Maximization of Solar Power Extraction from Photovoltaic Modules Using Energy Harvesting Solutions for Smart Cities

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Abstract. Smart cities integrate a wide and diverse set of small electronic devices that use Internet communication capabilities with very different purposes and features. A challenge that arises is how to feed these small devices. Among the various possibilities, energy harvesting presents itself as the most economical and sustainable. This paper describes the design and simulation of an electronic circuit dedicated to maximizing the solar power extraction from photovoltaic (PV) modules. For this purpose, an integrated circuit (IC) dedicated to energy harvesting is used, namely the LTC3129. This IC is a DC-DC converter that uses the maximum power point control (MPPC) technique, which aims to keep its input voltage close to a defined reference value. The designed circuit is used with three photovoltaic modules, each one of a different PV technology: monocrystalline silicon, polycrystalline silicon and amorphous silicon. These PV modules are installed in a weather station to correlate the power produced with the meteorological conditions, in order to assess which solar photovoltaic technology is best for a given location. The equivalent circuit of a solar cell is used in simulation to represent a photovoltaic module. The values of the components of the equivalent circuit are adjusted so they have the same characteristics of the modules installed in the weather station. With each module, a power resistor of the same value is used as load, for comparison purposes. For the case of the monocrystalline silicon technology, the use of the LTC3129 converter increases the power extraction by 47.6% compared to when this converter is not used between the PV module and the load.

Keywords: Photovoltaic modules · DC-DC converter · Maximum power point control · LTSpice software · LTC3129 DC-DC converter

1 Introduction

With the current growth of the world population, the global energy demand has been also increasing, which has been depleting the available fossil fuel resources [1]. Adding to the limitations of available resources, these types of energy are associated with global

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warming and depletion of the ozone layer. For this reason, renewable energy sources have been attracting the attention from scientists and governments as an alternative to fossil resources [2].

There is a diverse range of renewable energy sources, such as solar energy, geothermal energy, hydropower and wind power. Among these sources, solar energy is one of the most popular, due to the economic and environmental benefits of its conversion into electricity [2]. The most common method to convert solar energy into electricity is by the use of photovoltaic (PV) panels. The PV market is growing at a rate of 35–40% a year, being one of the fastest growing technologies [3].

Photovoltaics can be made from different materials. Depending on the material used, the characteristics of the PV cell, module or panel will be different. The most popular and used material is the silicon, which has a high availability in the Earth's crust. Variations of silicon are used to develop PV technologies, with crystalline silicon being the most prevalent. There are different sub-types of crystalline silicon, with the most popular being monocrystalline and polycrystalline silicon. Non-crystalline silicon is also a material adopted to make PV, especially with thin film technologies, with amorphous silicon being the most developed technology [4]. Of the three technologies mentioned, monocrystalline silicon PV modules are the most efficient, but also more expensive. Polycrystalline silicon PV modules are slightly less efficient [5], but less expensive than the monocrystalline silicon photovoltaics, with its efficiency/cost ratio making it the most type used of them all. Amorphous silicon PV modules have the advantage of being flexible and are very popular in small applications [4].

The most basic component of a PV is the solar cell. A single solar cell has its own electrical characteristics, which is not very useful for electrical energy. An association of solar cells, in series, parallel or both, forms a solar module, which can already be useful in small-scale applications, whereas, an association of multiple solar modules form a solar panel.

To decide the best solar panel technology for a specific geographical location, it is very important to have information about the weather conditions. Some factors that have impact the solar energy production, like the temperature and solar irradiance, can have different effects for different technologies of PV [6, 7], changing the power produced by solar panels or modules and, consequently, the MPP (Maximum Power Point). To solve this problem, the MPPT (Maximum Power Point Tracking) technique [8] is normally used. A MPPT algorithm will always search for the MPP and thus, maximize the power extraction from solar panels or modules.

For smaller power levels obtained from external energy sources, as is the case of photovoltaic modules, it is introduced the process called energy harvesting. This process is normally used to power wireless devices, such as wearable electronics or wireless sensor networks [9]. Besides solar, it is also used with energy sources like thermoelectric or piezoelectric [9]. Dedicated integrated circuits to energy harvesting that increase the efficiency of power extraction from these sources are normally used.

Concerning related work, in [10] the modelling and simulation of a photovoltaic energy harvesting circuit was developed. The converter LTC3105 was used with the equivalent circuit of a solar cell. The used converter is very similar to the converter used in this paper, but dedicated to smaller power sources. The objective of the paper was to find the optimal output power of the system used. In [11] a maximum efficiency extracting technique for endoscopic capsules using Wireless Power Transfer (WPT) was presented. The converter LTC3129-1 was used in order to boost the power conversion efficiency of the WPT receiver. The use of the converter outperformed an LDO (Low-Dropout) by boosting the power range of the endoscopic capsules.

The solution proposed in this paper was developed in the context of a PV module evaluation system that integrates a weather station and a client machine (smartphone or computer), as shown in Fig. 1. The weather station measures various meteorological variables, namely: wind speed, wind direction, solar irradiance, and temperature. This weather station prototype also integrates three PV modules of different technologies: monocrystalline silicon, polycrystalline silicon and amorphous silicon, which are three of the most common photovoltaics technologies. All the gathered data is pre-processed by a microcontroller and stored locally in an SD card before it is transferred to the client machine for analysis. The data collected by the weather station can be periodically transferred to a cloud server over the Internet, from where it can be accessed using the client machine, or be directly transferred to the client machine when the user approaches the weather station through the establishment of a wireless network connection between the weather station and the client machine. The weather station is powered by a LiPo battery and it is recharged by an extra PV module when the weather conditions allow. Based on the analysis of the data gathered by this system, it will be possible to correlate the power produced by each PV module with the particular meteorological conditions measured by the weather station, in order to evaluate which PV technology is best suited for a given location.

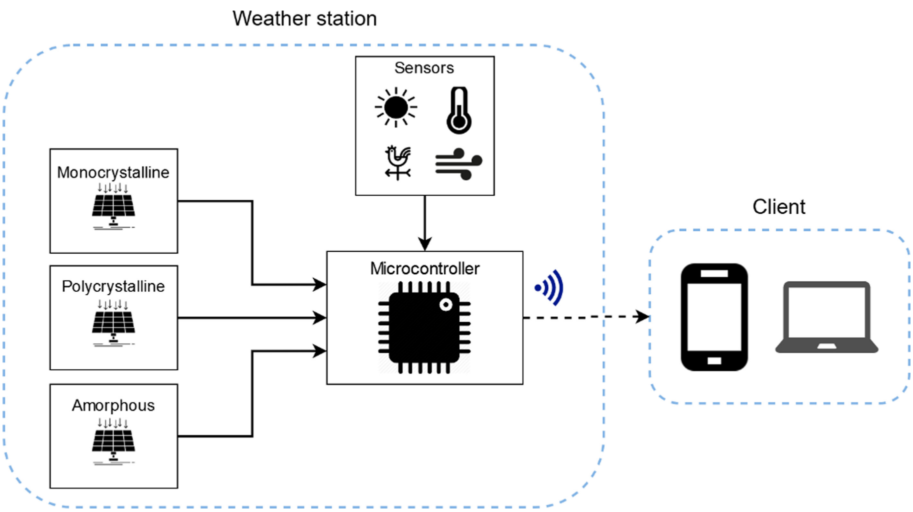

Fig. 1. System architecture in the context of a PV module evaluation system that integrates a weather station and a client machine (smartphone or computer).

The work described in this paper focuses on the design and validation of a circuit to maximize the power extraction from the PV modules installed in the weather station. This solution is based on the use of the LTC3129 [12] DC-DC converter, which implements the MPPC (Maximum Power Point Control) technique. To validate the designed solution, this work uses simulations developed with the LTSpice software [13]. LTspice is a SPICE-based analog electronic circuit simulator computer software, produced by the semiconductor manufacturer Analog Devices.

2 Designed Circuit for Maximization of Solar Power Extraction

This section describes the design of the circuit used to maximize the solar power extraction from the PV modules and explains the decisions behind the choices of the components. Table 1 shows the main characteristics of the three PV modules integrated in the weather station. For comparison purposes, the modules ideally would need to have the same area. However, such was not possible, since the acquired amorphous silicon module has a significantly larger area than the other ones. Therefore, to solve this problem, after measuring the power produced by each module, the average power per 1000 mm^2 is calculated to establish the comparison.

Table 1. Characteristics of the photovoltaic modules integrated in the weather station.

	Monocrystalline	Polycrystalline	Amorphous
Maximum power	1 W	1 W	0.6 W
Short circuit current	250 mA	250 mA	300 mA
Operating current	200 mA	200 mA	200 mA
Short circuit voltage	6 V	6 V	4.15 V
Operating voltage	5 V	5 V	3 V
Area	5100 mm^2	5580 mm^2	6696 mm^2

To maximize the power extraction by low power PV modules, integrated circuits with MPPT capabilities or variations of this technique are normally used. In one of these variations, called MPPC, the converter will try to have its input voltage equal to the set reference value. This technique takes advantage on the fact that the MPP voltage, unlike the current, does not vary much with variations in the weather conditions. Table 2 presents some converters dedicated to energy harvesting that can be used with low power PV modules, such as the ones installed in the weather station.

Taking into consideration the characteristics of the PV modules acquired, the LTC3129 [12] converter was chosen due to the voltage ranges of these modules. It allows an input voltage from 2.42 V to 15 V, which is suited for the PV modules voltage range, and a maximum output current of 200 mA. Depending on the operation mode adopted, the converter can achieve a quiescent current of just 1.3 µA. This converter has integrated MPPC capabilities, in which the reference voltage can be programmed.

Figure 2 presents the circuit with the LTC3129 converter used with each PV module. The datasheet [12] of the converter was followed in order to choose the components

Table 2. DC-DC converters dedicated to energy harvesting available in the market.

IC	Topology	Technique	Input voltage range (V)	Output voltage range (V)	Maximum power (mW)
LTC3105	Boost	MPPC	0.225–5	1.6–5.25	–
LTC3129	Buck/Boost	MPPC	2.42–15	1.5–15.75	–
LTC3331	Buck/Boost	–	3–19	3.45–4.2	–
BQ25570	Boost	MPPT	0.1–5.1	2–5.1	510
SPV1040	Boost	MPPT	0.3–5.5	2–5.2	3000

needed for the implementation of the converter. It is recommended to use an input capacitor higher than 22 μF when using the MPPC capabilities of the converter, so we used a capacitor of 47 μF.

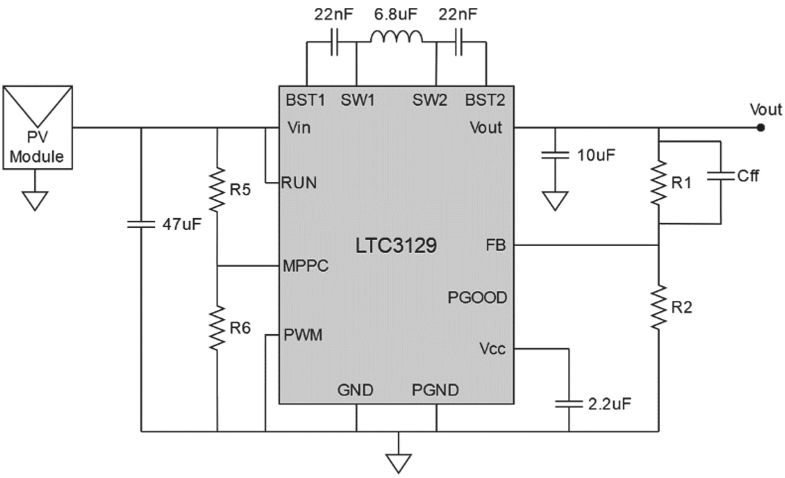

Fig. 2. Circuit using the LTC3129 converter for each photovoltaic module to maximize power extraction.

To achieve the goal of maintaining the input voltage equal to the programmed reference value, it is necessary to connect an external inductor to the converter. The current in the inductor is adjusted by the IC (Integrated Circuit) in order to maintain a minimum voltage at the input, when using high impedance sources, such as the case of PV modules. The reference voltage (V_{MPPC}) can be set with a voltage divider in the MPPC pin, according to Eq. (1) [12].

$$Vmppc = 1.175\left(1 + \frac{R5}{R6}\right) \quad (1)$$

The output voltage (V_{OUT}) can be determined with (2) [12] by using two resistors, one between the Vout pin and the FB pin, and another between the FB pin and ground.

The value of the output voltage can be set from 1.4 V to 15.75 V.

$$V_{OUT} = 1.175\left(1 + \frac{R1}{R2}\right) \tag{2}$$

To reduce the output ripple and increase the transient response, it is recommended the use of a feed-forward capacitor (C_{FF}) in parallel with R1 (in the order of MΩ). The value of this capacitor can be calculated with Eq. (3) [12].

$$C_{FF}(pF) = \frac{66}{R1} \tag{3}$$

At the output of the converter, a power resistor (R_L) of known value was added. The power (P) is then calculated with the voltage (V_{OUT}) measured at the output, using Eq. (4). This voltage is measured by the weather station using the microcontroller ADC (Analog-To-Digital Converter), and a voltage divider is dimensioned taking into account the maximum voltage allowed by the ADC (3.3 V).

$$P = \frac{Vout^2}{R_L} \tag{4}$$

The value of MPPC reference voltage and output voltage are set according to each module's characteristics. A converter is used for each PV module installed in the weather station.

3 Results and Discussion

To validate the designed circuit with the LTC3129 converter, simulations were developed using the LTSpice software. Since this software does not have a component for solar cell, module or panel, the equivalent circuit of a solar cell was used in the simulation. This circuit is composed by a current source, a diode, a series resistor and a shunt resistor [14]. The values of these components determine the characteristics of the PV modules. These values were adjusted to represent the characteristics of the PV modules used (Table 1). Since the monocrystalline and polycrystalline modules exhibit very similar characteristics, the same equivalent circuit was used. Figure 3 shows the equivalent circuits for the amorphous module and monocrystalline/polycrystalline modules.

The power-voltage relationship (P/V) graph was obtained for both equivalent circuits by doing a DC voltage sweep from 0 V to the open circuit voltage of the modules. Figure 4 shows the P/V graph for the monocrystalline and polycrystalline modules, whereas Fig. 5 shows the P/V graph for the amorphous module.

A 50 Ω load was added to the output of the equivalent circuit of the monocrystalline and polycrystalline module, in order to obtain the values of the output power without the converter, for comparison purposes. The graphs for both power and voltage of the circuit output were plotted, as shown in Fig. 6. It can be noticed that the output voltage (5.58 V, in red) is far from the voltage in the point of maximum power (5.00 V), and the output power (blue) is only 624 mW, also far from the MPP (1 W).

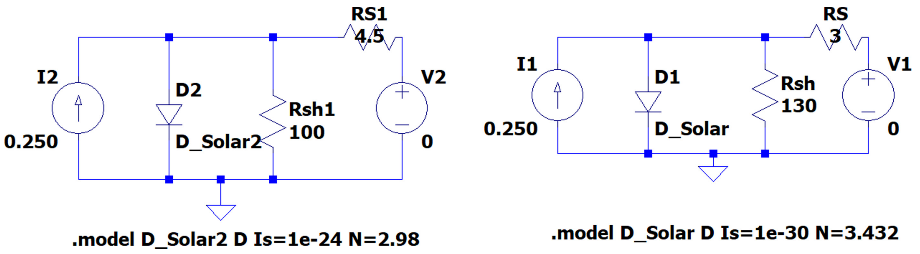

Fig. 3. Equivalent circuits and their components values for the photovoltaic modules: Amorphous module (left) and monocrystalline/polycrystalline modules (right).

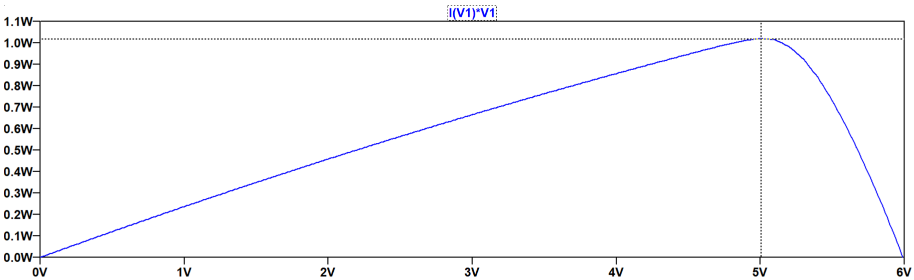

Fig. 4. Power vs. voltage graph for the monocrystalline/polycrystalline module (MPP with 5.00 V and 1.02 W).

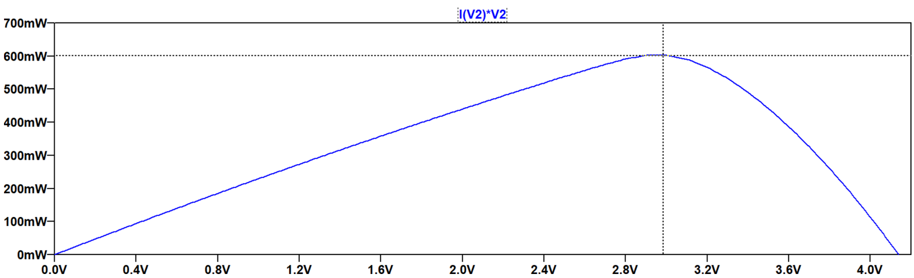

Fig. 5. Power vs. voltage graph for the amorphous module (MPP with 2.98 V and 603 mW).

For validation purposes in the simulation it was only used a single converter, in this case with the equivalent circuit of the monocrystalline and polycrystalline PV module. In practice, in the weather station, a converter would be used for each of the PV modules installed. The converter was added between the equivalent circuit of the PV module and the load, using the MPPC functionality. Figure 7 presents the circuit designed according to Fig. 2 in Sect. 2 of this paper.

The MPPC voltage (V_{MPPC}) was set to different values to test its impact in the power produced by the module. The value of the load was maintained at 50 Ω. In this case, it is assumed that the module is in ideal weather conditions (will produce maximum power). The results can be seen in Table 3.

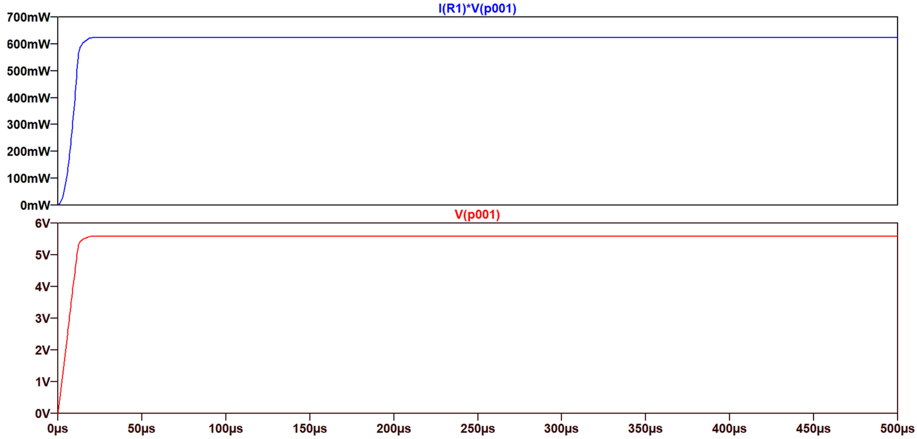

Fig. 6. Output power (624 mW) and voltage (5.58 V) in the equivalent circuit of the monocrystalline/polycrystalline module. (Color figure online)

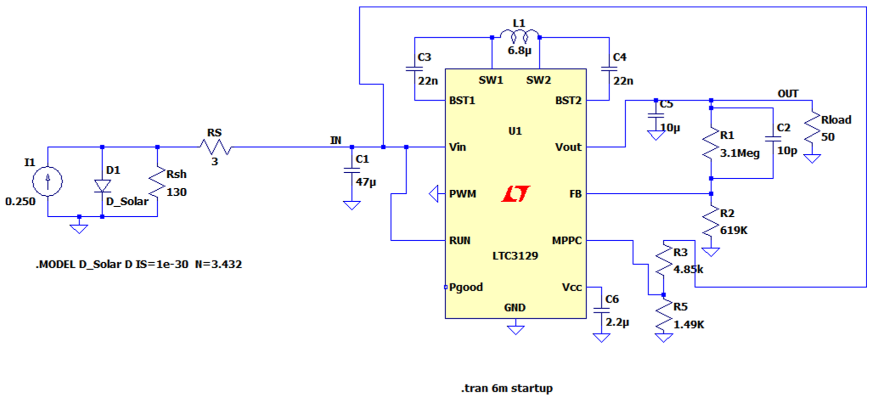

Fig. 7. LTC3129 converter between the model of the monocrystalline/polycrystalline module and the load.

Table 3. Obtained results by varying the MPPC reference voltage.

V_{IN} (V)	V_{MPPC} (V)	V_{OUT} (V)	*Load* (Ω)	*Output power* (mW)
3.94	4.0	6.09	50	741
4.45	4.5	6.47	50	837
4.77	4.8	6.68	50	892
5.00	5.0	6.79	50	921
5.42	5.5	6.15	50	759

The maximum output power is obtained when the value of V_{MPPC} is 5 V, which is the voltage of the maximum power point of the monocrystalline and polycrystalline PV modules. As expected, the converter will always try to maintain *Vin* close to the set value of V_{MPPC}. The output power is relatively higher than when the converter was not used between the module and the load (Fig. 6), with a 47.6% increase in the output power ($V_{MPPC} = 5$ V). Figure 8 presents the power graph in the converter output and the values of V_{IN} and V_{OUT}, for the best case in Table 3 ($V_{MPPC} = 5$ V).

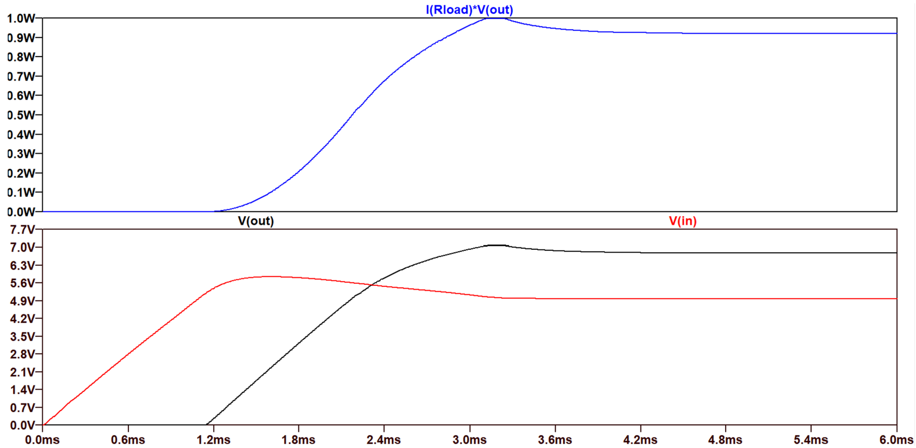

Fig. 8. Values of the output power in the converter and the values of V_{IN} and V_{OUT} ($V_{MPPC} =$ 5 V, $R_{LOAD} = 50\ \Omega$).

The results obtained previously were for a case in which the weather conditions are ideal, with the photovoltaic module producing the maximum power possible. To simulate the module in a situation where the weather conditions are not ideal (such that the voltage and current values are lower, and consequently, the value of the maximum power point also decreases), it was necessary to change some values of the equivalent circuit. For this purpose, the value of the current source was reduced from 250 mA to 200 mA and the ideality factor of the diode (N) was changed from 3.432 to 3.1. This resulted in an MPP of 4.50 V, instead of the previous value of 5.00 V. For the first graph in Fig. 9, the value of the reference voltage was maintained at 5.00 V, whereas for the second graph the reference voltage was changed to 4.50 V.

These results highlight a technical limitation of the MPPC technique when comparing to the MPPT technique. A MPPC reference voltage needs to be set when designing the circuit, but this voltage will not always be optimal. Although the voltage value of the MPP will not vary too much with changing weather conditions, unlike the current, there will still be situations in which the voltage at the MPP can move slightly from the programmed MPPC reference voltage. When designing a circuit using the MPPC technique, some study needs to be done in order to estimate the best value for the MPPC reference voltage. The best value will primarily depend on the photovoltaic module characteristics, but also on the average weather conditions of the location where the module is going to be installed.

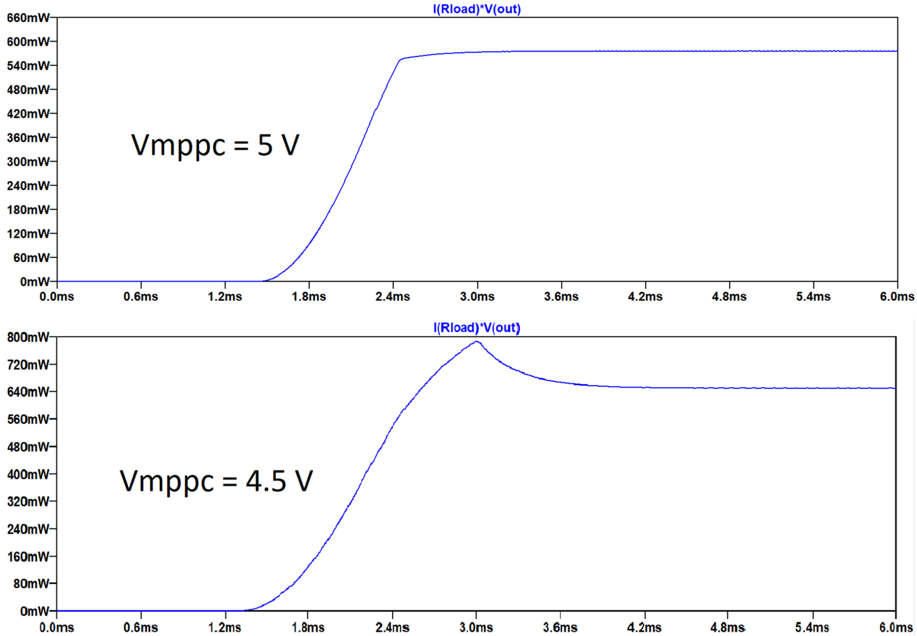

Fig. 9. Graphs of the output power of the converter when the PV module is not in ideal conditions (575 mW @ $V_{MPPC} = 5$ V; 651 mW @ $V_{MPPC} = 4.5$ V).

4 Conclusions

This paper presents the design and simulation of a circuit that maximizes the power extraction from PV modules. For this purpose, it uses the LTC3129 DC-DC converter, which implements the MPPC technique. Simulations were developed using the LTSpice software. To represent the PV modules in the simulation, their equivalent circuits were used, and the values of the components were changed to represent the acquired PV modules characteristics. The DC-DC converter was inserted between the PV module equivalent circuit and the load, and the MPPC technique was tested. As expected, the DC-DC converter always tried to maintain the input voltage close to the defined reference value, and so the MPPC technique was validated. When the reference voltage was set to the MPP voltage of the monocrystalline/polycrystalline module, there was an increase of 47.6% in the output power in the load when using the converter, compared to when the converter was not used, and thus, the maximization of power extraction from the PV modules was confirmed.

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