Optimizing Energy Extraction of a Medium-Concentration Solar Panel

Cristóvão Beirão da Cruz e Silva

Supervised by Prof. Doutor João Carlos Carvalho de Sá Seixas

Dep. Physics, IST, Lisbon, Portugal

and Doutor Luís Pina

WS Energia, Lisbon, Portugal

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Abstract

A Solar Cell is a semiconductor device that, due to it's physical properties, has an intrinsic relation between current and voltage, which is referred to as the current voltage curve of the device. This leads to the fact that maximum power output can only be obtained at a particular operating point. For this reason, a circuit that tracks this maximum power point is required in order to deliver maximum power. In general, the maximum power points of individual solar cells do not match, which leads to power loss; even when the system is at it's Maximum Power Point. Building upon techniques available in the literature, a Maximum Power Point Tracker, which operates at the sub-receiver level of a medium-concentration solar panel, is presented. Thus, power loss through the mismatch of the maximum power points of the solar cells is reduced, resulting in higher output power for the solar panel. The presented layout was validated through simulations and a prototype was developed and tested. The simulated and experimental data corroborated each other, proving the success of the design. With further optimizations, the proposed circuit could reduce the cost per kWh of solar energy, making it a competitive alternative to other energy sources. This falls in line with global efforts to turn solar technology into a competitive and sustainable energy source for the future.

Keywords: Solar Cell, Medium-Concentration, Maximum Power Point, Maximum Power Point Tracker

1 Introduction

Current solar technology characteristically exhibits efficiencies perceived as low values, 10 % to 20 % for commercially available Solar Cells. This efficiency is given at the Maximum Power Point of the Solar Cell. Solar Cells are characterized by an extremely non-linear current voltage relationship, given to first order approximation by Equation 1.

$$I_{PV} = I_{SC} - I_S \left(e^{\frac{q\,V}{n\,K_B\,T}} - 1 \right) \qquad (1)$$

This current voltage relationship leads to the power voltage relationship seen in Figure 1, where the previous mentioned maximum is clearly depicted.

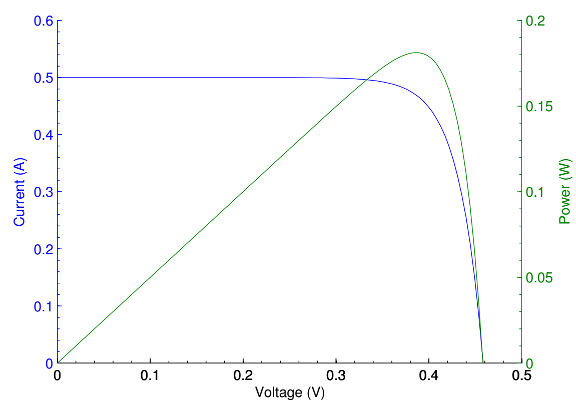

Figure 1: Current Voltage Curve & Power Voltage Curve of a Solar Cell

Solar Cells are further organized into Solar Panels through series and/or parallel connections of the Solar Cells. Unfortunately the maximum power points of the individual Solar Cells do not generally match each other and a series connection between two Solar Cells implies that the current through them should be the same, while a parallel connection implies that the voltage should be the same. In this way, when connecting the Solar Cells together, from the mismatch of the Maximum Power Points a loss of efficiency is expected. Furthermore, by simply connecting another device to the Solar Panel it is not guaranteed that the system will be operating at it's Maximum Power Point. Thus, Solar Panels are generally used in conjunction with a device called a Maximum Power Point Tracker. This device has the capability to dynamically change the load perceived by the power source, in this case the Solar Panel, so that the power source operates as close as possible to the Maximum Power Point. Typical applications of Maximum Power Point Trackers place a single tracker for a string of Solar Panels. This clearly is not ideal as there are many mismatches between the individual Solar Cells in the array of Solar Panels, leading to a significant loss of power. Currently some companies have started to offer trackers associated to individual Solar Panels.

2 Clustering Simulations

Taking into account the Maximum Power Point mismatches, an immediate solution would be to operate the individual Solar Cells at their Maximum Power Points, thus always receiving maximum power from the Solar Panel. However, such an approach is not practical for it requires a single Maximum Power Point Tracker per Solar Cell.

This would greatly increase the cost of Solar Panels. An intermediate solution must be found in order to benefit from a higher power output while simultaneously keeping the costs acceptable.

When considering a concentration Solar Cell, the power output of a single Solar Cell is greatly increased. A small mismatch in Maximum Power Points will then represent a much higher power loss.

For the simulations, a model of a Solar Cell was implemented. In this model the Solar Cell is represented as a current source, with a diode connected in parallel, in order to provide the exponential feature seen in the current voltage curve of the Solar Cells. To the model, two resistors were added, a series and shunt resistor, Figure 2.

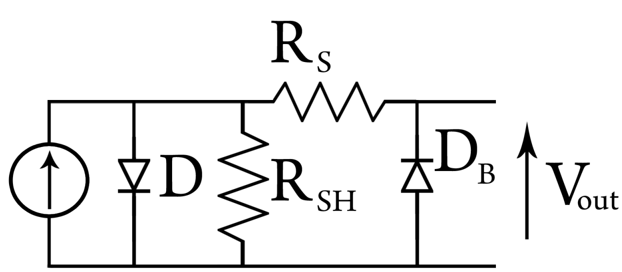

Figure 2: Solar Cell Model

Several simulations were then performed. In the simulations several different optical defects of the concentrating mechanism were considered as well as variations of the individual Solar Cells. In the simulations a few methods to join the Solar Cells were investigated. These Clustering mechanisms were inspired by the Solar Panel used in the study and the manner in which the Solar Cells were mounted in it. The Solar Cells were thus analyzed individually, calculating the maximum output power capable of being generated by that Solar Panel, in groups of 5 connected in series, this is called a sub-receiver, in groups of 3 series connected sub-receivers, called receivers and finally in groups of 7 receivers, a Solar Panel. Consulting the results of these simulations, Figures 3 to 6 are examples of the obtained outputs, it is clear that clustering by sub-receiver will result in higher power outputs for the Solar Panel, in average $15\,W$ per Solar Panel. The simulations also show that clustering by sub-receiver always produced more power than when clustering by Solar Panel, even if only by $4\,\%$.

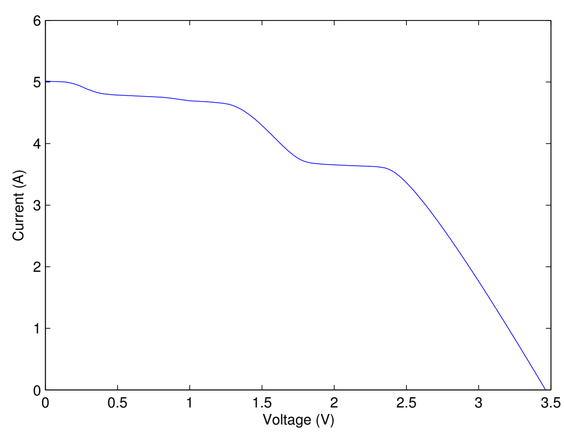

Figure 3: Simulated Sub-Receiver Current Voltage Curves

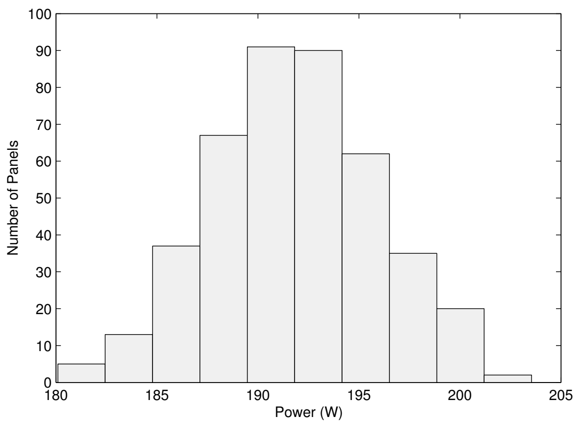

Figure 4: Solar Panel Power Output - Clustering by Solar Cell

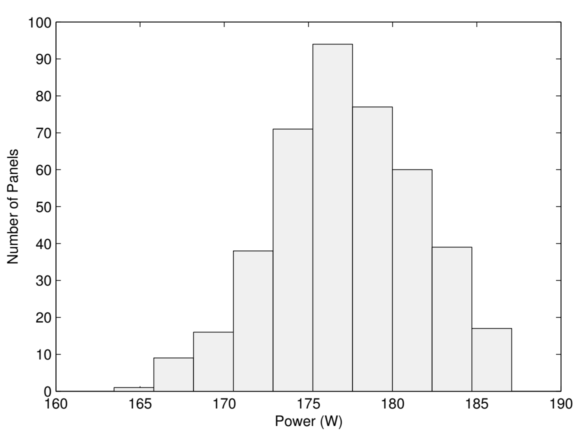

Figure 5: Solar Panel Power Output - Clustering by Sub-Receiver

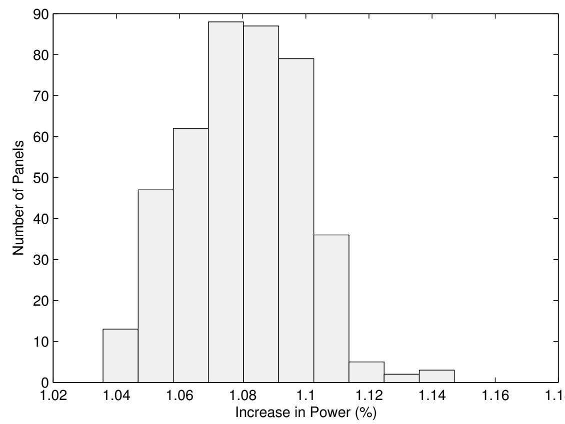

Figure 6: Increase of Maximum Available Power - Clustering by Sub-Receiver vs. by Solar Panel

3 Maximum Power Point Tracker Design

Taking into account the previous simulations, it was decided to implement a Maximum Power Point Tracker at the sub-receiver level. A Maximum Power Point Tracker has two main components, the converter stage and the control circuitry.

The converter stage is what allows the Maximum Power Point Tracker to control the operating point of the circuit. This is done through control of the relation between the input and output voltage of this stage, this control is performed by the control circuitry. There are several converter designs available in the literature, for this application a Boost converter was chosen. The most important equations that dictate this converter's behavior are given below.

$$\frac{V_{OUT}}{V_{IN}} = \frac{1}{1-D} \tag{2}$$

$$\Delta I_L = \frac{D\,T}{L}\,V_{In} \tag{3}$$

$$\Delta V_{OUT} = \frac{D}{1-D}\,\frac{V_{IN}\,T}{R\,C} \tag{4}$$

$$R_{IN} = (1-D)^2\ R \tag{5}$$

The control circuitry can be implemented either in an analogue circuit or a digital circuit. For this application a digital circuit was chosen for it's ease of reconfigurability and troubleshooting, provided by the micro-controller based approach taken.

For the tracking itself, many algorithms are proposed in the literature, with several variations upon the basic designs. The Perturb and Observe algorithm was chosen given that it is among the simplest algorithms available, providing a power output comparable to the best tracking algorithms. This algorithm periodically perturbs the operating point in one direction. It then verifies if the power given by the power source increased or decreased. If the power increased the following perturbation will be made in the same direction. If it is decreased, the following perturbation will be made in the opposite direction. This algorithm will be complemented by a sweeping algorithm in order to identify the absolute maximum of the power voltage curve and not a local maximum; a problem common to many tracking algorithms where they get stuck in local maxima.

4 Implementation

For implementing a prototype Maximum Power Point Tracker at the sub-receiver level the several components that consist the tracker should be chosen and dimensioned. As such, for the voltage and current sensors a design which reduced power consumption and provided filtering of the high frequency signal, introduced by the switching mechanism of the converter, was chosen. These sensors were dimensioned in such a way that the output voltage would take values between $0\,V$ and $2\,V$. This maximum value of $2\,V$ was chosen due to the accurate internal voltage reference provided by the micro-controller used.

The components for the converter were dimensioned with the aid of the equations that govern it's behavior. First, acceptable values for the ripple voltages and currents were assumed. Then inductor and capacitor values that provide that ripple or lower were calculated. For the capacitors a value was simply chosen. For the inductor further analysis through power loss were performed, obtaining Figure 7. It is now clear that inductor 1 is the one that provides lowest power loss, thus being the chosen inductor. Notice that inductor 5 is a fictitious inductor introduced to verify the effects of the inductance value on the power loss. A similar power loss analysis was then performed for the MOSFETS, resulting in Figure 8, permitting the MOSFETS to be chosen as well.

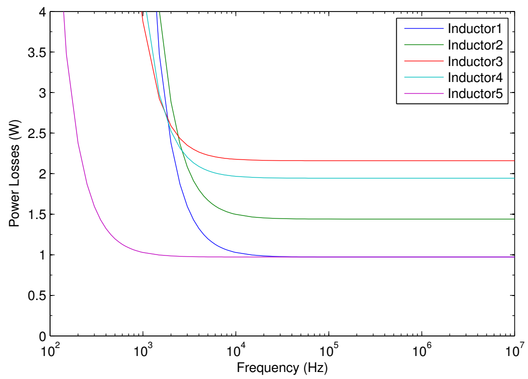

Figure 7: Inductor Power Losses

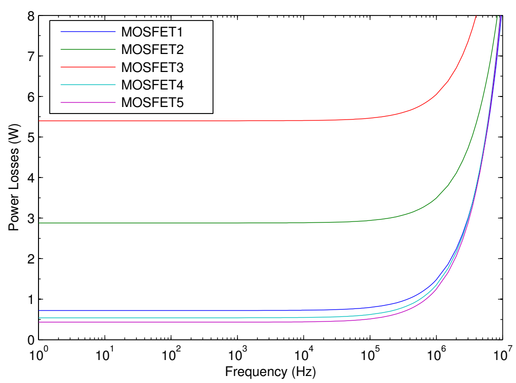

Figure 8: MOSFET Pair Power Losses

Once all the components were chosen, further simulations that take into account the behavior of these components could be performed. Two simulations were then set up. The first calculated the expected efficiency of the tracker, resulting in Figure 9. The second simulated in the time domain, the behavior of the tracker. An example output of the tracking simulation can be seen in Figure 10.

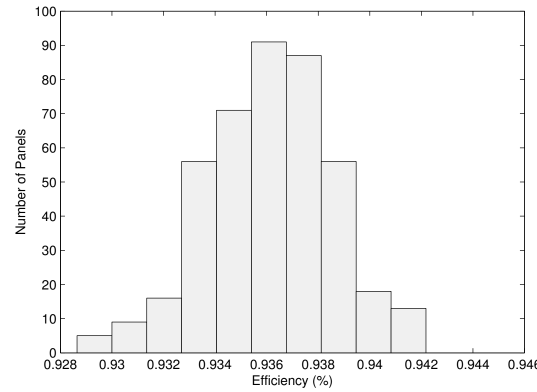

Figure 9: Per Solar Panel Average Efficiency of Sub-Receiver Maximum Power Point Tracker

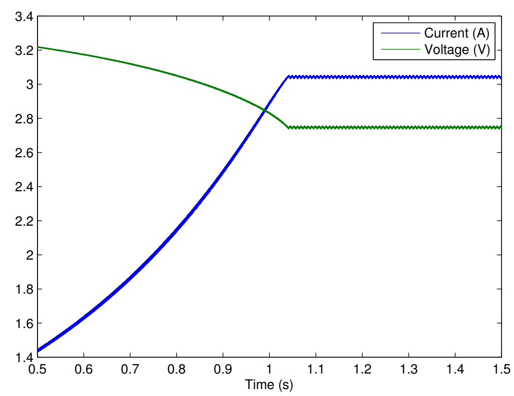

Figure 10: Perturb and Observe Simulation

5 Prototype Testing

With respect to the prototype, upon reception of the components and the printed circuit board, the prototype was assembled. A first set of preliminary tests were performed in order to verify the correct functioning of all the components. For the final test the prototype was set up to work like a boost converter, placing the voltage at the output as double the input voltage. This final test permitted measurements of the input and output power, allowing for an estimation of the efficiency of the converter of 0.9293 ± 0.0058.

As a final step the prototype was set up as a Maximum Power Point Tracker and connected to a sub-receiver. Unfortunately, it was not possible to perform an exhaustive and accurate set of measurements. However the tracking capability of the tracker was proven, demonstrating that the prototype was able to find and maintain the sub-receiver as close as possible to this point. As for the output voltage, the measuring device proved to be faulty, resulting in unreliable data. However the assumption that the output voltage deviates from the theoretical value by the same amount as that observed in the last test phase was taken.

The measured input voltage was $0.756\,V$, while the voltage at the Maximum Power Point was $0.793\,V$, taken from Figure 11, obtained with an IV-Tracer. The output voltage was then calculated to be $1.3213\,V$ which results in an output power of $0.4365\,W$. Considering the power at the maximum power point, $0.453\,W$, this results in an efficiency of 0.9635.

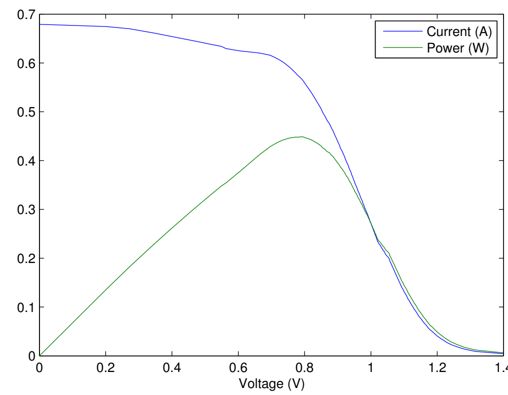

Figure 11: Current Voltage Curve Obtained from IV-Tracer

6 Conclusion

Clustering a medium-concentration Solar Panel by sub-receiver permits a significant gain in power output for the whole panel under the conditions simulated in software. With this in mind a Maximum Power Point tracker, based upon simple principles, was proposed. After dimensioning the several components, simulations of the circuit, along with some of the non-ideal characteristics of the components, were performed. These simulations proved that the design was capable of providing a good tracking of the Maximum Power Point with very good efficiencies, above 90 %.

The proposed design was then physically implemented. Unfortunately, extensive testing of the device was not possible, however preliminary results show good agreement with the simulated data.

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