good values for voltage ($v_{R,load} \approx 4.1V$) and
current \( i_{\text{load}} = 0.205 \text{A} \). The initial conditions \( v_{R,\text{load}} = 4.8 \text{V} \) and \( i_{\text{load}} = 0.240 \text{A} \) have no interest but it is interesting to see the system evolution to the ideal values for the charging process. Once again the system evolves to the ideal conditions for the charging process.

![Figure 23](image)

\[ R_{\text{load}} = 20 \Omega. \]

The following figures present the system simulation for \( R_{\text{load}} = 40 \Omega \). Figure 24 presents current in inductor \( L_1 \) and voltage across diode. Current in inductor is always \( i_{L_1} > 0 \): the converter is in CCM. When current in inductor decreases, the diode is forward biased (converter is working correctly). This figure allows us concluding that the circuit is well dimensioned: current \( i_{L_1} \) does not go to complete zero which allows the circuit to work in CCM.

![Figure 24](image)

\[ R_{\text{load}} = 20 \Omega / 40 \Omega. \]
Figure 25 presents the PWM signal ($V_{gate}$) that controls the transistor gate. It is observed that the duty cycle control is almost inexistent, except in some periods where the system tries to achieve again the duty cycle control, perhaps because of the capacitor discharge that periodically happens through the resistive load. These periods of time have correspondence to periods when the diode is forward biased. The switch $M_1$ is, most of the time, conducting (ON).

![Figure 25- PWM control - $R_{load} = 40\Omega$.](image)

A direct consequence of the lack of control of the system is the higher voltage value across the load (average value near 6V). Figure 26 presents voltage across the resistance $R_{load} = 40\Omega$. The achieved voltage is too high for the conditions stated in this project and so the system is no longer controlling the ratio power between the input voltage source (simulates the solar panel) and the resistive load.

![Figure 26- $V(R_{load})$ - $R_{load} = 40\Omega$.](image)
Initially the system tries to control voltage across the load (it is possible to see that circuit is trying to force voltage value to the reference value near 4V), but without success.

In order to provide the limit to which the system loses control (duty cycle ratio no longer working) some simulations were made and allowed the confirmation of value given by (29). Firstly, Figure 27 presents the situation where the system is being controlled ($R_{\text{load}} = 20\Omega$) contrasting to Figure 28 ($R_{\text{load}} = 40\Omega$) where the control is practically inexistental. If current $i_L$ is lower then 0.15A the system loses control ($V_{\text{gate}}$ starts presenting deficient control) which allows concluding that the current limit for control is achieved.

![Figure 27: $V_{\text{gate}}, i_L$ and $V_{\text{ramp-SG3524}}$ - $R_{\text{load}} = 20\Omega$.](image1)

![Figure 28: $V_{\text{gate}}, i_L$ and $V_{\text{ramp-SG3524}}$ - $R_{\text{load}} = 40\Omega$.](image2)
Figure 29 presents voltage across capacitor $C_1$, PWM signal ($V_{\text{gate}}$) and the signal associated to the PWM from the IC SG3524 for $R_{\text{load}} = 20\Omega$. It is possible to see that the capacitor is charging when the switch $M_1$ is OFF and discharging when $M_1$ is ON. This figure clearly states the system functioning: when voltage $V_{\text{set}}$ achieves $V_{\text{ref}}$ switch $M_1$ starts conducting.

![Figure 29](image)

Figure 29-$V_{\text{gate}}, V_{\text{ramp-SG3524}}$ and $V_{C_1} - R_{\text{load}} = 20\Omega$.

Figure 30 presents the system behaviour when in the presence of a resistive load equal to $R_{\text{load}} = 40\Omega$. The duty cycle ratio control has been lost but capacitor $C_1$ can be in charging process eventhough the transistor $M_1$ is conducting.

![Figure 30](image)

Figure 30-$V_{\text{gate}}, V_{\text{ramp-SG3524}}$ and $V_{C_1} - R_{\text{load}} = 40\Omega$. 
3.2.2 Power Variation

As previously stated, two schemes were simulated for both $R_{\text{load}} = 20\Omega$ and $R_{\text{load}} = 40\Omega$. The following figures will allow clarifying why was the resistance value $R_{\text{load}} = 20\Omega$ chosen in order to simulate the battery functioning.

Figure 31 presents the maximum power transfer rate that (operating in the maximum power point) the solar panel provides, more or less $P_{\text{max, PV}} \approx 1.2W$ (this value can also be verified in the PV datasheet). Therefore, the representation of the solar panel by an ideal voltage source and resistance is reliable for this system.

![Figure 31–PV Output Power.](image)

Figure 32 and Figure 33 presents the power across the 20 and 40 ohm load, respectively. In the individual graphs it is possible to look at the power loss: for $R_{\text{load}} = 20\Omega$ the system presents a power loss of $P_{\text{loss, } R=20\Omega} \approx 1.2 - 0.85 = 0.35W$ and for $R_{\text{load}} = 40\Omega$ the system presents a power loss of $P_{\text{loss, } R=40\Omega} \approx 1.2 - 0.89 = 0.31W$. With these results it is possible to conclude that the system is not ideal, even referring to a simulation program. Nevertheless, regardless of the load value, the system presents power conservation: the final power value achieved is very similar in both cases even if the system with $R_{\text{load}} = 40\Omega$ loses control.
3.3 CONCLUSIONS

The use of Pspice simulation program allows a better understanding of the system behaviour when in the presence of different loads. It can be generally stated that while the system is represented by a load of $R_{\text{load}} = 20\,\Omega$, it allows a controllable system. The duty cycle ratio control is a constant premise. For this reason the values obtained at the output of the system (voltage and current) are the ideal ones for an optimum battery charger (in this case, optimum values for the type of battery chosen). Although the losses presented in the system, probably due to losses of the transistor switching and internal resistance, the system presents a very good behaviour and a faithful representation of what will happen in reality.

As previously stated the system is very sensitive to load variations. The system starts loosing control for load values above $40\,\Omega$ presenting a load voltage higher that the one allowed to correctly charge the Li-Ion battery. As can be seen from (37) the maximum voltage value in the load that allows the duty ratio control of this system is close to $5.2\,V$. Therefore, the theoretical calculation is correct and the simulations give us the confirmation that the systems starts to lose control near this value.
4. IMPLEMENTATION IN SIMULINK

This section presents how the mathematical models of the components of the solar charger, described above, are implemented in Matlab/Simulink v2008. Simulink software and its facilities are used to model the proposed electric models depicted in Figure 34 presented in the previous sections. With Simulink facilities it is possible to characterise the MPPT algorithm (concluding about the voltage factor chosen) and to obtain an estimate charging time for the battery.

Simulink is a simulation program, which provides a graphical interface to build the models as blocks diagrams. It offers the advantage of building hierarchical models, namely presenting the possibility to view the system at different levels. This presents the advantage that the models can easily be connected together in order to simulate a system. Such models are also very useful to optimise the components of the PV system.

For practical use, the Simulink model blocks for each component of the PV system can be gathered in a library. On this thesis, the library contains model blocks for a PV module, a VMPPT power tracking and a battery. – see Figure 35. The input and output filter used are similar to those simulated in Pspice program.

Figure 34-Solar Battery Charger.

Figure 35–Simulink library for the Solar Charger.
The advantages of such a library are:

1. It gives a quick overview of which component models are available;
2. It is easy to just pick up the components from the library, build a certain system and simulate it.

4.1 MODELS LIBRARY

In accordance with (5) deducted above, it was possible to build the block of the solar panel (Figure 36). It represents the “detailed” Simulink implementation of the mathematical model of the PV module and allows simulating the nonlinear I-V and P-V characteristic.

The implicit function of the I-V characteristic of the solar module can be easily solved by this block. The value of \( i_{sc} \) is imposed on this process in order to limit the complexity of this block (its value is taken from the PV datasheet and is equal to \( i_{sc} = 0.15 \text{A} \)). This way, the only control variable is \( i_{sa} \). Thus, applying (5) it is possible to obtain the voltage characteristic of the solar panel that allows the simulation.

Analysing Figure 34 it is possible to detect a transfer function. Saturation and delay functions are introduced to limit the fast response of the “controlled voltage source”, as well as to improve convergence. The other variables are directly obtain / calculated from the PV datasheet.

A brief overview of the internal structure of other blocks of the Simulink library presented in Figure 34, are provided in Figure 37 and Figure 38, respectively. These figures contain the Simulink implementation of the mathematical models described in Section 2.
Figure 37 represents the VMPPT block in detail. This block is responsible for the implementation of the maximum power point tracking (voltage tracking). The logic in this block diagram is quite simple and perceptible. The block uses $i_{oc}$ and $V_{oc}$ to generate desired duty cycles for the charge unit. The panel open circuit voltage is calculated and multiplied by the $V_{MP}$ voltage factor. Thereafter the panel voltage corresponding to maximum power is computed and compared with $V_{oc}$ and the error is amplified through a proper gain to generate the desired duty cycle.

In accordance with the logic presented one of the two situations may occur:

1. $V_{MP} < V_{oc}$ - Means that the system is in saturation zone and transferred the maximum amount of power to the load. As a result and through Boolean logic, a ‘0’ is generated to control the gate of the switch that will lead to the cutting zone;

2. $V_{MP} > V_{oc}$ – Means that maximum power point has not yet been achieved. As a consequence, a ‘1’ is generated to allow the conduction of the switch.

Using Simulink internal library [12], Figure 38 shows the submask parameters of the battery used to simulate the Li-Ion battery model. The parameters were taken from the battery datasheet.

It is necessary to fill in the white spaces in order to modulate the respective battery:

- Nominal Voltage – The nominal voltage of the battery (Volts);
- Rated Capacity – The rated capacity in ampere-hour is the minimum effective capacity of the battery. The maximum theoretical capacity (when the voltage crosses 0 volts) is generally equal to 105% of the rated capacity;
• Initial State-of-Charge (SOC %) of the battery – 100% indicates a fully charged battery and 0% indicates an empty battery. This parameter is used as an initial condition for the simulation and does not affect the discharge curve;

• Full charge Voltage – The voltage factor (% of the nominal voltage) corresponding to the fully charged voltage, for a given nominal discharge current. For example, a battery cell with a nominal voltage of 1V and a fully charged voltage factor of 110% has a fully charged voltage of 1,1V. Note that the fully charged voltage is not the no-load voltage;

• Internal Resistance (internal resistance of the battery in ohms) - When the model is used, a generic value is loaded, corresponding to the nominal voltage and the rated capacity of the battery. The resistance is supposed to be constant during the charge and the discharge cycles and does not vary with the amplitude of the current;

• Capacity @ Nominal Voltage - The capacity (% of the rated capacity) extracted from the battery until the voltage drops under the nominal voltage. This value should be between 0% and 100%;

• Exponential Zone - The voltage (% of the nominal voltage) corresponding to the end of the exponential zone. For example, a battery with a nominal voltage of 1 volt and an exponential voltage of 105% indicates that the exponential zone ends at 1,05 volt. The capacity (% of the rated capacity) extracted from the battery until the voltage drops under the exponential voltage. This value should be between 0% and 100%;

Figure 38–Mask Parameters–Li-Ion Battery.

Note: The submask present in Figure 38 allows the simulation of the Li-ion battery for a constant current charging process.
**Assumptions:**
- The internal resistance is assumed constant during the charge and the discharge cycles and does not vary with the amplitude of the current;
- The parameters of the model are deduced from discharge characteristics and assumed to be the same for charging;
- The capacity of the battery does not change with the amplitude of current;
- The temperature does not affect the model's behaviour;
- The Self-Discharge of the battery is not represented. It can be represented by adding a large resistance in parallel with the battery terminals;
- The battery has no memory effect.

**Limitations:**
- The minimum no-load battery voltage is 0 volt and the maximum battery voltage is not limited;
- The minimum capacity of the battery is 0 Ah and the maximum capacity is not limited. So the maximum SOC can be greater than 100% if the battery is overcharged.
4.2 SIMULATION RESULTS

4.2.1. PV Model

The goal of this section is to validate the solar panel model, described in Section 2.1. It is first shown how the block simulates his V-I and P-I characteristic. Then, it is shown, just outside the PV Model block, the plots for current and voltage. It is important to refer that the Simulink implementation of the PV module is made ignoring the irradiance and cell temperature in order to facilitate the simulation.

![Figure 39–V-I and P-I Characteristic–PV Block.](image)

Figure 39 presents V-I and P-I characteristics of the solar panel used in this thesis. These Figures allow concluding about the chosen voltage factor for the MPPT tracking and the validation of the solar panel. The maximum power point (looking at V-I characteristic) can be found at approximately 75% of the open circuit voltage. Regarding this, it is possible to see that the chosen $M_V = 0.75$ is a very good approximation.

Analysing P-I characteristic it is possible to see that the solar panel modulation in Simulink environment is very reliable. The maximum output power for the solar panel (according to available elements from the PV datasheet) respects the maximum operating point achieved.
Figure 40 presents graphical view for current $i_{sa}$ and voltage $v_{sa}$ (current and voltage just outside the simulated PV block), respectively. Current $i_{sa}$ stabilizes near the maximum value allowed for solar panel ($i_{sa} = 0.15\, \text{A}$) and voltage $v_{sa}$ presents an average output voltage near $7.5\, \text{V}$. These results allow monitoring the MPPT.
4.2.2. Resistive Load

In order to see the performance of VMPPT technique, Figure 34 was used with a resistive load ($R_{\text{load}} = 20\Omega$) instead of the initial battery model. Figure 41 shows computed voltage, current and power characteristics across the $20\Omega$ resistive load, respectively. Once again the results obtained shows that the system is “funnelling” to ideal maximum operation point: voltage across the load is near the optimal value for charging, $4.2V$, current is equal to $0.225A$ and the output power reflects the power delivered from the solar panel.

Figure 41–Voltage, Current and Power characteristics- $R_{\text{load}} = 20\Omega$. 
4.2.3. Li-Ion Battery

This section focuses on the analysis and understanding of the battery behaviour, and on the simulation results of the Li-Ion model.

Figure 42 presents the amount of time that Li-ion battery, initially fully discharged, takes to full charge. Respecting the simulated conditions, described above, the system predicts approximately seven hours (in ideal conditions for voltage and current) until battery achieves maximum voltage and SOC=1. The maximum operating voltage is 4,2V when SOC of the battery reaches SOC=1.

![Figure 42-Voltage and SOC-Li-Ion battery.](image)

Figure 43 illustrates the nominal current discharge characteristic for Li-Ion battery used. It is possible to identify the main areas that characterise the discharge event. It is important to refer that in simulated model there is no control on discharge: the battery will discharge completely.

![Figure 43–Nominal current discharge–Li-Ion Battery.](image)
4.3 CONCLUSIONS

Respecting the results achieved it is possible to conclude the following points:

1. The PV simulation ensures that the theoretical assumptions, namely the voltage factor assumed, is a very approximate value of what can be expected in real implementation of the solar panel;

2. The resistive load simulations ensures (and comparing with the previous simulations obtained in Pspice) that the system is working correctly and is being controllable, always seeking to reach the maximum power peak, as can be seen with the results achieved across the resistive load;

3. The simulation using the Li-Ion battery model gives an ideal response of the system: the total time of battery charging (approximately seven hours). This is a very good charging average, knowing that the amount of time that the same Li-Ion battery takes to full charge using a DC power supplier is approximately three hours.
5. DESIGN

In order to experimentally test the performance of the proposed solar charger, the solar battery charger prototype of Figure 44 was constructed using one polycrystalline PV module, one Li-Ion battery, a VMPPT buck type tracker (MOSFET power switch), a microcontroller PIC18F4585 and an IC SG3524. The measured voltage, current and power waveforms at the output of the solar panel as well as the input of the Li-Ion battery are shown in the following sub-chapters.

![Diagram of the proposed solar charger](image)

**Figure 44-Detailed diagram of the proposed solar charger.**

5.1 HARDWARE DESIGN

The hardware that was used was the PICDEM 2 Plus demonstration board from Microchip Technology Incorporated. PICDEM 2 Plus is a simple board that demonstrates the capabilities of PIC18 devices such as PIC18F4585. Connected to this board there is the PV panel (see Figure 45) and also a breadboard which contains the DC/DC buck converter developed in previous chapters and the IC SG3524. Into the output of the buck converter there is the Li-Ion battery connected to.

![Hardware components](image)

**Figure 45-Hardware components.**
5.2 SOFTWARE DESIGN

The software development was done using the Microchip’s MPLAB IDE v.8.0. MPLAB, a windows based integrated development environment, allows the creation of source code using the built in editor. The MPLAB environment has the ability to assemble, compile and link the source code using various language tools. This environment also allows the user to debug the executable logic while watching program flows with a simulator. Voltage maximum power point tracking program was written in C language, compiled with MPLAB and downloaded to the Microchip embedded development tool ICD2 directly to the PIC.

The MPPT method implemented was the Voltage Maximum Power Point as stated previously. After initialisation, the main program loop measures the open circuit voltage \( V_{oc} \) across the solar panel from input RA1/AN1 (analogue input) on Port A. The voltage \( V_{oc} \) is then multiplied by voltage factor \( M_v \), equal to 0,75. According to achieved result, PWM mode is activated and the value of the duty cycle is given by \( V_{MP} \). Once the PWM output is generated the program will wait approximately 1 minute allowing the digital to analog conversion to occur (output low pass filter).

After this interrupt the main program loop measures the voltage across the battery from input RA0 (analogue input) on Port A. If the voltage achieved is equal to 4,2 V the battery is full of charge and the system turns off. If not the open circuit voltage across the solar panel is measured again and the main loop starts from the beginning. It is presented in Figure 46 the VMPPT flowchart for this process.
5.3 EXPERIMENTAL RESULTS

The experimental results are divided in two schemes:

- Laboratory tests: solar panel was substituted by an ideal voltage source and the simulation occurs with a resistive load (similar to what was performed in Pspice environment);
- Field tests ran in open space, enabling the use of the solar panel and the Li-Ion battery (similar to the simulations in Simulink).

The tests were carried out with the help of a digital oscilloscope, to record different plots from the several test points, and a digital multimeter in order to describe the system voltage and current evolution on the battery and in the solar panel output.
5.3.1 Laboratory Tests

The laboratory tests were made in the laboratory of the Electronic Section. As in the same conditions stated for the *Pspice* simulations (stated in Section 3) the solar panel was replaced by an ideal voltage source of 10V and the simulation ran with a resistive load. The results obtained are stated in the following figures.

Figure 47 presents the PWM signal generated by the PIC and the respective mean voltage value after the LPF. Applying the VMPPT algorithm, the PWM signal just outside the PIC port, is consistent with the voltage factor, $M_v = 0.75$, applied. It is possible to identify that the positive duty cycle is near 75%, which means that the system is being controlled (duty ratio control). The mean voltage value of the duty cycle is 3.7446V. Just outside the low pass filter the value obtained is equal to 3.72V.

<table>
<thead>
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<td>Fall Time</td>
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<tr>
<td>Neg. Duty Cycle</td>
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<tr>
<td>Neg. Overshoot</td>
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<tr>
<td>Maximum</td>
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<tr>
<td>Minimum</td>
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Figure 47-PWM signal (before and after LPF).

Figure 48 presents a zoom in of the voltage $V_{ref}$ (just outside the LPF). According to this plot the achieved mean voltage value is 3.75V with a delta of 118mV (the voltage ripple is near 3%). Once again the voltage ripple respects the assumed value in the theoretical calculations. The value achieved for $V_{ref}$ means that the system is working at the MPPT. By comparing Figure 48 with Figure 20 it one may observe a very good agreement between the simulation and the practical work.
Figure 48 - $V_{\text{ref}}$, DC and AC value (laboratory results).

Figure 49 presents the voltage across capacitor $C_1$. The achieved mean voltage value is 7.72V with a delta of 0.280V. According to these results the voltage ripple is near 3%, which respects the theoretical calculations for capacitor $C_1$.

Figure 49 - $V_{C1}$, DC and AC value (laboratory results).

Figure 50 presents the PWM signal ($V_{\text{gate}}$) for different load resistances. Regarding the simulations achieved in Pspice environment there is a very good agreement with the following results: for the load resistance equal to $R_{\text{load}} = 20\,\Omega$ the system presents a duty cycle ratio control (please compare with Figure 27) and for $R_{\text{load}} = 40\,\Omega$ the system present deficient control (compare with Figure 25). It is practically inexistent.
Figure 50-PWM control for different load resistances.

Figure 51 presents the voltage across different resistive loads. Once again comparing with the simulations in Pspice the following results are very similar to those obtained in Section 3 (compare with Figure 23 and Figure 26, respectively).

Figure 51-V(\(R_{\text{load}}\)) for different load resistances (DC and AC value).
5.3.2 Field Test

The field test occurred on the 29th July 2008. According to the Portuguese Institute for Meteorology temperatures around 25 to 26 Celsius degrees were expected. The experimental tests occurred in very good conditions. With the collaboration of INETI (“Instituto Nacional de Engenharia, Tecnologia e Inovação”) it was possible to acquire the irradiation values for this day according to Figure 52.

![Irradiation 29th July 2008](image)

Figure 52-Irradiation values.

In order to obtain the entire solar charger characterisation the operating characteristics of the PV module used had to be known. In order to evaluate the V-I and P-I characteristic of the PV, the panel was connected in series with a regulator resistance (see Figure 53). The voltage and current were measured between 0Ω, short circuit, and 100 Ω, open circuit.

![Figure 53-PV evaluation](image)

Figure 53-PV evaluation.

The following characteristics were measured. Note that the V-I characteristic was measured before VMPPT algorithm was tested to ensure consistent results.
As can be seen from the above plots the maximum power of the module used was approximately 1,1W and occurred when $i_{\text{max}} = 0,15A$ and $v_{\text{max}} = 7,8V$. Comparing these plots with the ones achieved (see Figure 39), according to Simulink simulations, it is possible to conclude that the computed results show good agreement with measurements achieved. Again, the value chosen for the voltage factor $M_v$ shows good agreement with the results obtained.

In order to validate the proposed VMPPT charging technique several figures were obtained. Figure 56 and Figure 57 presents the voltage and current evolution during the battery charge. The initial SOC is set to 3,4V in order to accelerate the charging process and to focus in the charging characteristic area that shows utmost importance. The system charges the battery according to a
current, which varies between 0.2A to 0.18A (see Figure 57), until the battery voltage reaches 4.2V at which the charge mode is disconnected. Under the conditions above the battery takes about seven hours to achieve its maximum capacity. The present results of the battery charging process are in very good agreement between with the simulation results depicted in Figure 42.

![Li-Ion-charging voltage](figure56.png)

**Figure 56-Li-Ion charging voltage.**

![Li-Ion-charging current](figure57.png)

**Figure 57-Li-Ion charging current.**

Figure 58 and Figure 59 presents the power across the PV solar panel and the Li-Ion battery for the charging process, respectively. Regarding the maximum power that the solar panel can deliver into the load \( P_{max, PV} \approx 1.3W \) it is worth noting that the system presents losses around 0.4W. These losses were already been observed in the simulations using Pspice (see Figure 32).
In order to get an idea of the Li-ion battery discharge characteristic an experimental test with constant current was conducted. The initial State of Discharge (SOD) was set to 4.06V. The discharge occurred at a constant current of 0.15A. At this rate the battery took approximately 8 hours to achieve 3.42V, as depicted in Figure 60. The plot presents the nominal area of the discharge characteristic (see Figure 43).
5.4 CONCLUSIONS

The environmental operating conditions were essential to get good results. Based on the experimental results the following conclusions are drawn:

- The close agreement between simulation and experimental work shows that the proposed electrical model accurately predicts battery charge: the battery charging process occurred in the expected time;
- The system presents a duty cycle ratio control imposed by the microcontroller (VMPPT algorithm) that allows the system to permanently achieve the maximum power point for different environment conditions;
- The input and output filters are well dimensioned regarding the theoretical calculations (3% voltage ripple and DC/DC converter always in CCM);
- The solar panel respects the supplier information: according to the V-I and P-I characteristics achieved;
- The results allowed to re-enforce the idea that the system is not ideal: there are losses in the system that affect the efficiency of the entire process;
- The experimental work also allowed verifying the system behaviour and control.

Figure 60-Li-Ion discharging process.
6. CONCLUSIONS

6.1 SUMMARY OF RESULTS

The current thesis intends to give a contribution for the solar battery charging process by implementing a MPPT control system that allows a safe and fast charging process using a duty cycle ratio control. By doing this, it is attended to achieve better performance and efficiency for the charging process. The voltage maximum power point tracking (VMPPT) algorithm was used and allowed to simulate the system behaviour for different conditions. For the theoretical analysis, Matlab/Simulink and Pspice facilities are employed and a microcontroller based tracker prototype capable of implementing VMPPT is constructed and used to charge a Li-Ion battery. Based on the results presented before, the following conclusions may be stated.

In Chapter 2, it was made a total description of the system. It were presented electrical models for each of the components namely for the photovoltaic solar cell and for the Li-ion battery. The charger unit (DC/DC converter and the MPPT algorithm) and the control unit (microcontroller PIC18F4585 and IC SG3524) were presented and dimensioned in order to correctly achieve the pre-determined goals for this thesis. Throughout this chapter the MPPT technique implemented is explained and the interconnection of the different elements is set in a clear way.

The simulation of the system in Pspice environment, made in Chapter 3, allowed a better understanding of the system behaviour when in the presence of different resistive loads. The system dynamics is affected for different loads and as a consequence the duty cycle ratio control, that allows the implementation of the VMMPT algorithm, can and as stated will be affected. As evidenced the system control is affected for voltage values above approximately 5.20V that corresponds to a resistive load of 40Ω. Using this simulation tool it was also possible to characterise the system losses during the entire process. As was expected most of the losses presented come from the switch presented in the DC/DC converter.

In Chapter 4, using Matlab/Simulink tool it was possible to conclude that the theoretical assumptions made, namely the voltage factor $M_v$ used, is a very approximate value of what can be expected in real time implementation. Other important aspect was the possibility to directly compare the system behaviour: resistive load vs. Li-Ion battery model. The results achieved are in good agreement which is an indicator that the system is properly dimensioned and correctly interconnected. The system is always controlling and seeking for the MPPT. It was also possible to
obtain an estimate for the charging process, approximately seven hours for a Li-ion battery fully discharged.

Finally in Chapter 5, was carried out the practical component of this thesis. All the components were interconnected and the solar battery charger prototype was tested. The close agreement between simulation and experimental work shows that the electrical models and the sizing of the entire system accurately predict the system behaviour. The experimental work allowed seeing the real implementation of the VMPPT and the functioning of the microcontroller. The battery charger allowed to correctly charging the Li-ion battery and during this process it was possible to see, through measurements in real time, the permanent adjustment in order to achieve always the maximum power transfer from the PV to the battery. The field test occurred in a sunny day and allowed to charge the battery in approximately seven hours.

Briefly, the main goal for this thesis has been achieved. The construction of a solar charger prototype using a microcontroller, which is based on a MPPT algorithm, was implemented and tested in a real life possible usage. The final prototype allows verifying the utility and efficiency of the VMPPT algorithm in order to constantly transfer the maximum power from the PV to the load. Beyond the practical advantage of getting a real solar charger this thesis also allowed to understand the system dynamics and behaviour for different conditions on the load and even for environmental issues.

### 6.2 FUTURE SCOPE OF WORK

Future studies into maximum power point tracking could include the use of a different DC/DC converter and also some different MPPT algorithm such as Current MPPT (CMPPT) for example, could be implemented.

Another extension of this project could be to design the DC/DC converter in full. The converter design could be done to optimise the components and in turn increasing the power efficiency. By optimising the DC/DC converter the MPPT algorithms would achieve improved efficiencies and power tracking capabilities.

Finally a future work can also improve the developed software in order to efficiently use the capabilities of the microcontroller. A final prototype could then be design and implemented in order to have a final portable prototype for the solar charger.
REFERENCES


## ANNEX1 – Solar Panel Datasheet

### Data Sheet

#### Electrical Specifications

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<th>2W</th>
<th>3W</th>
<th>4W</th>
<th>5W</th>
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<td>1.8V</td>
<td>2.0V</td>
<td>2.2V</td>
<td>2.4V</td>
<td>2.6V</td>
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<tr>
<td>Nominal Current (mA)</td>
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<td>1.05A</td>
<td>1.45A</td>
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</tr>
<tr>
<td>Nominal Power (W)</td>
<td>0.8W</td>
<td>1.8W</td>
<td>2.6W</td>
<td>3.5W</td>
<td>4.3W</td>
<td>5.2W</td>
</tr>
</tbody>
</table>

#### Performance

**High Temperature Performance**

High operating temperatures reduce voltage output while slightly improving current. As a result, high temperatures are not useful. Devices are generally designed to maintain performance within a certain range. If voltage drops below the minimum necessary to charge a battery, SolarTech recommends using external devices to minimize this problem. SolarTech specifications list this as STC for all its OEM products.

**Mechanical Characteristics and Design Considerations**

**Active Area**

A module's **Active Area**—the front area that generates electrical power—is a critical design consideration. Using any photovoltaic product in an area covered by a mounting bracket or held down, power may be reduced and the product may cease to function. For optimal performance, the Active Area must never be shaded.

#### Diagram

![Diagram of Active Area Dimensions](image)

**Active Area Dimensions**

<table>
<thead>
<tr>
<th>Model</th>
<th>A (mm)</th>
<th>B (mm)</th>
<th>C (mm)</th>
<th>D (mm)</th>
<th>E (mm)</th>
<th>F (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N506</td>
<td>331.6</td>
<td>681.3</td>
<td>251.2</td>
<td>147.6</td>
<td>111.1</td>
<td>31.0</td>
</tr>
<tr>
<td>N5101</td>
<td>331.6</td>
<td>681.3</td>
<td>251.2</td>
<td>147.6</td>
<td>111.1</td>
<td>31.0</td>
</tr>
<tr>
<td>S5025</td>
<td>331.6</td>
<td>681.3</td>
<td>251.2</td>
<td>147.6</td>
<td>111.1</td>
<td>31.0</td>
</tr>
<tr>
<td>S5045EB</td>
<td>381.3</td>
<td>762.5</td>
<td>251.2</td>
<td>147.6</td>
<td>111.1</td>
<td>31.0</td>
</tr>
<tr>
<td>S5060EB</td>
<td>431.5</td>
<td>843.8</td>
<td>251.2</td>
<td>147.6</td>
<td>111.1</td>
<td>31.0</td>
</tr>
<tr>
<td>S5060EB</td>
<td>481.8</td>
<td>925.1</td>
<td>251.2</td>
<td>147.6</td>
<td>111.1</td>
<td>31.0</td>
</tr>
</tbody>
</table>

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### Data Sheet

#### Variables Affecting Performance

The current and power output of photovoltaic modules are roughly proportional to illumination intensity. At a given intensity, a photovoltaic module's operating voltage is determined by the characteristics of the cell. If the load is a battery, the battery's internal resistance will lower the operating voltage, whereas increasing the load current will decrease the module's output power. However, the battery's charging requirements are met when the module operates in a parallel condition.

#### Maximum Charging Power by Design

Solarex CSM modules are designed to produce maximum power near their specified voltage range. Grid tied inverters are used to produce useful output and current over the expected range of operating conditions.

### Solarex MEGA + Series Module Products

<table>
<thead>
<tr>
<th>Model</th>
<th>MEGA Module</th>
<th>MW</th>
<th>Current (A)</th>
<th>Voltage (V)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAX-1</td>
<td>1.60 x 2.84</td>
<td>2.5</td>
<td>50</td>
<td>18</td>
<td>.50</td>
</tr>
<tr>
<td>MAX-2</td>
<td>2.50 x 2.84</td>
<td>3.5</td>
<td>70</td>
<td>20</td>
<td>.38</td>
</tr>
</tbody>
</table>

### Solarex SA-Series Plate Products (suitable for kitchen use)

<table>
<thead>
<tr>
<th>Model</th>
<th>SA-0110P</th>
<th>SA-0410P</th>
<th>SA-0610P</th>
<th>SA-0910P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (W)</td>
<td>110</td>
<td>410</td>
<td>610</td>
<td>910</td>
</tr>
<tr>
<td>Dimensions (mm)</td>
<td>91 x 91</td>
<td>410 x 91</td>
<td>610 x 91</td>
<td>910 x 91</td>
</tr>
</tbody>
</table>

### SA-Series Components (suitable for solar use)

<table>
<thead>
<tr>
<th>Component</th>
<th>SA-0110P</th>
<th>SA-0410P</th>
<th>SA-0610P</th>
<th>SA-0910P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (kg)</td>
<td>2.5</td>
<td>10.5</td>
<td>16.5</td>
<td>22.5</td>
</tr>
<tr>
<td>Dimensions (mm)</td>
<td>91 x 91</td>
<td>410 x 91</td>
<td>610 x 91</td>
<td>910 x 91</td>
</tr>
</tbody>
</table>

*Note: All components are suitable for use with SA-Series modules.*
ANNEX2 – DC/DC Components

Mosfet 2N6660

N-Channel Enhancement-Mode MOSFET Transistors

**PRODUCT SUMMARY**

<table>
<thead>
<tr>
<th>Part Number</th>
<th>V_{BR(esc)} Min (V)</th>
<th>R_{DS(on)} Max (Ω)</th>
<th>V_{GSMIN} (V)</th>
<th>I_{D} (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2N6660</td>
<td>&gt; 60</td>
<td>1 @ V_{DS} = 10 V</td>
<td>0.8 to 2.2</td>
<td>1.1</td>
</tr>
<tr>
<td>VQ1004J/P</td>
<td>&gt; 60</td>
<td>3.5 @ V_{DS} = 10 V</td>
<td>3.8 to 5.5</td>
<td>0.48</td>
</tr>
</tbody>
</table>

**FEATURES**
- Low On-Resistance: 1.3 Ω
- Low Threshold: 1.7 V
- Low Input Capacitance: 35 pF
- Fast Switching Speed: 8 ns
- Low Input and Output Leakage

**APPLICATIONS**
- Direct Logic-Level Interface: TTL/CMOS
- Driver: Relays, Solenoids, Lamps, Hammers, Displays, Memories, Transistors, etc.
- Battery Operated Systems
- Solid-State Relays

**ABSOLUTE MAXIMUM RATINGS**

- **Symbol**
- **Single**
- **Total Quad**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>VQ1004J</th>
<th>VQ1004P</th>
<th>VQ1004/J/P</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drain-Source Voltage</td>
<td>V_{DS}</td>
<td>60</td>
<td>60</td>
<td>V</td>
</tr>
<tr>
<td>Gate-Source Voltage</td>
<td>V_{GS}</td>
<td>±20</td>
<td>±30</td>
<td>±30</td>
</tr>
<tr>
<td>Continuous Drain Current</td>
<td>I_{D}</td>
<td>1.1</td>
<td>0.46</td>
<td>A</td>
</tr>
<tr>
<td>@ T_{J} = 25°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ T_{J} = 100°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulsed Drain Current</td>
<td>I_{Dp}</td>
<td>3.8</td>
<td>3.26</td>
<td>3.26</td>
</tr>
<tr>
<td>@ T_{J} = 25°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ T_{J} = 100°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rss</td>
<td></td>
<td>3.25</td>
<td>1.3</td>
<td>2</td>
</tr>
<tr>
<td>@ T_{J} = 25°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ T_{J} = 100°C</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum Junction-to-Ambient Resistance</td>
<td>R_{JSA}</td>
<td>170</td>
<td>156</td>
<td>156</td>
</tr>
<tr>
<td>@ T_{A} = 25°C</td>
<td></td>
<td></td>
<td></td>
<td>μA</td>
</tr>
<tr>
<td>Maximum Junction-to-Ground Resistance</td>
<td>R_{JSG}</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ T_{A} = 25°C</td>
<td></td>
<td></td>
<td></td>
<td>μA</td>
</tr>
</tbody>
</table>

Notes:
- *a* This parameter is subject to maximum junction temperature.
- *b* This parameter is not specified with JEDEC.
## Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Test Conditions</th>
<th>Typ$^a$</th>
<th>Min</th>
<th>Max</th>
<th>Min</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Static</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drain-Source Breakdown Voltage</td>
<td>$V_{BR(x,s)}$</td>
<td>$V_{DS} = 0, V$, $I_{G} = 10, \mu A$</td>
<td>75</td>
<td>60</td>
<td>100</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Gate-Thermal Voltage</td>
<td>$V_{G2N40}$</td>
<td>$V_{DS} = 6, V$, $I_{G} = 1, nA$</td>
<td>1.7</td>
<td>0.8</td>
<td>2</td>
<td>0.8</td>
<td>2.5</td>
<td>mA</td>
</tr>
<tr>
<td>Gate-Body Leakage</td>
<td>$I_{GS}$</td>
<td>$V_{GS} = 0, V$, $V_{DS} = 2, V$</td>
<td>$\leq 100$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td>Zero Gate Voltage Drain Current</td>
<td>$I_{DSS}$</td>
<td>$V_{DS} = 50, V$, $V_{GS} = 5, V$</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V_{DS} = 40, V$, $V_{GS} = 5, V$</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V_{DS} = 25, V$, $V_{GS} = 5, V$</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td>On-State Drain Current$^b$</td>
<td>$I_{DSS}$</td>
<td>$V_{DS} = 0, V$, $I_{G} = 10, \mu A$</td>
<td>0.5</td>
<td>1.5</td>
<td>1.5</td>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V_{DS} = 5, V$, $I_{G} = 2.5, \mu A$</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A</td>
</tr>
<tr>
<td>Drain-Source On-Resistance$^c$</td>
<td>$R_{ON}$</td>
<td>$V_{DS} = 10, V$, $I_{D} = 1, A$</td>
<td>1.3</td>
<td>3</td>
<td>3.5</td>
<td></td>
<td></td>
<td>$\Omega$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V_{DS} = 0, V$, $I_{D} = 1, A$</td>
<td>2.4</td>
<td>4.2</td>
<td>4.5</td>
<td></td>
<td></td>
<td>$\Omega$</td>
</tr>
<tr>
<td>Forward Transconductance$^d$</td>
<td>$g_{m}$</td>
<td>$V_{DS} = 15, V$, $I_{D} = 0.5, A$</td>
<td>350</td>
<td>170</td>
<td>170</td>
<td></td>
<td></td>
<td>$mS$</td>
</tr>
<tr>
<td>Common Source Output Conductance</td>
<td>$g_{os}$</td>
<td>$V_{DS} = 15, V$, $I_{D} = 0.1, A$</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$mS$</td>
</tr>
<tr>
<td>Diode Forward Voltage</td>
<td>$V_{F}$</td>
<td>$I_{D} = 3.35, A$, $V_{GS} = 5, V$</td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td><strong>Dynamic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Input Capacitance</td>
<td>$C_{iss}$</td>
<td>$V_{DS} = 24, V$, $V_{GS} = 0, V$, $f = 1, MHz$</td>
<td>35</td>
<td>50</td>
<td>60</td>
<td></td>
<td></td>
<td>pF</td>
</tr>
<tr>
<td>Output Capacitance</td>
<td>$C_{oss}$</td>
<td>$V_{DS} = 24, V$, $V_{GS} = 0, V$, $f = 1, MHz$</td>
<td>35</td>
<td>65</td>
<td>60</td>
<td></td>
<td></td>
<td>pF</td>
</tr>
<tr>
<td>Reverse Transfer Capacitance</td>
<td>$C_{rss}$</td>
<td>$V_{DS} = 24, V$, $V_{GS} = 0, V$, $f = 1, MHz$</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td></td>
<td></td>
<td>pF</td>
</tr>
<tr>
<td>Drain-Source Capacitance</td>
<td>$C_{gd}$</td>
<td>$V_{DS} = 24, V$, $V_{GS} = 0, V$, $f = 1, MHz$</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>pF</td>
</tr>
<tr>
<td><strong>Switching$^4$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turn-On Time</td>
<td>$t_{ON}$</td>
<td>$V_{DS} = 25, V$, $R_{L} = 25, k\Omega$, $I_{D} = 1, A$, $V_{GS} = 10, V$, $R_{G} = 25, k\Omega$</td>
<td>8</td>
<td>10</td>
<td>10</td>
<td></td>
<td></td>
<td>ns</td>
</tr>
<tr>
<td>Turn-Off Time</td>
<td>$t_{OFF}$</td>
<td>$V_{DS} = 25, V$, $R_{L} = 25, k\Omega$, $I_{D} = 1, A$, $V_{GS} = 10, V$, $R_{G} = 25, k\Omega$</td>
<td>8.5</td>
<td>10</td>
<td>10</td>
<td></td>
<td></td>
<td>ns</td>
</tr>
</tbody>
</table>

**Notes:**
- $^a$: $T_{A} = 25\, ^\circ C$, unless otherwise noted.
- $^b$: For $I_{D} > 0.5\, A$, limits are specified per tester.
- $^c$: $I_{D}$ refers to the maximum continuous forward current.
- $^d$: For $I_{D} > 0.5\, A$, limits are specified per tester.
- $^e$: $T_{J}$ is limited to $175\, ^\circ C$.
- $^f$: This parameter is defined for $V_{DS} = 25\, V$, $R_{L} = 25\, k\Omega$, $I_{D} = 1\, A$, $V_{GS} = 10\, V$, $R_{G} = 25\, k\Omega$.

Vishay Siliconix

www.Vishay.com + Feedback 408-970-5600
Document Number: 70222
11-2
8-VQ2029-REV01, 21-SEP-30

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TYPICAL CHARACTERISTICS (25°C UNLESS NOTED)
Diode D1N5817

FEATURES
- Plastic package has Underwriters Laboratory Remanufacture Classification R-0
- Metal silicon junction, majority-carrier conduction
- Guard ring for overvoltage protection
- Low power loss, high efficiency
- High current capability, low forward voltage drop
- High surge capability
- For use in low-voltage, high-frequency inverters, free-wheeling, and polarity protection applications
- High temperature soldering guaranteed: 260°C, 110 seconds at terminals.
- 3.97 (0.0mm) lead length, 30s (2.34g) reflow

MECHANICAL DATA
- Type: JDEC WEL6 80-8 molded plastic body
- Terminals: Plated axial lead, solderable per MIL-STD-750, method 202
- Polarity: color band denotes cathode end
- Mounting Richardson: Any
- Weight: 0.012 ounce, 0.3 gram

MAXIMUM RATINGS AND ELECTRICAL CHARACTERISTICS
(Ratings at 25°C ambient temperature unless otherwise specified, single-phase, half-wave, resistive or inductive)
- Rated: For capacitive load (deviate by 20%)

<table>
<thead>
<tr>
<th>Symbol</th>
<th>1N5817</th>
<th>1N5818</th>
<th>1N5819</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>VRRM</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>Volts</td>
</tr>
<tr>
<td>VBR</td>
<td>14</td>
<td>21</td>
<td>38</td>
<td>Volts</td>
</tr>
<tr>
<td>VCEO</td>
<td>20</td>
<td>20</td>
<td>40</td>
<td>Volts</td>
</tr>
<tr>
<td>VRMS</td>
<td>24</td>
<td>24</td>
<td>45</td>
<td>Volts</td>
</tr>
<tr>
<td>IFSM</td>
<td>1.5</td>
<td></td>
<td></td>
<td>Amps</td>
</tr>
<tr>
<td>IR</td>
<td></td>
<td></td>
<td></td>
<td>Amps</td>
</tr>
<tr>
<td>UDF (at Tu=70°C)</td>
<td></td>
<td></td>
<td></td>
<td>Volts</td>
</tr>
<tr>
<td>IF</td>
<td>0.455</td>
<td>0.555</td>
<td>0.900</td>
<td>Volts</td>
</tr>
<tr>
<td>IF</td>
<td>0.750</td>
<td>0.875</td>
<td>0.900</td>
<td>Volts</td>
</tr>
<tr>
<td>IR</td>
<td>0.5</td>
<td></td>
<td></td>
<td>mA</td>
</tr>
<tr>
<td>TIA</td>
<td>10.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TJC</td>
<td>150°C</td>
<td></td>
<td></td>
<td>µF</td>
</tr>
<tr>
<td>TRM</td>
<td>20.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRJ</td>
<td>15.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TTJS</td>
<td>-65 to 125</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1. Pulse test, 300 µs pulse width, 1% duty cycle
2. Thermal resistance (from junction to ambient) Vertical, P.C.6, Mounted, with 1.5X1.5"(38X38mm) copper pads
3. Measured at 1.0 MHz and reverse voltage of 0 volts

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Page 1 of 2
ANNEX 3 – Control Unit

PIC 18F4585
Due to the size of the PIC18F4585 datasheet please consult Microchip Website.

IC SG3524
Due to the size of the ICSG3524 datasheet please consult Farnell vendor Website.
ANNEX 4 – Li-ion Battery

VARTA Microbattery

Specification

1. General
   - Li-ion Battery Pack in plastic sleeve incl. safety circuit, cable and wire connectors
   - Weight: approx. 20g
   - Code: LP553450 UCC
   - PCM: P/N: 1326F12
   - NTC: None
   - Polarity: PDR33609

2. Electrical Specification
   -Rated Capacity: 1150mWh/minimum, 1130mWh typical
   -Nominal Voltage: 3.7V
   -Max. Continuous Discharge Current: 1.0A (cell data sheet)
   -Max. Continuous Charge Current: 1.8A (cell data sheet)
   -Internal Resistance: AC (1mV) approx. 120mΩ
   -Discharge Limit: C/10 (discharge 80% of initial cap., 10°C)
   -End Protection
     -Overvoltage Protection: 4.29V ± 2.0mV
     -Overvoltage Protection: 4.00V ± 10mV
     -Overcurrent Protection: 2.000V ± 30mV
     -Overtemperature Protection: 2A in 2s (failure, 2s time delay, 2.00V ± 10mV)

3. Ambient Conditions
   -Temperature Range
     -Operating: 0°C to 45°C
     -Storage: -20°C to 60°C
     -Charge Retention/Storage: 1 year at -20°C to 25°C + 70
     -3 month at -20°C to 45°C + 70
     -1 month at -20°C to 65°C + 70
   -Humidity: 65 ± 20% RH
   -Safety
     -Please follow local Handling and Safety Precautions

Circuit Diagram

These dimensions are considered approximate.