

A Modular PV Regulator Based on Microcontroller with Maximum Power Point Tracking

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Abstract— We can find many different types of commercial regulators in the market, these devices basically can be divided into two categories according to their operation mode: The first ones modulate the input voltage with PWM (pulse width modulation) to hold the constant voltage in the output necessary to charge the battery. The other ones operate in the MPP (maximum power point) of the PV (photovoltaic) array, tracking it by different ways depending on the type of regulator; these regulators are called MPPTs (maximum power point trackers). The increase of power using a maximum power point tracker can be up to 25%. This paper presents a regulator which can operate in the maximum power point of PV arrays regardless of the meteorological conditions and the effects of them in the dispersion of the PV array characteristics. Parallel connection of this kind of regulators is also proposed, which allows installation without the need of get rid of previous equipment.

I. INTRODUCTION

A typical photovoltaic installation is composed of: PV panels, regulator, batteries and the inverter. The regulator is the element which is connected between the PV panels and the batteries and its mission is to keep the batteries charged and avoid their overcharge.

We can find many different types of commercial regulators in the market, but considering the operation mode we can divide these regulators into two categories: The first ones modulate the input voltage with PWM (pulse width modulation) to hold the constant voltage in the output necessary to charge the battery.

The other ones operate in the MPP (maximum power point) of the PV array, tracking it by different ways depending on the type of regulator, these regulators are called MPPTs (maximum power point trackers). The increase of power using a maximum power point tracker can be up to 25%.

To obtain the maximum power from an array of PV cells under fixed meteorological conditions a regulator which implements a control that allows this is necessary. A very usual method to operate in the MPP is to fix PV array voltage in a value proportional to the open circuit voltage of the PV

array, this method is easy to implement but does not work well when the PV arrays are subjected to varying meteorological conditions. Other less usual method to track the MPP is to feedback the input or the output power of the regulator, this way requires reading the current and the voltage, either in the input or in the output, and multiply them, this can be done using an analog multiplier or by a microprocessor.

This article proposes a regulator which can operate in the maximum power point of PV array regardless of the meteorological conditions and the effects of them in the dispersion of the PV array characteristics. Parallel connection of these regulators is also proposed, which allows doing enlargements in this installation while keeping the old regulators.

II. POWER TOPOLOGY

The power topology of the regulator has been selected attending to the electrical requirements and the cost. Given that galvanic isolation is not needed between the PV arrays and the battery, a few-component topology is desirable to reduce the cost and minimize power losses.

Specifications:

- *Output voltage*: As necessary to feed a 12 V battery, between 12 V and 14 V.
- *Input voltage*: Between 24 V and 50 V.
- *Output ripple current*: Less than 1 A.
- *Input ripple current*: Less than 500 mA.
- *Power*: 250 W.
- *Size*: The size is not critical.
- *The regulator has to allow parallel connection.*

Initially the regulator was thought to feed 12 V batteries, provided that most of high power commercial PV arrays supply a voltage of about 24V the Buck topology was chosen because of its simplicity. Some monocrystalline 24-V PV arrays have

This work has been supported by the FICYT

the maximum power point voltage in about 35 V, in this case the regulator can be used to feed 24 V batteries too.

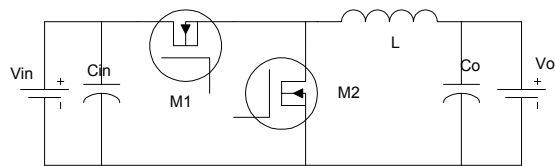


Figure 1: Buck with synchronous rectification

The selected topology is the buck converter. It has a low number of components and only one magnetic device. To maximize the efficiency of the converter the traditional buck topology can be modified towards a synchronous rectification structure [Figure 1], in which the diode is replaced by a MOSFET, thus reducing conduction losses.

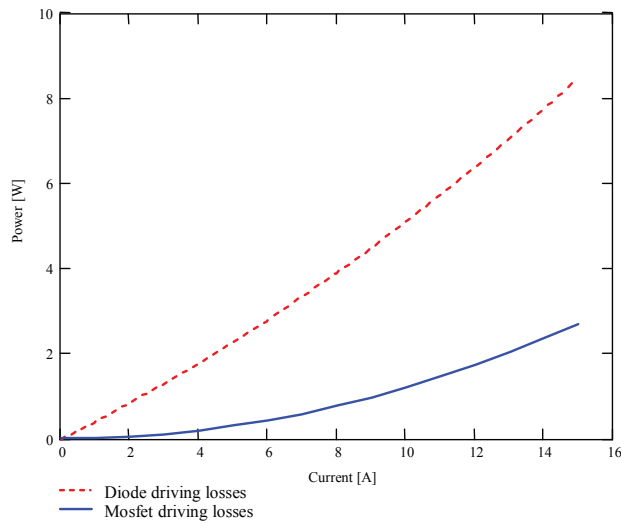


Figure 2: Comparison between diode and mosfet driving losses

Figure 2 shows the comparison between the driving losses in a schottky diode and in a 12 mOhm mosfet (the switching losses have been also taken into account). It can be seen that conduction losses are significantly greater in the diode. On the other hand synchronous rectification involves more control complexity, which bounces on the final cost of the design, so this technique is only justified when a high efficiency or high power density is required.

One requirement of the topology is that it must be modular allowing several regulators to be connected in parallel feeding the same battery or batteries. With the proposed topology it will be possible to make an expansion of the installation by just acquiring the regulators needed to supply the extra power. The majority of the commercial regulators are not modular because they operate as voltage sources, and voltage sources can not be connected in parallel, to facilitate this, the regulator proposed must behave as a current source.

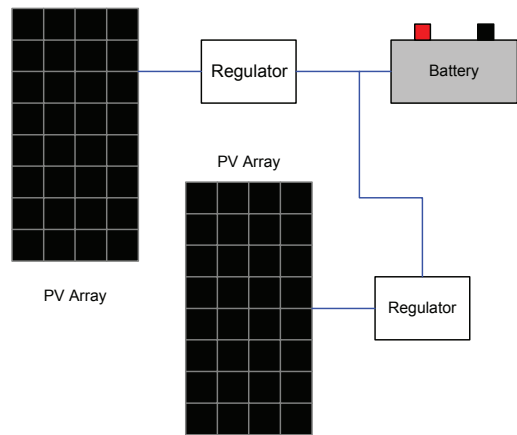


Figure 3: Schematic of the connection of two regulators in parallel

Figure 3 shows a diagram of the connection of a pair of these regulators with only one battery.

Figure 4 displays the schematic of the feedback closed loop used by this regulator. As can be seen it is a typical feedback for this type of converters, which uses an internal PID regulator. The whole loop is analog and the magnitude used to provide the feedback is the output current, instead of the output voltage. The measurement of the output current is done by a current sense (MAX4172), which reads the voltage drop on a shunt resistor and amplifies it. This is quite a precise method to sense the current but it has to be taken into account that the use of a shunt implies power losses, hereby the shunt is of very low resistance (5 mhm).

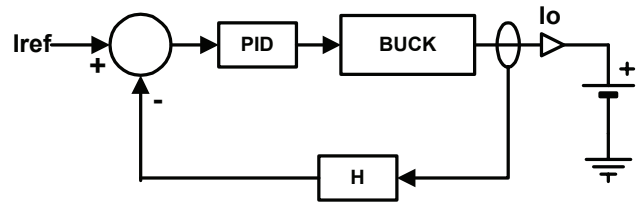


Figure 1: Schematic of the feedback loop

III. CONTROL METHOD

In the previous section the power topology and the analog control of the converter to operate as a current source have been exposed. Although this internal control is essential for the converter operation, it does not make the converter operate in a way to extract the maximum power of the PV array.

If we take a look at Figure 4 again, we can observe an arrow labeled as Iref; this is the internal current reference which will determine the output current, therefore the operation point of the converter. This implies that this reference will have to be modified in order to reach the MPP of the PV array. The regulator has been designed to operate with a battery as load. If we assume that the battery has low voltage variation, this parameter can be assumed to be constant for the dynamic behavior of the converter, taking this into account the output

power can be maximized by maximizing the output current, which implies a saving of components and programming.

$$\frac{dP}{dI} \approx V \Rightarrow dP = V \cdot dI = V \cdot K \cdot dI_{ref} \quad (1)$$

Equation 1 shows the relation between output power and current, where V is the battery voltage and I_{ref} is the current reference (see Figure 4), K is the parameter that relates the output current and the reference current. As can be seen the relation between I_{ref} and P is linear, and a variation in the former gives place to a proportional variation in the output power. Knowing all the explained before, understanding the method used to search the Maximum Power Point of the PV array is simple. To track the maximum power point the I_{ref} voltage is increased in steps, while the output current is being read. When a step involved in a zero or negative slope of the output current is reached, the maximum power point has been found.

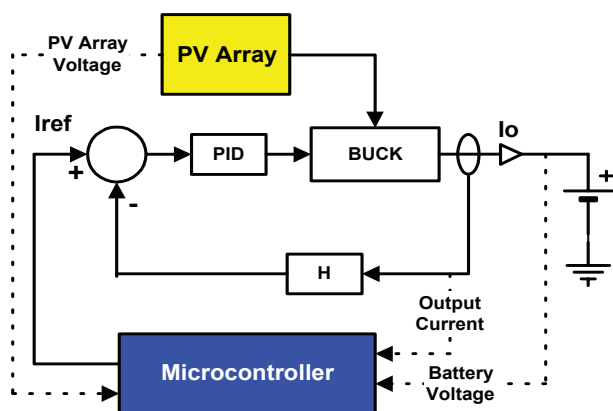


Figure 5: Block diagram of the whole circuit

The current reference voltage (I_{ref}) is provided by a microcontroller unit, which is also assigned to reading the output current and other magnitudes that will be examined later. In Figure 5 we can see the block diagram of the whole circuit, which is similar to the one in Figure 4, only two blocks representing the PV Array and the Microcontroller have been added, with the latter being in charge of providing the current reference voltage. With the objective of reducing the complexity and cost of the prototype a microcontroller with analog capabilities has been selected instead of using external analog modules; the AD converter included in the microcontroller has 10 bit resolution and various channels to read the external analog magnitudes (Battery Voltage, PV array Voltage and Output Current). On the other hand, the utilized microcontroller does not include a DA converter, but does include an internal PWM generator which can be used as one by filtering the PMW signal. Its resolution depends on the

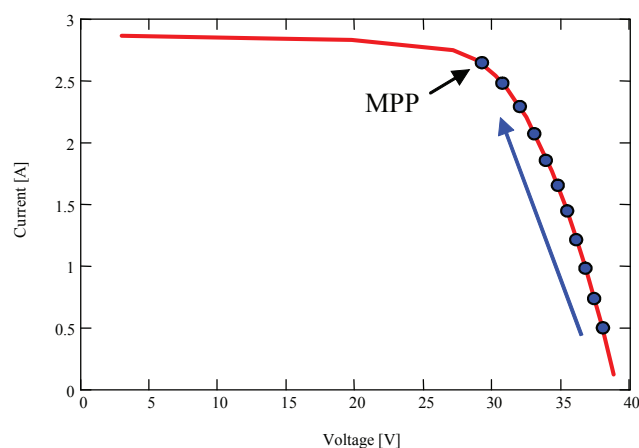


Figure 6: PV I-V Curve

PWM frequency for demands of the microcontroller; the selected value for the prototype allows 200 steps for the whole range of I_{ref} .

In Figure 6 we can see the PV I-V curve where the circles represent the several steps chosen to track de MPP. A high input current step implies a high output current step thereby a high power one. The amount of shown steps is token, the real number depends on the resolution of the microcontroller D/A converter (the internal PWM generator in this case).

IV. CONTROL SOFTWARE

The algorithm starts by turning the power section off, ensuring that operation is not started in an unknown current state. After this, the current reference is set to the minimum value and the power section is turned on. Subsequently the tracking of maximum power point starts. In this stage, the current reference is incremented in steps, in each one the output current is measured, the time between steps should be the necessary to allow the reflection of the current reference in the output current, so depends on the dynamics of the whole system including the PV array. When a value where the output current has experimented a decrease is reached, the current of the step before is selected as the maximum power point one.

Figure 7 shows the flowchart of MPPT function, where its proceeding is detailed. After the maximum power point has been tracked the regulator remains in that operation point until a variation on the PV array or battery voltage is produced. As soon as there is any voltage change (PV or battery) a new power point tracking begins.

Another important parameter to determine is the number of current reference steps, which is directly related to the step value. The minimum step value is fixed by the resolution of the digital to analog converter (the internal PWM generator) but this value can be increased by software if it results too low, a bigger number of steps implies more points to track, which means more time to find the MPP. On the other hand a little number of steps implies less time to track the MPP but less precision in the search.

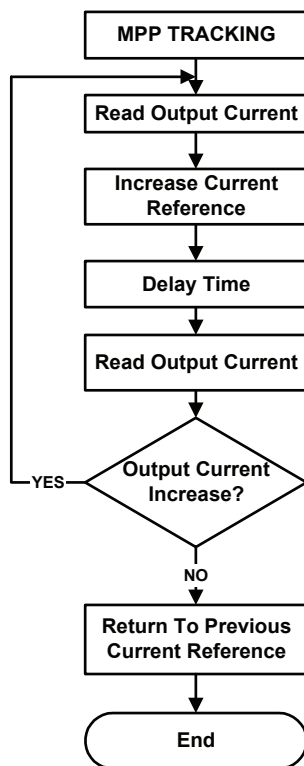


Figure 7: MPPT function flowchart

After reaching the maximum power point the regulator remains in that operation point until a variation on the PV array voltage is produced, which can be modified in two ways:

An increment in the voltage, taking into account the output current is fixed, means the MPP has incremented, in this case the regulator starts to search a new MPP from the former tracked before, which reduces the searching time.

A decrement in the voltage means that the MPP has reduced, but the regulator is still operating in the MPP tracked before (higher), this poses a question: How can that power be extracted from the PV array? The answer is it cannot, but due to the dynamics of the system the process delays a few milliseconds, so this is the time the microcontroller has to decrease the current reference and thereby reduce the power OK. If this reduction was not achieved the result would be the direct connection between the PV array and the battery (because of the power topology) which means lost of power because of it is not being operating in the PV array MPP. The suitable decrease of the current reference depends on the PV array and the meteorological conditions, however there is a direct relation between the decrease needed and the PV Array voltage reduction. After decreasing the current, and having the PV Array voltage stabilized, there is not security of been operating in the MPP, so a new track of the MPP from the current operation point is required.

Battery charging is another important task of the regulator, which has been designed to operate with Pb batteries (lead-acid

or sealed lead-acid). A simple way to charge this type of batteries for stand-by use is to keep the cell voltage in a constant value, avoiding exceeding the initial current from a value usually provided by the manufacturer. The charging philosophy is to supply the maximum power that can be extracted from the PV array until the battery voltage cell reaches about 2.3 V (14 V in a 12 V battery and 28 V in a 24 V one). With this method the current injected into the battery could be greater than the desired value, although the output current of the converter is measured. Limiting this current is not a smart way of avoiding overcurrent because the battery can be connected in parallel with a load, so the output current is not the battery current. Despite this, battery overcurrent is not a problem since used batteries are mid-size or greater (more than 40 Ah).

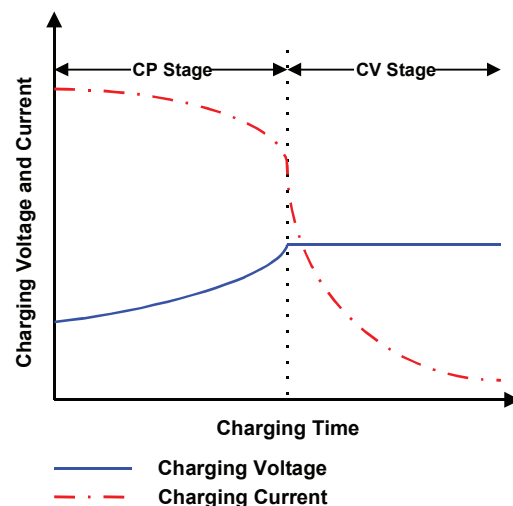


Figure 8: Charging Stages

In operation if the cell voltage exceeds the maximum value allowed, the current will be reduced until it is reached again changing the operation mode from constant power to constant output voltage. In case the current cannot be further reduced and the cell voltage remains over 2.3 V, the regulator is turned off to avoid battery overcharge.

In Figure 8 the battery charging stages under constant solar radiation conditions can be observed. Two stages can be identified, the first one is the Constant Power Stage where the power that can be supplied is fixed by the solar radiation existing, the second stage is the Constant Voltage one, where the cell voltage has reached the maximum value allowed. In this last stage the maximum power of the PV array is not extracted to avoid battery overcharge.

V. EXPERIMENTAL RESULTS

In this chapter the experimental results obtained with the build prototype will be seen. These results include the output and input ripples, the MMP tracking, the accuracy tracking the MMP and the efficiency of the power section.

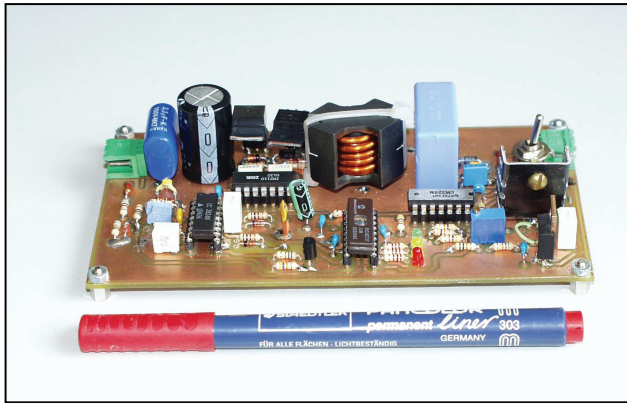


Figure 9: Prototype image

Figure 9 shows the prototype image and its size compared with a marker.

A. Current and Voltage Ripples

The following results were obtained operating with a 24 V PV array and a 12 V battery, the power consumption was 100W:

Input Voltage Ripple: 0.5 V.

Output Voltage Ripple: 0.5 V.

Input Current Ripple: 100 mA.

Output Current Ripple: 400 mA.

The prototype designed has both low current and voltage ripples in the input and output which increases the already long life of the PV array, and improves the stability of the whole system.

In Figure 10 we can see the input and output current and voltage ripples. In the top right side of the image the configuration of the input oscilloscope channels is indicated thereby the ripple values can be checked.

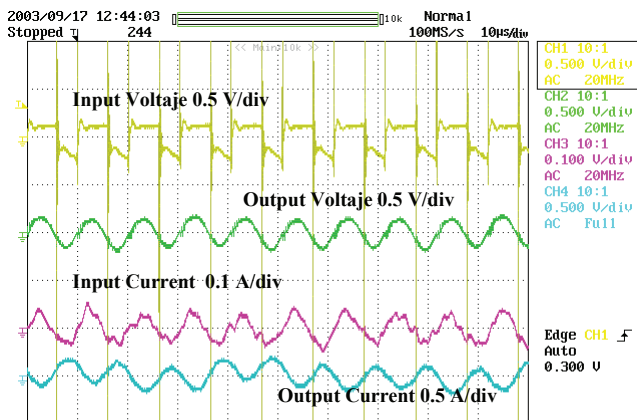


Figure 10: Current and voltage ripples

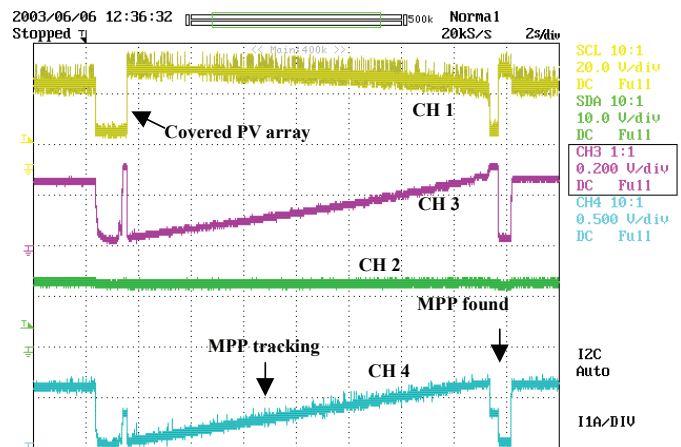


Figure 11: MPP Tracking

B. MPP Tracking

MPP tracking is one of the most important features on PV regulators because the loss of power between operating in the MPP of the PV array and not operating in it can be up to 25 %. Figure 11 shows the most important input and output parameters of the regulator (voltage and current) in the MPP tracking: Input voltage (Channel 1), Output voltage (Channel 2), Input current (Channel 3) and Output current (Channel 4) after covering the PV array, thus can be observed the whole MPP tracking from a zero current initial state until the MPP.

Initially the PV array was covered to force a new MPP track. As can be seen, the PV array voltage checks for a decrement while the Output current increases; when a point where the current does not increment is reached, the MPP has been found. The output voltage (battery voltage) remains almost constant in the whole process, which means the output power is being increased while the output current rises.

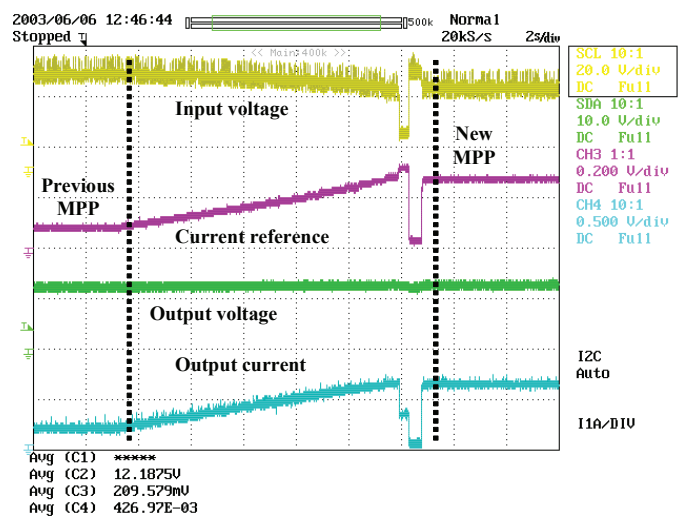


Figure 12: MPP tracking from a previous MPP

The MPP tracking does not have to start necessarily from a zero power initial point. In Figure 12 we can see the MPP tracking from a previous less power MPP. When the microcontroller detects a sufficient increase of the PV array voltage, it starts seeking a new one; this increase is due to a raise in the solar radiation and means the MPP of the PV array is greater than the one we are operating in.

As mentioned before an important task of the regulator is avoiding the battery overcharge by not exceeding a defined output voltage (14 V or 28 depending on the type of battery used). Although the converter feedback magnitude is the current, the microcontroller verifies the battery voltage constantly, and if this value is reached the regulator changes the operation mode to the constant output voltage and abandons the maximum power point mode.

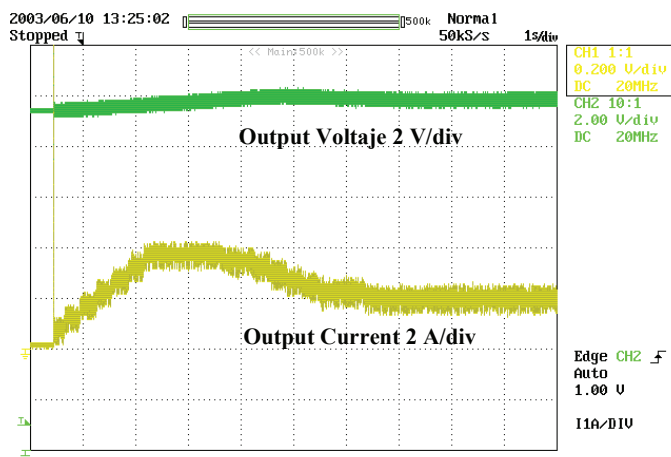


Figure 13: Output voltage and current evolution

Figure 13 shows the evolution of the output voltage and current; a reduction of the output current while the voltage stays almost constant can be observed.

C. MPP Tracking Accuracy

The tracking accuracy is the precision in the maximum power point search, in other words, this parameter tells the difference between the operating MPP and the real MPP of the PV array. The accuracy tracking the MPP is a very important characteristic of the regulator, to measure this, a Shell SM-110-24 PV Array Power and I-V curves have been experimentally obtained in constant meteorological conditions, making a load sweep with a programmable load. To confirm the regulator really works in the MPP, it was connected to the PV array (same meteorological conditions) and its input power was measured.

Figure 14 shows the I-V and Power curves experimentally obtained under resolute constant solar irradiation. The power curve indicates that maximum power point is in 50.1 W, in this case the measured input power into the regulator was of 49.1 W.

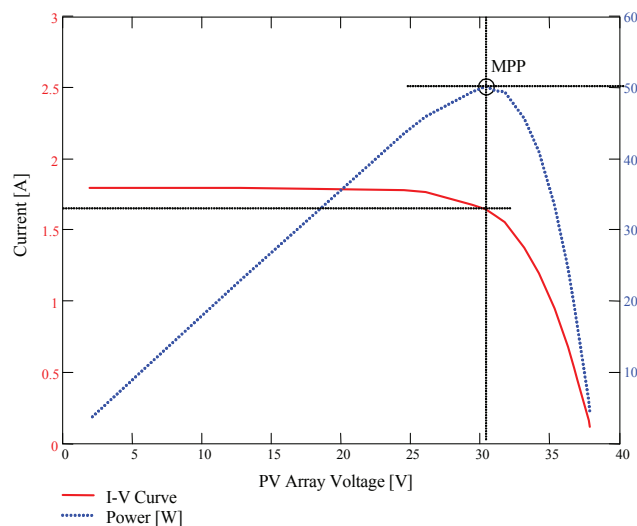


Figure 14: I-V and Power curves

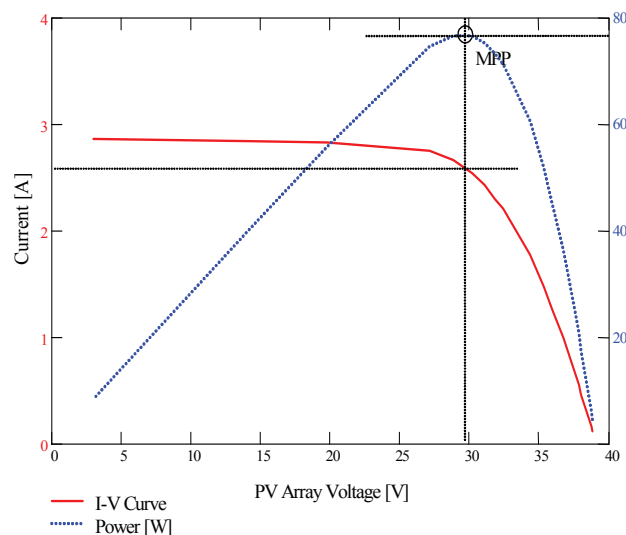


Figure 15: I-V and Power curves

Figure 15 is analog to figure 14 with the difference that the solar irradiation is greater thereby the output power of the PV array is greater too. In this situation the maximum power point of the PV array was 76.6 W and the input power of the regulator was 75.6 W.

Either result confirms the regulator really operates in the MPP of the PV array with an error less than 2 %.

D. Power Stage Efficiency

Besides the tracking accuracy, the efficiency of the power stage is other important parameter with impact on the power that can be extracted from the PV array. The used topology (synchronous rectification buck) brings on a theoretic increment in the efficiency supported by the experimental results obtained, with an efficiency that reaches up the 95 %.

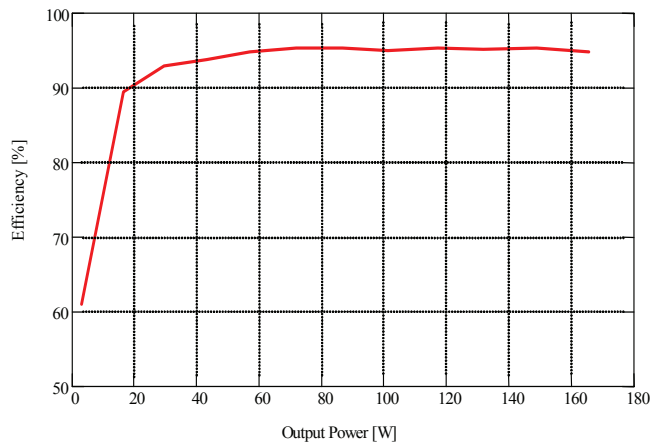


Figure 16: Efficiency vs. Output power

Figure 16 displays the Output power vs. the Efficiency. The latter is small at low loads, but reaches the 90% with 20 W output power. The efficiency keeps in values around 95 % at middle and high loads and is very constant in a wide power range.

VI. REFERENCES

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