Manuscript Draft

Manuscript Number:

Title: POWER GAIN AND DAILY IMPROVEMENT FACTOR IN STAND ALONE PHOTOVOLTAICS SYSTEMS WITH MAXIMUM POWER POINT TRACKING CHARGE REGULATORS. CASE STUDY: MEDITERRANEAN CLIMATE.

Article Type: Original Paper

Keywords: Keywords: stand-alone photovoltaic systems, charge regulator, maximum power point tracking, pulse width modulation, improvement factor

Corresponding Author: Dr. Francisco Muñoz, Ph D

Corresponding Author's Institution: Universidad de Jaén

First Author: Francisco Muñoz, Ph D

Order of Authors: Francisco Muñoz, Ph D; Gabino Jimenez, Engineer; Manuel Fuentes, Dr

Abstract: The performance reability of a Stand-alone photovoltaic system (SAPV) depends on the long-term performance of the batteries. In this way, a charge controller becomes an essential device which not only prevents the batteries from suffering deep discharges and overvoltages but monitors the battery state of charge (SOC) in order to maximize the charging efficiency and the energy availability. At present, Pulse Width Modulated (PWM) charge regulators dominate the market of this type of components in SAPV systems. However, in recent years more manufacturers have developed controllers with strategies for Maximum Power Point Tracking (MPPT) to improve the energy management. There are several important differences between PWM and MPPT technologies and unique advantages to each one. PWM charge controllers do not always make optimum use of the available power given by the maximum power point. These power losses depend on battery voltage, irradiance and temperature. Nevertheless, they can be avoided by using a MPPT charge controller which operates the array at its maximum power point under a range of operating conditions, as well as regulates bat¬tery charging. Apart from battery SOC, the advantage, in terms of energy gain, provided by this type of charge regulator depends on weather conditions (i.e. location). This paper will study the power gain provided by this type of charge controllers depending on the module temperature and the battery voltage. Afterwards, it will be provided a study of the gain in energy yield, also indicated as improvement factor, F, for SAPV systems installed in Mediterranean climates. Moreover, it will be analyzed the suitability of MPPT charge controllers and their benefits in this type of climate. The results given here may be not only interesting for SAPV systems with no access to the electricity grid, but either to grid-connected PV (GCPV) systems with self-consumption as a possible operating mode and battery backup GCPV systems.

POWER GAIN AND DAILY IMPROVEMENT FACTOR IN STAND ALONE PHOTOVOLTAICS SYSTEMS WITH MAXIMUM POWER POINT TRACKING CHARGE REGULATORS.

CASE STUDY: MEDITERRANEAN CLIMATE.

F. J. Muñoz*, G. Jiménez, M. Fuentes*
**Grupo IDEA. Departamento de Ingeniería Electrónica*
y Automática. Universidad de Jaén
Campus las Lagunillas. 23071 – Jaén. Spain.
e-mail: fjmunoz@ujaen.es. phone: +34 953 212810. fax: +34 953 211967

HIGHLIGHTS

- It is analyzed the power gain provided by Maximum power point (MPPT) charge controllers depending on the module temperature and the battery voltage. Moreover, it is provided an analysis of the sensitivity of the power gain to irradiance and battery State of charge (SOC).
- It is provided a study of the gain in energy yield, also indicated as improvement factor, F, for Stand- alone photovoltaic (SAPV) systems with MPPT charge controllers installed in Mediterranean climates.
- It will be analyzed the suitability of MPPT charge controllers, only in terms of energy yield, and the possible benefits of MPPT charge controllers in this type of climatic conditions.
- The results given here may be not only interesting for SAPV systems with no access to the electricity grid, but either to grid-connected PV (GCPV) systems with self-consumption as a possible operating mode and battery backup GCPV systems.

POWER GAIN AND DAILY IMPROVEMENT FACTOR IN STAND ALONE PHOTOVOLTAICS SYSTEMS WITH MAXIMUM POWER POINT TRACKING CHARGE REGULATORS.

CASE STUDY: MEDITERRANEAN CLIMATE.

F. J. Muñoz*, G. Jiménez, M. Fuentes*

**Grupo IDEA. Departamento de Ingeniería Electrónica*
y Automática. Universidad de Jaén

Campus las Lagunillas. 23071 – Jaén. Spain.

e-mail: fjmunoz@ujaen.es. phone: +34 953 212810. fax: +34 953 211967

ABSTRACT

The performance reability of a Stand-alone photovoltaic system (SAPV) depends on the long-term performance of the batteries. In this way, a charge controller becomes an essential device which not only prevents the batteries from suffering deep discharges and overvoltages but monitors the battery state of charge (SOC) in order to maximize the charging efficiency and the energy availability.

At present, Pulse Width Modulated (PWM) charge regulators dominate the market of this type of components in SAPV systems. However, in recent years more manufacturers have developed controllers with strategies for Maximum Power Point Tracking (MPPT) to improve the energy management. There are several important differences between PWM and MPPT technologies and unique advantages to each one. PWM charge controllers do not always make optimum use of the available power given by the maximum power point. These power losses depend on battery voltage, irradiance and temperature. Nevertheless, they can be avoided by using a MPPT charge controller which operates the array at its maximum power point under a range of operating conditions, as well as regulates battery charging. Apart from battery SOC, the *advantage, in terms of energy gain, provided by this type of charge regulator depends on weather conditions (i.e. location). This paper will study the power gain provided by this type of charge controllers depending on the module temperature and the battery voltage. Afterwards, it will be provided a study of the gain in energy yield, also indicated as improvement factor, F, for SAPV systems installed in Mediterranean climates. Moreover, it will be analyzed the suitability of MPPT charge controllers and their benefits in this type of climate. The results given here may be not only interesting for SAPV systems with no access to the electricity grid, but either to grid-connected PV (GCPV) systems with self-consumption as a possible operating mode and battery backup GCPV systems.*

Keywords: stand-alone photovoltaic systems, charge regulator, maximum power point tracking, pulse width modulation, improvement factor.

1. Introduction

The success of a Stand-alone photovoltaic system (SAPV) depends on the long-term performance of the batteries, that is, if the latter are charged properly and kept in a high state of charge without undergoing frequent deep discharges. In this way, a charge controller becomes an essential device in this type of systems which manages to disconnect the PV array when the battery is fully charged and can shut down the load when the battery reaches a given state of discharge. Moreover, it monitors the battery state of charge (SOC) in order to make optimum the charging efficiency and the energy availability to the user.

At present, PWM technology dominates the market of charge controllers in SAPV systems. However, during the last years more manufacturers have developed controllers with strategies for Maximum Power Point Tracking (MPPT) in order to make optimum the energy management [1]. These so-called MPPT charge controllers have steadily increased their share in the world market.

There are several important differences between PWM and MPPT technology and unique advantages to each one. SAPV systems with PWM charge controllers connect the PV array directly to the battery voltage. Since the battery voltage determines the operating point on the I-V and P-V curves, they can not usually manage to reach the maximum power point, P_{MPP}, as figure 1 shows. When the battery voltage usually presents little variations, it will be the array current which determines the array power in SAPV systems without MPPT charge controller. Under usual operating conditions, the generated current by the PV generator in a SAPV system with PWM charge regulator will be between the shortcircuit current, I_{SC}, and the maximum power point current, I_{MPP}. In this way, the power provided by the array in this type of systems, $P_{APWM,i}$, for a given battery voltage, $V_{S,i}$, is given by equation (1)

$$P_{APWM,i} = I_{APWM,i} \cdot V_{S,i} \qquad (1)$$

Where V_{Si} represents any battery voltage comprised between the upper and lower voltage thresholds provided by the PWM charge regulator (see shaded area in Figure 1) and $I_{APWM,i}$ is the current provided by the array for the given battery voltage.

A MPP tracker essentially consists of a regulated DC-to-DC converter which periodically tracks along the I–V curve of the PV generator and determines the MPP power. Then, the power is transformed by the DC-DC converter circuit into another voltage and current required by the battery. So, a MPPT charge controller has high input voltage (array output voltage), low input current (array output current), lower output voltage (battery voltage), and higher output current (battery current). It must be noticed that these devices will have associated some intrinsic losses, and the efficiency of the MPPT charge regulator should be considered. A well-designed MPPT charge controller will have an overall efficiency greater than 95%, with many units currently being marketed having advertised efficiencies that are close to 98% [2]. However, these are maximum values that are reached under determined operating conditions, for instance, array input power and the selected battery voltage.

As it can be seen, PWM series and shunt charge controllers do not always make optimum use of the available power given by P_{MPP}. The power losses when using a PWM instead of a MPPT charge regulator can amount to lie between 10% and 40% [3], depending on battery voltage, irradiance and temperature. According to MPPT charge controller manufacturers, these charge controllers may increase output power by around 15% to 30% in a properly sized stand-alone PV system that integrates a battery [4]. Such large gains will only be achieved when the battery is in a low state of charge (low voltage) and the module temperature of the PV array is low. Nevertheless, average gains are likely to be significantly less (about 10%) [5].

In a first approach, and after a brief discussion about the advantages that provide each type of charge controller, this paper will develop an analysis of the sensitivity of the power gain to irradiance and battery SOC. Moreover, it will be studied the power gain provided by MPPT charge controllers depending on the module temperature and the battery voltage. These results, that are regardless of the type of climate, may be of interest for SAPV engineers and designers in order to know the dependency of the power gain on the variables mentioned above.

When using a MPPT charge controller, the power gain mentioned above may have associated an energy gain that may strengthen the choice of this type of charge controller. As the latter depends on weather conditions (i.e. location) and battery SOC it is very important to determine it for a given type of climate. In this way, it will be provided a study of the gain in energy yield, also indicated as improvement factor, F, for SAPV systems installed in Mediterranean climates. Additionally, it will be analyzed the suitability of MPPT charge controllers, only in terms of energy yield, and the possible benefits of MPPT charge controllers in this type of climatic conditions. The results given here may be not only of interest for SAPV systems with no access to electricity but either to grid-connected PV (GCPV) systems with self-consumption as a possible operating mode and battery backup GCPV systems. Both sort of systems need charge controllers as they use batteries as storage systems. From 2008 to second quarter of 2012, residential PV electricity system prices have decreased by almost 60% in the most competitive markets, and in some markets, the cost of PV-generated electricity is already cheaper than residential electricity retail prices. Due to falling PV system prices and increasing electricity prices, the number of such markets is steadily increasing [6].

2. PWM versus MPPT charge controllers

Apart from the energy gain, MPPT charge controllers can manage to be connected to array with different output voltages. On the other hand, it is desirable to combine a certain number of cells in series to provide enough array voltage and manage an adequate battery charging in SAPV systems with PWM charge controllers. In this way, the PV generator used in this sort of systems should have a given open circuit voltage to operate as a current source in the voltage interval defined by the battery. Single silicon cell open-circuit voltages are typically close to 0.6 V, and maximum power voltages are close to 0.5 V at 25°C. If mono and polycrystalline modules are considered, 36-cell and 72-cell modules should be used in order to charge, respectively, 12 V and 24 V batteries. These modules will provide open circuit voltages of 21.6 V and 43.2 V respectively, and will manage to charge properly the battery even at high module temperatures. However, since 1999, more PV modules have been used in grid-connected systems worldwide than in stand-alone systems and nowadays the percentage is lower. Of the total world-wide 70 GW of solar photovoltaic electricity generation capacity at the end of 2011, a conservative estimate is that they account for approx. 400 MW to 800 MW [6]. In grid-connected system with no battery backup, it is now common to design the PV array so that the maximum open-circuit voltage is just under 600 Vdc. These arrays are connected directly to maximum power point tracking inverter inputs. So many modern modules have 54 to 72 cells, and sometimes even more, what provides higher open-circuit voltages and higher module power ratings. The use of this type of modules in SAPV systems with PWM charge regulators will provide a considerable waste of energy when charging a 12 V battery and an inappropriate battery charging for 24 V systems if modules with less than 72 cells in series are used. MPPT charge controllers can manage to be connected to array with different array output voltages, as long as these values are over the battery voltage, and convert the power to the rated battery voltage. This fact offers a great flexibility when selecting the array and module voltage in SAPV systems with MPPT charge controllers.

Another advantage in MPPT charge controllers is the use of smaller wiring between the photovoltaic array and the charge controller, which involves lower power loss in the wiring [2] and saves costs in long distance installations. In addition, wiring the array at higher voltages results in having more modules in series and fewer in parallel and therefore may eliminate some of the series fusing PV output breakers. MPPT charge controllers can also allow to array expansion without increasing the size of wires and conduits. On the other hand, PWM charge controllers have limited capacity for system growth. When adding more PV modules to the system, the installation size would need to increase in order to pass the additional current coming from the new modules. If MPPT charge controller is used and the array is rewired to a higher voltage, the amperage can be the same or lower. It is often possible to use the existing wire [7].

Nevertheless, there are advantages using PWM charge controllers. This type of charge controllers are built on a time tested technology. They have been used for years in PV systems and are well established. Moreover, they are available in many sizes for a variety of applications and are much less expensive than MPPT charge controllers. The price of MPPT charge controllers may be duplicated in relation to PWM charge regulators. MPPT charge controllers work good in large stand-alone systems as from 100 W. However, it is important to set on a case-by-case basis whether an MPPT charge controller is worth the extra cost or whether this money might not be better spent on additional solar modules. In this case, it is very important to be sure about the energy gain that may provide the MPPT charge regulator in the selected location. Using an MPPT charge controller also ramps up system complexity, and it is highly unlikely that the life span of the device's power electronics will be as long as the solar generator into which it is integrated [4].

3. Power gain and Improvement Factor in MPPT charge controllers

It must be highlighted that the actual benefits of MPPT charge controllers depend on both the operating temperature of the array and the battery SOC (i.e. battery voltage), in terms of power gain. Figure 2 shows real I-V and P-V curves of monocrystalline module #1 (depicted in table 1) at different irradiances and module temperatures. It has been emphasized the battery voltage interval for a 12 V lead acid battery which may range, in a normal daily operation, from 12.6 V to 14.4 V. The latter determines the upper threshold, called the ‘voltage regulation’ (VR) provided by the charge regulator and the former represents the voltage level that corresponds to a 20% depth of discharge (DOD). These battery voltages have associated a SOC of 80% and 100%, respectively, [8]. This range may represent the desired daily SOC limits for a battery in a SAPV system.

When an array operates under cold conditions, it will produce a high MPP voltage which will provide a large difference between the array and the battery voltage and thus more potential power gain from MPPT, as it is shown in figure 2-a (G_I=316 W/m^2 and T_m=22ºC). Furthermore, it can be observed the deeper the battery discharge, the lower battery voltage and the power gain increases. When experiencing both conditions, an extremely discharged battery and a cold day, the system will have the largest voltage difference and thus a significant potential power gain from the MPPT feature compared with the power provided by a PWM charge regulator [9].

As module temperature increases, the MPP voltage of the photovoltaic module is reduced, so the latter approaches the battery voltage interval, which it is shown in figures 2-b (G_I=557 W/m^2 and T_m=37ºC) and 2-c (G_I=743 W/m^2 and T_m=44ºC). In these conditions, the power gain from MPPT charge regulators diminishes. For higher module temperatures, the maximum power point voltage may be comprised between the battery voltage interval and the power gain. In this case it will be almost negligible. This fact is highlighted in figure 2-d where it is given the I-V and P-V curves for G_I= 924 W/m^2 and T_m= 59ºC.

As it has been previously stated, it is obvious that depending on the location, there may be substantial cold weather seasonal gains from MPPT but perhaps minimal gain in the hot summer. In the next paragraphs it is going to study the power gain. Moreover, figures such as Daily Improvement Factor, F, which may provide the suitability of MPPT charge controllers in terms of energy gain in Mediterranean climate is going to be analyzed .

3.1.Outdoor measurement system

A current–voltage curve tracer (IVCT) was designed to get I-V curves of two 12 V silicon monocrystalline modules, table 1, during a several months test and measurement campaign [10] carried out in the city of Jaén (South of Spain, Latitude 38ºN, longitude 3ºW). This system provided a huge set of I-V curves (more than 5.000) for different irradiances and module temperatures.

The equipment was designed to be installed in the laboratory in the High Technical School building at University of Jaén. An open rack was mounted and located on the roof of this building, facing south with a tilt angle of 35 degrees. This structure allowed to handle up modules with their respective reference cells and temperature sensors. The IVCT was designed to get I-V curves of each PV module. The IVCT is based on a power supplier (KepcoTM BOP36-12M), a datalogger (AgilentTM 34970A), a class 0.5-60mV/10A KainosTM precision shunt resistor, coplanar reference cells (of the same technology of the PV modules tested to neglect the effect of spectral mismatch) to measure the incident global irradiance and two class B – according to International Electrotechnical Commission (IEC) 60751:2008– four-wire resistive thermal detector (RTD) Pt100 thermally bonded to the backskin of each one of the two calibrated PV modules to measure the cell temperature, The schematic of the system is shown in Figure 3.

To measure multiple PV modules –as in this case- a switchgear box of high-power relays is used. Labview^{TM} software running on a personal computer drives this IVCT so that the I-V curve and cell temperature of each PV module together with the incident global irradiance has been periodically scanned every 2 minutes. Modules were left at open circuit between subsequent scans. The sets of I–V curve data and related parameters are stored as separate text files with a time stamp. Each one of these files includes 100 measurements of current, voltage, and cell temperature, together with one measurement of the incident global irradiance. Concerning cell temperature inside the module, it is typically warmer than on the back surface. Some contributions point out that the average cell-to-backskin temperature drop is 2.5ºC with a total range of ±1ºC [11]. The 2.5ºC correction increment is systematic and must be added to each backskin reading to estimate actual cell temperature [12].

The calibration in STC of all significant electrical parameters of the two PV modules was entrusted to the accredited independent laboratory (AIL) CIEMAT-IER

(Madrid). Namely, two nominal 106-Wp ISOFOTÓN I-106 m-Si module (glass-cell-glass package) The monocrystalline PV modules was rated 96·6 Wp ± 2·2% and 97·5 Wp ± 2·2% by the CIEMAT-IER laboratory. The most characteristic electrical parameters in STC of these PV modules are gathered in table 1.

3.2. Instantaneous parameters. Power and Intensity Gain in MPPT versus PWM charge controllers

A study concerning the power gain provided by a photovoltaic array in a SAPV system with MPPT charge controller versus the power given by the same SAPV system using a PWM charge controller will be developed. The latter are actually the most widespread in the market.

The input power in the MPPT charge controller, P_{inMPPT}, can be calculated from the following expression, [13], Figure 4:

$$P_{inMPPT} = \eta_{MPPT} \cdot P_{MPP} \qquad (2)$$

Where P_{MPP} indicates the maximum power point power in the photovoltaic array and η_{MPPT} represents the MPPT algorithms efficiency. The latter can be obtained as the ratio between the MPP estimation and the measured value at the input of the charge controller.

The power provided by a MPPT charge controller, $P_{outMPPT}$, can be defined as follows:

$$P_{outMPPT} = \eta_C \cdot P_{inMPPT} \qquad (3)$$

Where η_C depicts the MPPT charge controller efficiency.

Therefore, using Equations (2) and (3), $P_{outMPPT}$ can be expressed as:

$$P_{outMPPT} = \eta_C \cdot P_{inMPPT} = \eta_C \cdot \eta_{MPPT} \cdot P_{MPP} \quad (4)$$

The performance of MPPT charge controllers has been tested in terms of instantaneous parameters to determine the efficiency of the charge controllers and their tracking algorithms. These results indicate that a 90% efficiency of the controller is an appropriate minimum threshold for an adequate equipment performance, whereas the state of the art allows efficiencies up to 95%. Besides, the efficiency of the MPPT algorithm should be above 80% during searching time and between 98% and 100% when the MPP is reached [13].

On the other hand, the output power in a charge regulator without MPPT, P_{outPWM}, can be considered as follows:

$$P_{outPWM} = I_{outPWM} \cdot V_S = I_{inPWM} \cdot V_S \qquad (5)$$

Where I_{outPWM} indicates the output current and I_{inPWM} represents the input current in the charge controller and is determined by the photovoltaic array and the battery voltage, V_S. It must be stated that this type of charge controllers are directly coupled so $I_{inPWM} = I_{outPWM}$. This is true for series charge controllers, meanwhile for shunt ones it will be certain if the net array current is considered [14]. Moreover, it must be emphasized that PWM charge regulator losses may be considered negligible.

In this way, the power gain, P_{gain}, in a SAPV system with MPPT charge controller versus a charge controller without MPPT (i.e. PWM) can be expressed:

$$P_{gain} = \frac{P_{outMPPT}}{P_{outPWM}} \qquad (6)$$

This power gain will be equivalent to the current gain, I_{gain}, which is given by the ratio between the output current in a MPPT charge controller, $I_{outMPPT}$, and the output current in a PWM charge controller, I_{outPWM}.

$$P_{gain} = \frac{P_{outMPPT}}{P_{out,PWM}} = \frac{I_{outMPPT} \cdot V_S}{I_{outPWM} \cdot V_S} = \frac{I_{outMPPT}}{I_{outPWM}} = I_{gain} \qquad (7)$$

In order to develop the study mentioned above and to provide a broader perspective, I-V curves obtained with the current–voltage curve tracer (IVCT) described in section 3.1 will be grouped in different intervals within a 50 W/m^2 and 5ºC step (e.g. one of the interval considered will range between 450-500Wm^2 and 25-30ºC). For every I-V curve in these intervals, apart from the maximum power point, it will be only considered every current/power value in the I-V curve comprised between the following voltage values: the upper threshold, called the 'voltage regulation' (V_R) provided by the charge regulator, which in 12 V flooded batteries may reach 14.4 V, and the voltage level that corresponds to a 20% DOD: 12.6 V for these type of batteries which will be noted as $V_{DOD\ 20\%}$. The latter can represent a desired daily DOD for a battery in a SAPV system [8]. The I-V pairs of the I-V curves that remain outside these voltage limits will be discarded. For each one of these intervals previously defined, it will be obtained the average power gain as equation (8). In order to get the theoretical maximum power gain values, it has been also discarded either the MPPT efficiency of the MPPT algorithms, η_{MPPT}, and the MPPT charge controller efficiency, η_C,:

$$P_{gain} = \frac{\sum_1^N P_{gain,i}}{N} = \frac{\sum_1^N \frac{P_{outMPPT,i}}{P_{out,PWM,i}}}{N} = \frac{\sum_1^N \frac{\eta_C \cdot \eta_{MPPT} \cdot P_{MPP,i}}{I_{outPWM,i} \cdot V_{S,i}}}{N} = \frac{\sum_1^N \frac{\eta_C \cdot \eta_{MPPT} \cdot P_{MPP,i}}{I_{inPWM,i} \cdot V_{S,i}}}{N}$$

$$= \frac{\sum_1^N \frac{P_{MPP,i}}{I_{inPWM,i} \cdot V_{S,i}}}{N} \qquad (8)$$

where N machtes to the number of I-V pairs comprised in the considered interval and $P_{gain,i}$ to each power gain, respectively. The power provided by the array in a PWM charge regulator is given by the product of $I_{in,PWM}$ which represents the current provided by the array and the battery voltage, $V_{S,i}$ for the given V-I pair, (please see Figure 1).

It must be noted that the irradiance and module temperature values of these I-V curves can range from 300 W/m^2 to 1100 W/m^2 and from 25ºC to 70ºC, respectively. V-I scans at G_I<300 W/m^2 have been disregarded due to the poor quality of current measurements for these irradiance levels. As a 0.5 – 60mV/10A shunt resistor was used to measure the module current, the expanded uncertainty in this case could be higher than 5% [10]. Disregarding V-I scans at low irradiation profiles does not affect our further conclusions significantly. Such low irradiances are negligible relative to the total daily irradiation in Mediterranean climates, their exclusion does not have significant influence in the results presented here. In fact, only some 10% of the incident global irradiation was collected below 300 W/m^2 during the experimental campaign.

Figure 5 shows the variation of the power gain depending on the irradiance and module temperature. There is much less dependency on irradiance than on temperature. For a given module temperature interval, the power gain remains almost the same for any irradiance considered. On the other hand, and as it could be expected, there is a clear dependency on module temperature: the power gain is inversely proportional to cell temperature. The lower module temperatures provide the higher power gains, rounding 0.20 for module temperatures near 30ºC. Power gains associated to high module temperatures, over 65ºC, are minimal, rounding 0.02.

However, in this initial analysis it has not been considered the battery voltage. This variable, as it has been previously stated, has a deep impact on the power gain. The sensitivity of the power gain to module temperature and battery voltage over the typical operating conditions in Mediterranean climates is shown in Figure 6. In this case, the data (i.e. I-V pairs corresponding to the maximum power point and those comprised between the voltage thresholds mentioned above) have been gathered in different intervals depending on both the module temperature and the battery voltage. As it was done in figure 5, for each one of these intervals previously defined, it will be obtained the average power gain through equation (8).

Low module temperatures and low battery voltages (i.e. low state of charge) report the highest intensity and power gains, which are slightly over 0.20 for module temperatures below 25ºC and battery voltages lower than 12.6 V. On the other hand, power gains for module temperatures higher than 65ºC and battery voltages above 14 V are negligible. It must be noted that the power gain provides a minimum even before reaching the regulating voltage and then tends to slightly increase. This fact can be clearly understood if figure 2-d is remembered. For very high module temperatures, the battery voltage interval may comprise V_{MPP}. In this case, there will be power gain for battery voltages lower than the maximum power point voltage. When the battery voltage takes the same value as V_{MPP}, the power gain will be null, increasing again as the battery voltage gets higher.

4. Daily Parameters. Improvement Factor

In order to estimate the gain in energy yield, a daily parameter such as the improvement factor, F, can be used [13]. Using the daily data mentioned in section 3.1, this parameter is calculated through equation (9), and provides a comparison between the daily output energy provided by a MPPT charge controller, $E_{OUTMPPT,}$ equation (10), and the one given by a PWM charge controller, E_{OUTPWM}, equation (11). The results may depend on weather conditions and battery state of charge. As battery voltage may play a strong influence on the improvement factor, it has been calculated it for different mean daily batteries voltages ranging from 12.6 V to 14.4 V with a voltage step of 0.2 V.

$$F = \frac{E_{outMPPT} - E_{outPWM}}{E_{outPWM}} \cdot 100 \qquad (9)$$

$E_{OUTMPPT}$ includes both the effect of the controller efficiency and the MPPT algorithm.

$$E_{outMPPT} = \sum_{1}^{M} P_{MPP.i} \cdot \eta_{MPP} \cdot \eta_{C} \cdot t_r \qquad (10)$$

$$E_{outPWM} = \sum_{1}^{M} I_{outPWM,i} \cdot V_{S,i} \cdot \eta_{PWM} \cdot t_r \qquad (11)$$

t_r represents the time between the scan of the I-V curves provided by the IVCT, specifically, 2 minutes. M shows the daily number of I-V pairs for the given battery voltage. These daily parameters have allowed the months under study to get the monthly average daily improvement factor. It has been considered different scenarios depending on the instantaneous accuracy of the MPPT algorithms, (η_{MPPT}), the MPPT charge controller efficiency, (η_{C}) and the PWM charge controller efficiency, (η_{PWM}), Figures 7 y 8.

Although it is not an entire year campaign, the achieved results may illustrate some interesting issues to be taken into account when dealing with MPPT charge regulators in Mediterranean climates. As it could be expected, the lower the battery voltage, the higher improvement factor. In an ideal scenario ($\eta_{MPPT} = \eta_C = \eta_{PWM} = 100\%$), and for a 12.6 V mean daily battery voltage, these values range from 6%, corresponding to September, to 12% obtained in November. It must be highlighted that in 2007 September was hotter and the summer months were cooler as usual. There are no data for either December or January, but it is expected to get higher improvement factors at this voltage. On the other hand, the lower improvement factors are obtained for a 14.4 V battery voltage. For this voltage, the improvement factors are more constrained, ranging from 3% (November) to 1% (rest of the months). It must be stated that in an ideal scenario the improvement factor is always positive, regardless of the mean daily battery voltage considered.

The improvement factor is not only reduced but they can even reach negative values if more realistic scenarios, which takes into account real charge controllers efficiencies, are considered. For PWM charge controllers, it has been taken into account efficiencies of 96% and 98%. An appropriate minimum acceptable threshold to MPPT controller efficiency is 90% although the state of the art allows efficiencies above 95% when working around the nominal power. For this reason, the MPPT charge controller efficiencies considered are 90%, 95% and 97%. The MPPT efficiency algorithms considered in any case is 98% [13]. It has been studied the improvement factor provided by different combinations between the mentioned efficiencies. The results emphasize the improvement factor reduction. It is obvious that the best improvement factors are got if both the highest η_C and the lowest η_{PWM} are considered (i.e. $\eta_C = 97\%$ and $\eta_{CPWM} = 96\%$). In this case, the improvement factor may be around one percentage point lower than the ideal scenario. No negative values are reached for any of the mean daily battery voltages considered.

As it could be expected, the results provided by η_C =95 η_{PWM} =96% and η_C =97 η_{PWM} =98% are very similar. For both cases, the improvement factor may be decreased by at least three percentage points compared with the ideal scenario. For mean daily battery voltages over 13.6 V, the improvement factor may be not only negligible (lower than 2%) but may be even negative for most of the months under study. It must be highlighted that negative improvement factor implies energy losses instead of energy gain when using MPPT charge controllers. Only November provides no negative values. For the rest of the winter months for which there is no data (December and January) it is expected no losses in the energy yield and improvement factors may be always positive. Moreover, the improvement factor should provide in these months better results than November when the ambient temperatures would be lower.

For η_C =95 η_{PWM} =98% the improvement factor is reduced by more than 5 percentage points compared with the ideal scenario. In this way, the results obtained in the ideal scenario duplicates the results got in this scenario. For any month, except November, the improvement factor is negligible or negative for mean daily battery voltages over 13.2 V. The improvement factor provides negative values even in November, which is the coldest month for which there is data.

As it can be observed, MPPT charge controller efficiencies of 90% provides the poorest results: the improvement factor may be negative for most of the mean daily battery voltages considered. This interesting fact emphasizes that MPPT charge regulator efficiencies around and below this value will not only provide an energy gain compared with a PWM charge regulator, but it will even provide energy losses that may reach 9%.

5. Conclusions

There are several important differences between PWM and MPPT technology and unique advantages to each one. After a brief discussion about the advantages that provide each type of charge controller, this paper has focused either on the power gain and the gain in energy yield, also indicated as improvement factor. The power and intensity gain provided by MPPT versus PWM charge controllers depending on module temperature and battery voltage has been illustrated. Furthermore, the power gain provides a gain in energy yield, also called improvement factor, F, which constitutes a parameter that manages to study the suitability of MPPT charge controller for a given climate. In this paper it has been analyzed F for the Mediterranean climate. Different scenarios (i.e MPPT and PWM charge controller efficiencies) have been considered.

The variation of the power gain depending on irradiance and module temperature has been illustrated. As it could be expected, there is little dependency on irradiance. On the other hand, there is a clear connection on module temperature: the power gain is inversely proportional to cell temperature. The lower module temperatures provide the higher power gains, reported for module temperatures near 30ºC, which are slightly above 0.20. Meanwhile, power gains associated to high module temperatures, over 65ºC, are minimal, rounding 0.02. As it has been considered ideal MPPT and PWM charge regulators, power gain is always positive.

As the battery SOC has a deep impact on the power gain, the sensitivity of the power gain to module temperature and battery voltage has been also analyzed. Low module temperatures and low battery voltages (i.e. low state of charge) report the highest intensity and power gain, which are slightly over 0.20 for module temperatures below 25ºC and battery voltages lower than 13.6 V. On the other hand, power gains for module temperatures higher than 65ºC and battery voltages above 14 V are negligible. This fact highlights the need for efforts to analyse the suitability, in terms of energy yield, of MPPT charge controllers in a given location, specifically those with a hot climate.

A daily parameter such as the improvement factor, F, has been used in order to calculate the monthly average daily gain in energy yield for Mediterranean climate. Apart from an ideal scenario ($\eta_{MPPT} = \eta_C = \eta_{PWM} = 100\%$), if both the highest η_C and the lowest η_{PWM} is considered (i.e. $\eta_C = 97\%$ and $\eta_{PWM} = 96\%$), the improvement factor is always positive, regardless of the month and the mean daily battery voltage considered. MPPT charge controllers will always provide a gain in energy yield when being compared with PWM ones.

For the rest of scenarios, the results highlight the improvement factor reduction. As it could be expected, the results provided by $\eta_C = 95$ $\eta_{PWM} = 96\%$ and $\eta_C = 97$ $\eta_{PWM} = 98\%$ are very similar. For mean daily battery voltages over 13.6 V, the improvement factor may be not only negligible (lower than 2%) but may be even negative for most of the months under study. Only winter months may provide no negative values. Moreover, these results demonstrate that SAPV systems with batteries that spend most of the time at high SOC may not benefit of a high improvement factor if a MPPT charge controller is used in Mediterranean climates and taken into account real charge controller efficiencies.

At this point it must be highlighted an interesting issue that should be taken into account when choosing the type of charge regulator in the design phase of a SAPV system. If the worst month (where the ratio between monthly average daily load and the monthly average daily Peak Sun Hours is the highest) matches to a winter month there may be a substantial energy gain when using a MPPT charge controller instead of a PWM one. The former may be a good choice. However, if the worst month is a summer month, the energy gain with a MPPT charge controller in Mediterranean climate may be minimal. Moreover, it may provide less energy yield than a PWM charge regulator. The designer is encouraged to review both the MPPT and PWM charge controller efficiencies in the corresponding data sheets and to make a deep analysis in order to know if MPPT charge regulators, in terms of energy yield, should be discarded.

As it can be observed, MPPT charge controller efficiencies of 90% provides the poorest results. The improvement factor may be negative for most of the mean daily battery voltages considered. MPPT charge regulator efficiencies around and below this value will not only provide an energy gain compared with a PWM charge regulator, but it will even provide energy losses that may reach 9%.

It is obvious that for Mediterranean climates there may be substantial cold weather seasonal gains from MPPT but perhaps minimal gain in the hot summer when using MPPT instead of PWM charge controllers. Apart from the battery SOC and weather conditions, the suitability of MPPT charge controllers in terms of energy yield in Mediterranean climate depends on MPPT and PWM charge controllers efficiencies. In order to get a substantial improvement factor, MPPT charge controller efficiency should be above 95%. Below this value, and if the worst month is a summer one and η_{PWM} may reach 98%, MPPT charge controllers should be discarded. Moreover, if η_C is below 90%, regardless if the worst month is a summer or a colder one, PWM charge controllers may provide better energy yields.

The results given here may be not only of interest for SAPV systems with no access to electricity but either to grid-connected PV (GCPV) systems with self-consumption as a possible operating mode and battery backup GCPV systems. Both types of systems need charge controllers for they use batteries as storage systems.

References

[1] Brand B. Seeking the power peak. Market survey on charge controllers 2008. Photon International 2008; 114-129.

[2] Roger A. Messenger, J. Ventre. Photovoltaic Systems Engineering. CRC Press, 2010, pp-79.

[3] The German Solar Energy Society. Planning and Installing Photovoltaic Systems. A guide for installers, architects and enginners. James & James, London, pp-113.

[4] H. Haberlin. Photovoltaics. System Design and Practice. John Wiley and Sons, 2012, pp-246.

[5] Tom Markvart & Luis Castañer, 2003. Practical Handbook of Photovoltaics: fundamentals and applications. Elsevier, UK.pp-583.

[6] Jäger-Waldau A. PV Status Report 2012 (EUR 25749-2012) ISBN 978-92-79-26073-8 (also downloadable at http://re.jrc.ec.europa.eu/refsys/).

[7] Solar Energy International. Photovoltaics. Design and Installation Manual. New Society Publishers, 2004, pp-75.

[8] IEA PVPS Task 3, 1998. Report IEA-PVPS T3-05:1998. Recommended Practices for Charge Controllers.

[9] R. H. Wills. Maximum Power Point Tracking Charge Controllers for Telecom applications – Analysis & Economics. In Proceedings of the 26th PVSC; Sept. 1997, Anaheim, CA, pp. 1109-1112.

[10] Fuentes M., Nofuentes G., Aguilera J., Talavera D. L. Application and Validation of Algebraic Methods to Predict the Behaviour of Crystalline Silicon PV Modules in Mediterranean Climates. *Solar Energy* 2007; **11**: 1396-1408.

[11] King D.L., Kratochvil J.A., Boyson W.E., Bower W., 1998. Field experience with a new performance characterization procedure for photovoltaic arrays. In: Proceedings of the 2nd World Conference on Photovoltaic Solar Energy Conversion, Vienna, Austria, pp. 1947-1952.

[12] Whitfield K., Osterwald C. R., 2001. Procedure for determining the uncertainty of PV module outdoor performance. Progress in Photovoltaics: Research and Applications. **9**: 87-102.

[13] M. Camino-Villacorta et al. Test procedure for maximum power point tracking charge controllers characterization. Progress in Photovoltaics 2012; **20**: 310-320.

[14] F. J. Muñoz, M. Torres, V. Muñoz, M. Fuentes. Monitoring Array Output Current and Voltage in Stand alone Photovoltaic Systems with PWM Charge Regulators. *Journal of Solar Energy Engineering* 2013; **13**. DOI: 10.1115/1.4007939

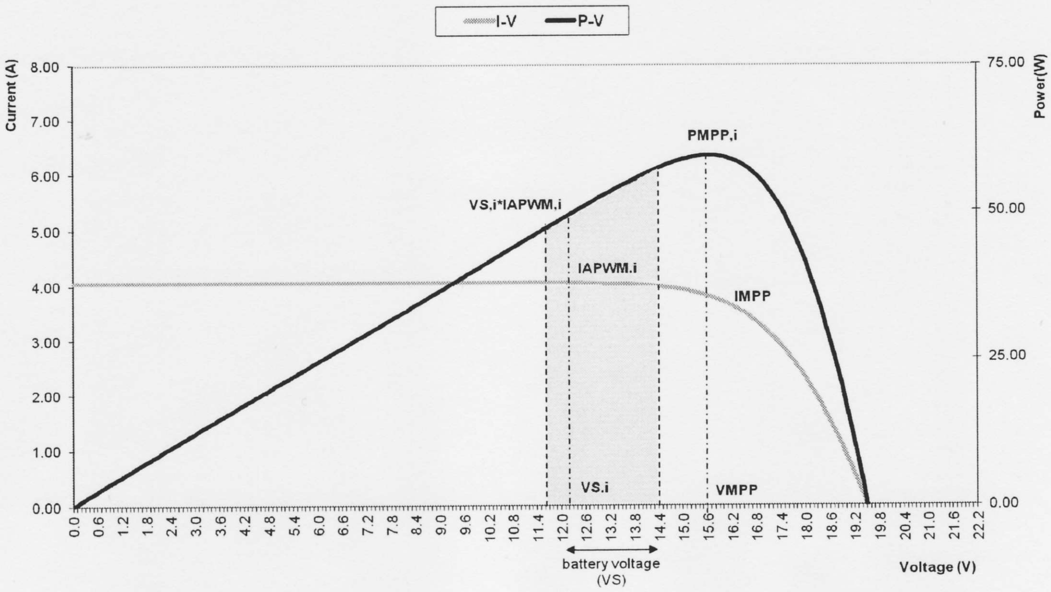

Figure 1. I-V and P-V characteristic for a monocrystalline PV module I-106 (G_I=600 W/m^2 and T_m=50°C). The shaded area corresponds to the upper and lower thresholds determined by a charge regulator when operating with a 12 V. battery in a SAPV system.

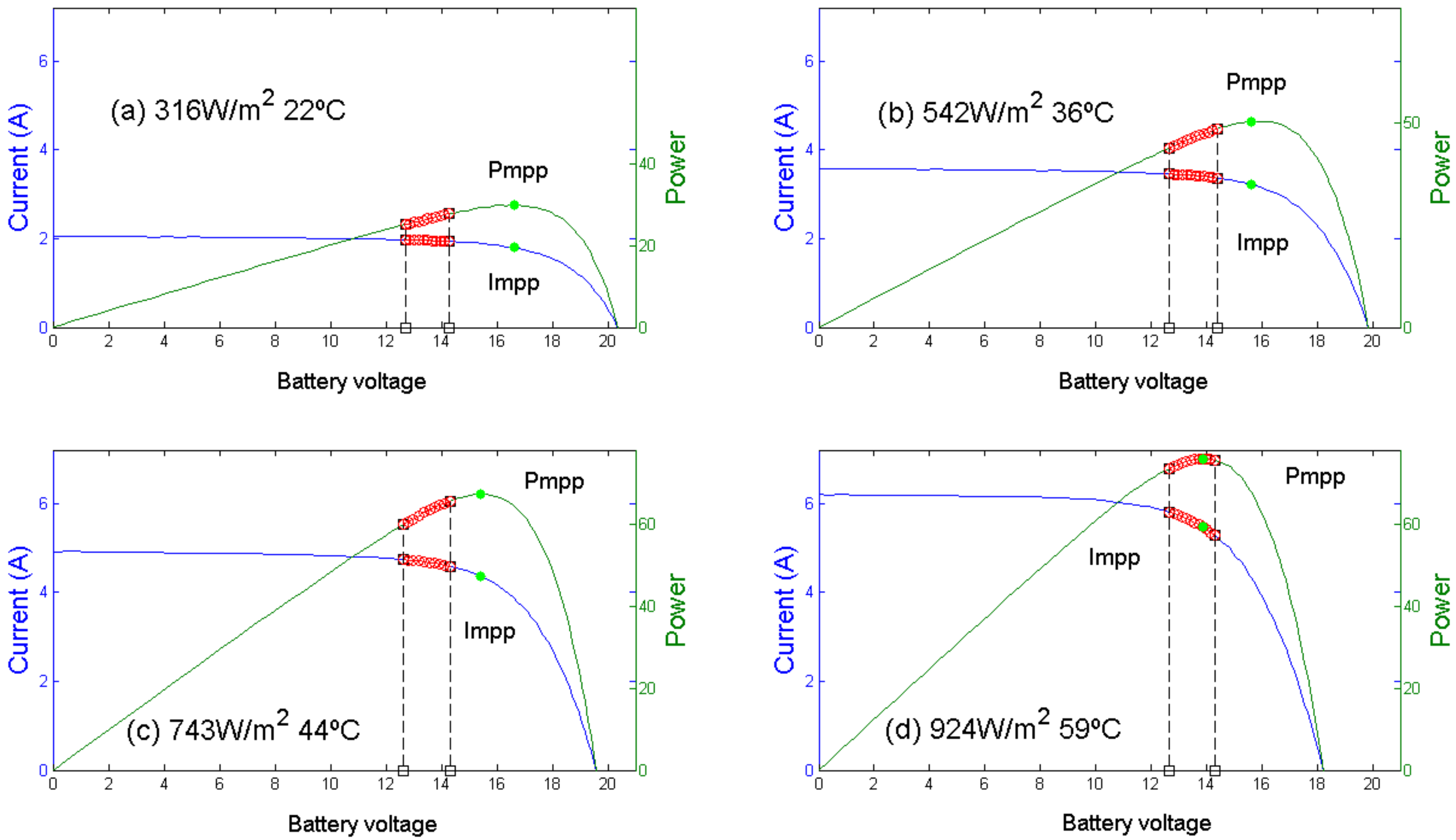

Figure 2. I-V and P-V curves for different irradiances and module temperatures.

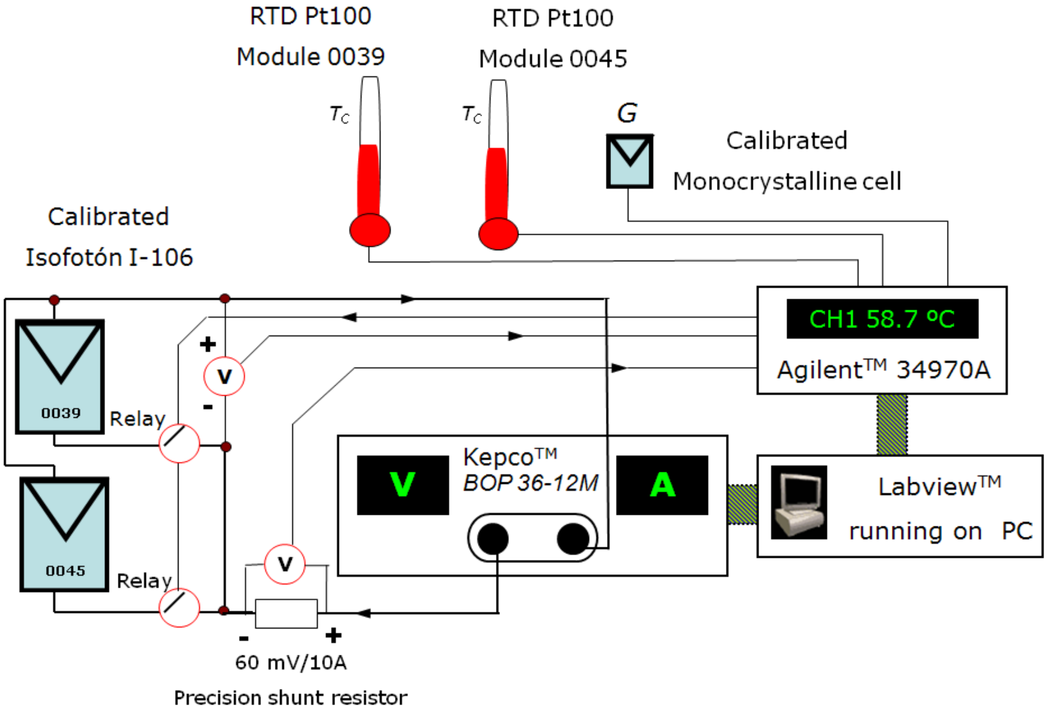

Figure 3. Diagram of the outdoor measurement system (IVCT) developed in the Solar Energy Laboratory of the High Technical School building at University of Jaén

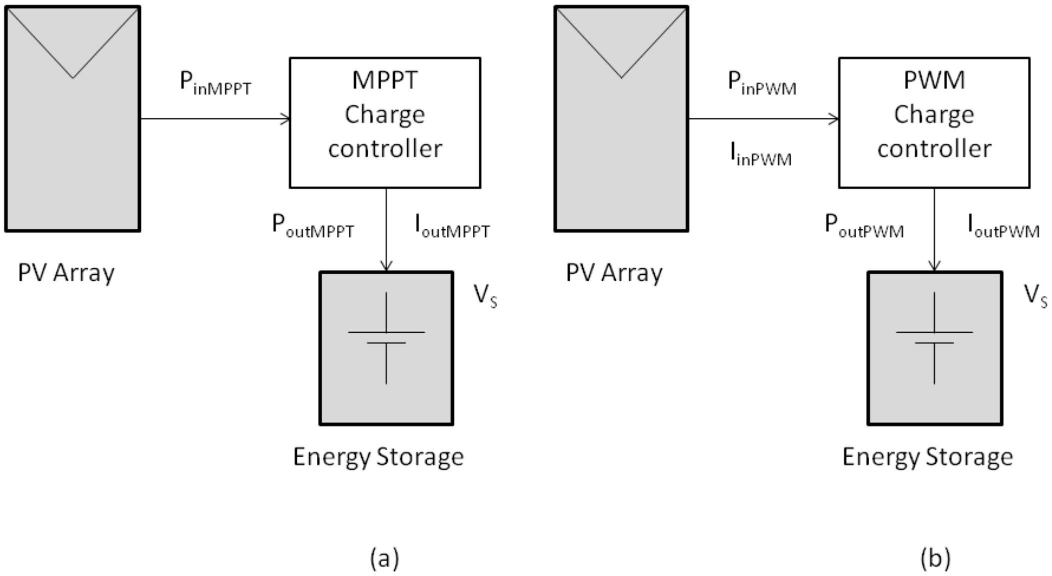

Figure 4. Parameters to be considered in MPPT (a) and PWM (b) charge regulators in order to get the power gain.

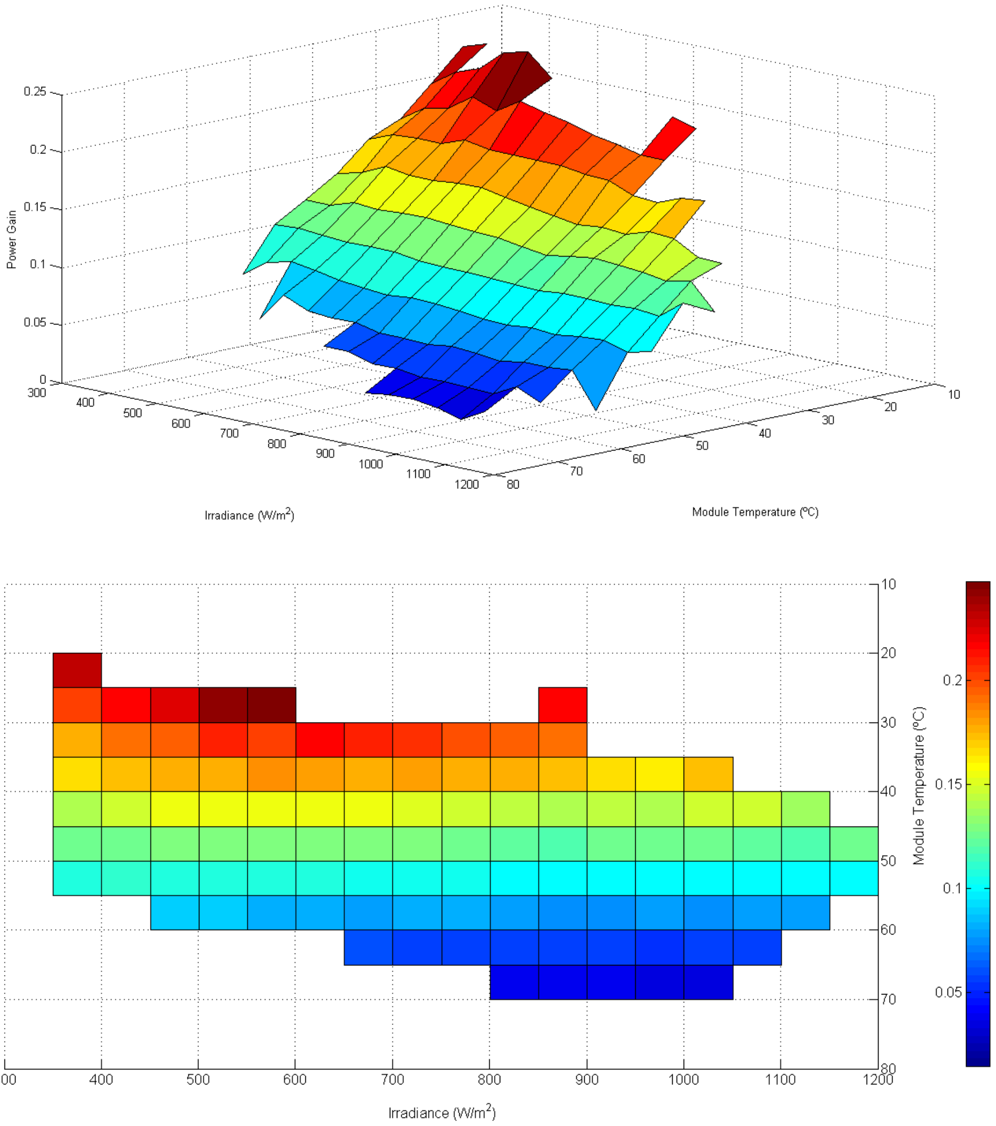

Figure 5. Sensitivity of intensity gain in a MPPT charge controller related to module temperature and irradiance.

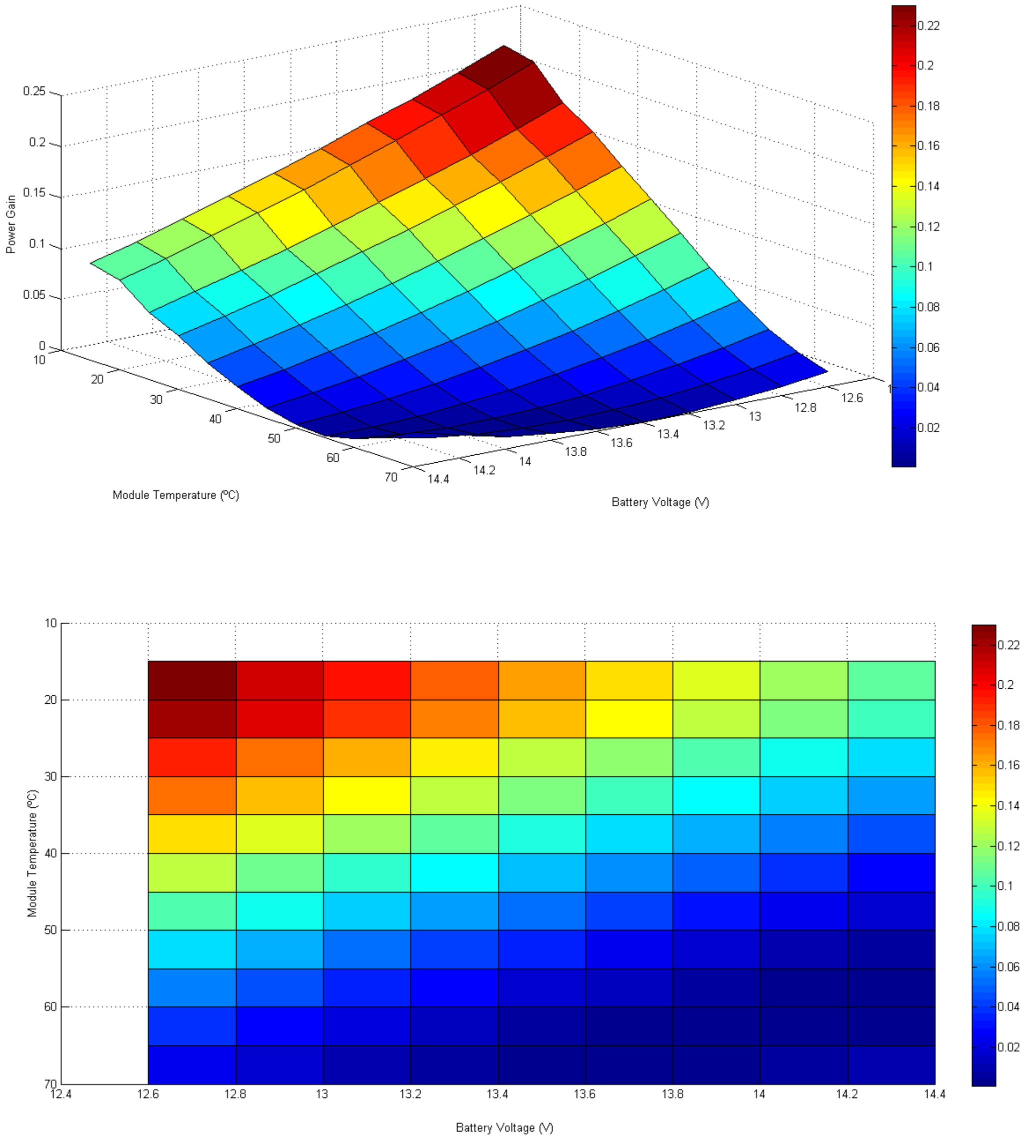

Figure 6. Sensitivity of intensity gain in a MPPT charge controller related to module temperature and battery voltage.

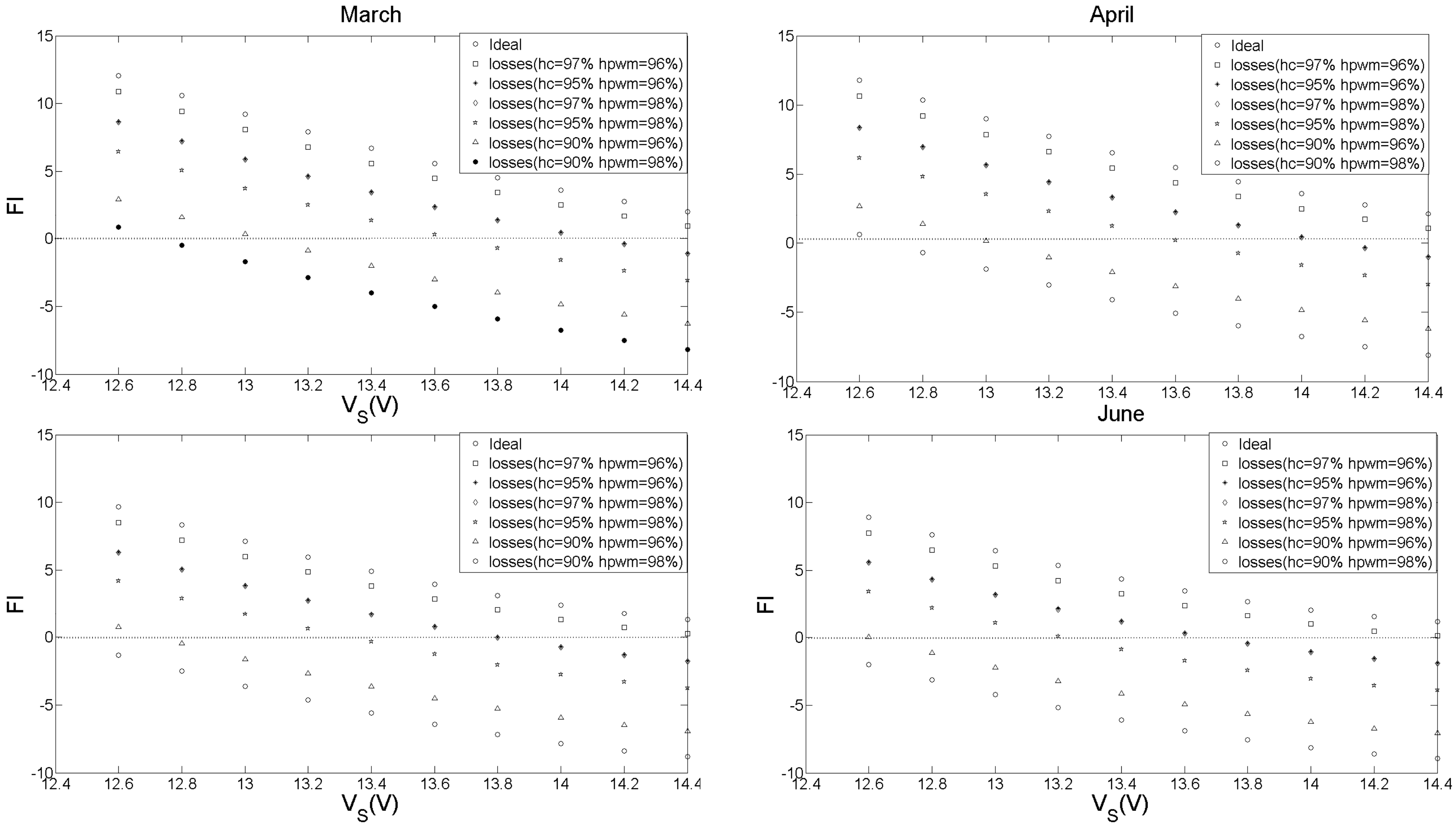

Figure 7. Monthly average daily improvement factor for different mean daily battery voltages. For PWM charge controllers it has been taken into account efficiencies of 96% and 98%. For MPPT charge controller the efficiencies considered are 90%, 95% and 97% as an appropriate minimum acceptable threshold to MPPT controller efficiency is 90% although the state of the art allows efficiencies above 95% when working around the nominal power. The MPPT efficiency algorithms considered in any case is 98%..

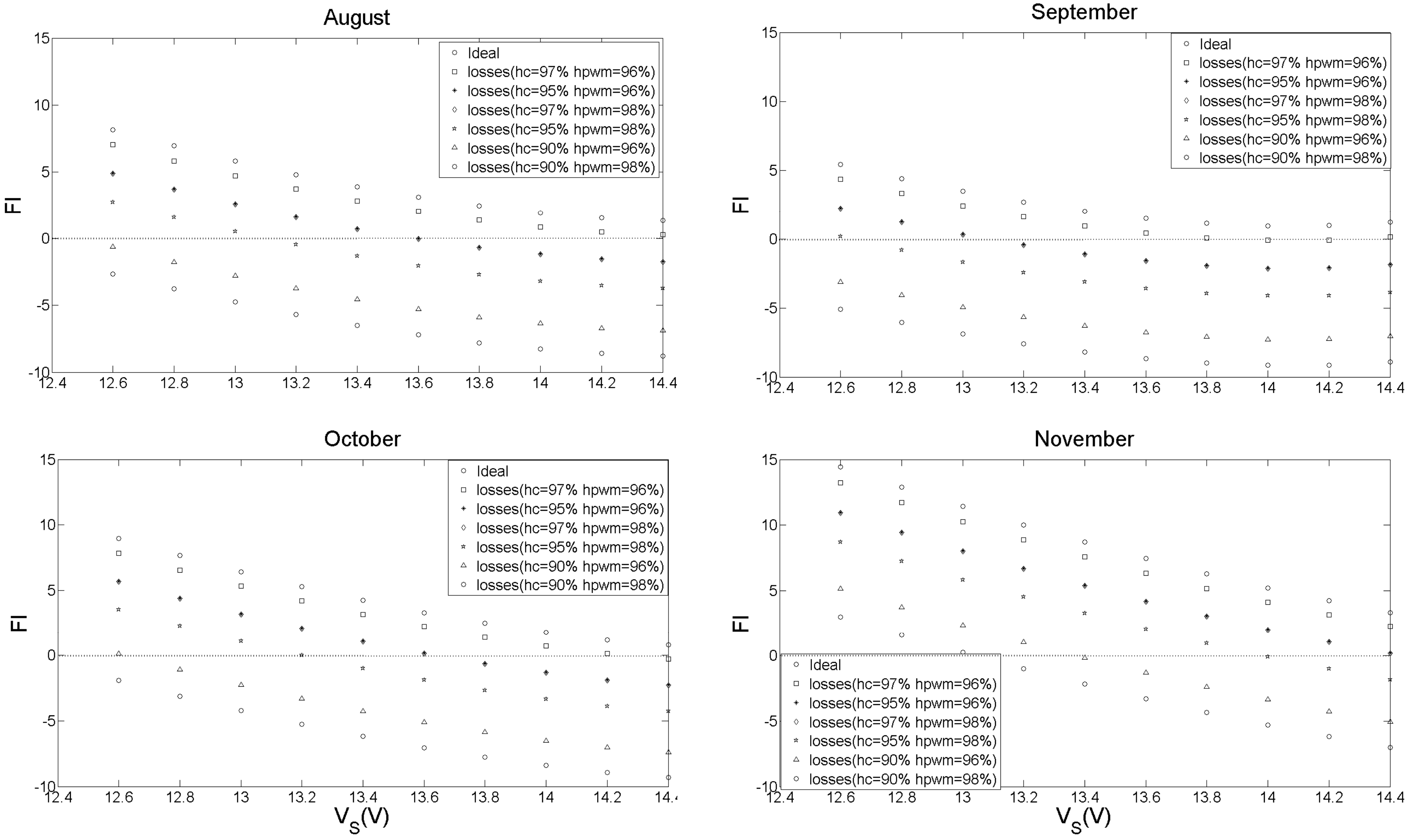

Figure 8. Monthly average daily improvement factor for different mean daily battery voltages. For PWM charge controllers, it has been taken into account efficiencies of 96% and 98%. For MPPT charge controller the efficiencies considered are 90%, 95% and 97% as an appropriate minimum acceptable threshold to MPPT controller

efficiency is 90% although the state of the art allows efficiencies above 95% when working around the nominal power. The MPPT efficiency algorithms considered in any case is 98%.

Table 1: Characteristic electrical parameters of the two I-106 PV modules as provided by the manufacturer and the accredited independent laboratory (AIL).

	Manufacturer	*Module 1 AIL*	*Module 2 AIL*
Module maximum power in STC (W) $P_{MOD,M}^{*}$	106 W ±10%	96·6 W ± 2·2%	97·5 W ± 2·2%
module open circuit voltage in STC (V) $V_{MOD,OC}^{*}$	21·6 V	21·39V ± 0·3%	21·20V ± 0·3%
module short circuit current in STC (A) $I_{MOD,SC}^{*}$	6·54 A	6·42 A ± 1·8%	6·47 A ± 1·8%
module voltage at maximum power in STC(V) $V_{MOD,M}^{*}$	17·4 V	16·72 V ± 0·3%	16·72 V ± 0·3%
module current at maximum power in STC (A) $I_{MOD,M}^{*}$	6·1 A	5·73 A ± 1·8%	5·83 A ± 1·8%