

## Conference Paper

# An Experimental Analysis of the Electrical Parameter Variation of a Photovoltaic Module

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## Abstract

Photovoltaic (PV) energy has been asserting itself in recent years as a true alternative for the electricity production in the future. It is well known that the accuracy of PV parameters is crucial to achieve optimal control of PV systems under any operating conditions. Although many attempts have been made to study the operating ranges of PV parameters, this remains a current research topic given the diversity of PV technologies. In this paper, the PV parameters variation with irradiance and temperature levels is experimentally analysed for a polycrystalline (poly-Si) silicon PV module. The experiment considers experimental data from 130 I-V characteristic curves measured over a typical day, considering several irradiance and temperature levels in the range 29–1023 W/m<sup>2</sup> and 19–68 °C, respectively. The results show that PV parameters vary considerably with irradiance and temperature levels for poly-Si technology.

**Keywords:** Photovoltaic module, Photovoltaic parameters, Single-diode model, Irradiance and temperature influence

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## 1. Introduction

The search for alternative energy sources and reducing fossil fuel consumption is a crucial task nowadays, since the world is constantly changing and societies demand for energy continues to grow and live. In this direction, research on the use of solar energy and different technologies of exploitation has been growing every year, not only because it is a renewable energy resource, but also because it is a clean and environmentally friendly energy. Particularly, the photovoltaic (PV) energy production has enormous potential and has been demonstrating an encouraging growth in the present decade, but still far from achieving a satisfactory capacity in view of its availability of exploitation. Although the advances have been constant and PV energy is increasingly captivating users, either by its increasingly reduced cost, or by emerging innovative technologies that are entering the market in several formats and according to consumer needs, the increased PV capacity installed, its optimal exploitation, and

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the development of more efficient PV systems remains a current concern for which we must join efforts.

The main component of these systems is the PV module, since it is responsible for converting solar radiation directly into electrical energy based on the PV effect [1]. Therefore, PV modules are usually exposed to adverse weather conditions that over time eventually lead to their degradation and consequently loss of efficiency. Moreover, the electrical power produced by them is strongly affected by the irradiance received by the solar cells that compose them, as well by its temperature. Thus, to accurately model the current-voltage (I-V) characteristic curve, that describes the behaviour of a PV module under any operating conditions, an appropriate mathematical model is indispensable, as well as obtain accurate values for the electrical parameters of the respective model, called PV parameters. It is important to note that PV parameters assume different values for each type of PV technology, since each technology in its constitution integrates distinct materials, in addition, they can also vary with degradation or aging.

In this paper, we are focused on analysing how the PV parameter variation, caused essentially by operation at different irradiance and temperature levels, can affect the I-V characteristic curve. The main goal is to understand to what extent the irradiance and temperature levels can influence the PV parameters of a module manufactured with polycrystalline (poly-Si) silicon. For this, the Sharp ND-R250A5 PV module was selected, and its modelling was performed using the single-diode mathematical model. In a first phase, a quantitative variation of PV parameters was carried out in order to analyse its influence on the I-V characteristic curve, namely at the maximum power point (MPP). In a second phase, the PV parameters variation with the irradiance and temperature over a day was studied. The obtained results in both cases were conclusive and clearly shown the importance of obtaining accurate PV parameters when one intends to model the I-V characteristic of a PV module.

## 2. Mathematical Model

A PV module can be characterized by different mathematical models with greater or less complexity, however the most widely used in the literature is the single-diode model because it establishes a good compromise between simplicity and accuracy [2].

Figure 1 shows the single-diode model [3], [4] which includes a current source representing the photoelectric current ( $I_{ph}$ ), a diode representing the PN junction and two resistances representing the losses in the circuit. The series resistance ( $R_s$ ) reflects

the ohmic losses and is responsible for the slope of the I-V curve in the open-circuit zone. While the parallel resistance ( $R_p$ ) translates leakage current losses and is responsible for the slope of the I-V curve in the short-circuit zone [2].

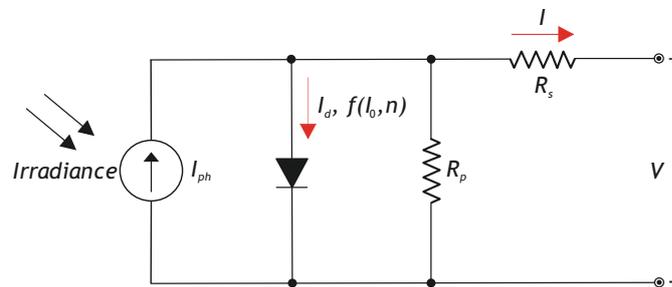


Figure 1: Equivalent circuit of the single-diode mathematical model.

Applying Kirchhoff's laws to the circuit of Figure 1, the output current ( $I$ ) is given by equation (1).

$$I = I_{ph} - I_0 \left[ \exp \left( \frac{V + I \times R_s}{n \times V_t} \right) - 1 \right] - \frac{V + I \times R_s}{R_p} \tag{1}$$

where  $V$  is the output voltage;  $n$  is the diode ideality factor;  $I_0$  is the reverse saturation current of the diode; and  $V_t$  is the thermal voltage which is given by equation (2), being  $N_s$  the number of cells connected in series,  $k$  the Boltzman constant (1.3806503E-23 J/K),  $T$  the temperature in Kelvin and  $q$  the electron charge (1.60217646E-19 C).

$$V_t = \frac{N_s \times k \times T}{q} \tag{2}$$

Therefore, the single-diode model considers five PV parameters  $\{I_{ph}, I_0, n, R_s, R_p\}$ .

### 3. Irradiance and Temperature Influence

One of the most influential factors concerning the operation of PV modules is undoubtedly the intensity of irradiance and temperature to which they are subjected. This is because the current produced is directly dependent on the incident irradiance, while the voltage hardly varies with this variable. Yet, an increase in the cells' temperature of a PV module, due to energy that is not fully absorbed and that which is dissipated as heat, leads to a decrease in efficiency. This decrease results from the fact that the  $V_{oc}$  voltage decreases as the temperature increases. On the other hand, the  $I_{sc}$  current also depends on the cell's temperature, increasing slightly with the temperature rise. However, this increase is not enough to compensate for the power loss due to the temperature effect on voltage. The manufacturers datasheets provide two temperature coefficients, being  $\alpha_i$  the variation coefficient of current with temperature expressed in

A/°C or %/°C and  $\alpha_v$  the variation coefficient of voltage with temperature expressed in V/°C or %/°C [5].

In order to consider the irradiance and temperature influence on the photoelectric current,  $I_{ph}$ , equation (3) appears [5].

$$I_{ph} = I_{ph,STC} \times \frac{G}{G_{STC}} \times [1 + \alpha_i(T - T_{STC})] \quad (3)$$

where  $G$  is the irradiance [ $\text{W/m}^2$ ] and STC means standard test conditions.

Considering a linear variation in the difference between PV module temperature and ambient temperature ( $T_a$ ) with the incident irradiance,  $G$ , the module temperature can be determined by nominal operating cell temperature (NOCT) by equation (4) [5].

$$T = T_a + \frac{NOCT - 20}{800} \times G \quad (4)$$

## 4. Variation of photovoltaic parameters

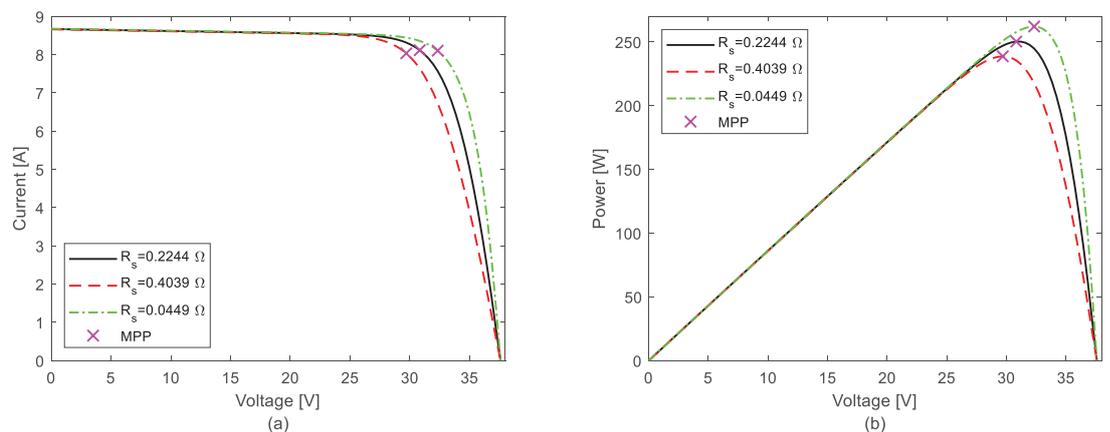
In order to accurately model the I-V characteristic curve of a PV module based on the single-diode model, it is essential to determine accurate values for the five parameters  $\{I_{ph}, I_0, n, R_s, R_p\}$ . This section firstly presents the results of quantitative variation of the parameters  $R_s$ ,  $R_p$  and  $n$ , and later the variation of the five parameters by influence of the irradiance and temperature levels. As previously mentioned, the Sharp ND-R250A5 PV module with 60 poly-Si cells (156.5 mm  $\times$  156.5 mm) connected in series [6], was the considered in this work.

## 5. Quantitative Variation

In order to analyse the variation of the parameters  $R_s$ ,  $R_p$  and  $n$  quantitatively it was necessary to determine the five parameters values in the STC. For this, the data provided by the manufacturer were considered and the five parameters  $\{I_{ph}, I_0, n, R_s, R_p\}$  determined based on the respective equations which can be found in [5].

Thus, each of the three parameters ( $R_s$ ,  $R_p$  and  $n$ ) has been independently varied, maintaining constant the remaining parameter values, i.e., equal to that determined by the respective equations. In order to ensure a variation of the parameters within the ranges indicated in the literature for the technology (Poly-Si) [7]–[9], to which the respective PV module belongs, a variation for  $R_s$  and  $R_p$  of  $\pm 80\%$  was considered in relation to the previously determined value. Already for  $n$  the variation considered was  $\pm 40\%$  in relation to the previously determined value. Since equation (1) is implicit in

$I$ , after determining the parameter values, the Newton-Raphson method was used to estimate the current values in each of the different situations. The results are shown by Figures 2 – 4, where the black line corresponds to the value of the respective parameter without any variation (i.e., determined by the respective equation), while the red line and the green line correspond to the variation above and below of this value, respectively. Considering the variation of  $R_s$ , Figures 2(a) and (b) show a significant influence on both I-V and P-V characteristic curves, this variation displaces the MPP, either by increasing or decreasing  $R_s$ . As expected, the slope of the characteristic curve varies greatly to the right of the MPP and the decrease in  $R_s$ , unlike the increase, contributes considerably to a higher maximum power.



**Figure 2:** Characteristic curves obtained by the variation of  $R_s$ : (a) I-V; (b) P-V.

Regarding the variation of  $R_p$ , Figures 3(a) and (b), a shift of MPP is also observed in both I-V and P-V characteristic curves, but less significant. This is because there is only a considerable displacement of MPP by the decrease of  $R_p$ , which justifies why some literature approaches consider that  $R_p \rightarrow \infty$  neglecting its value. In accordance with what was mentioned in section “Mathematical model”, the variation of  $R_p$  causes the slope of the characteristic curve to vary mainly to the left of the MPP. Since a variation of  $\pm 80\%$  was considered, it can be concluded that any value of  $R_p$  above the optimal value slightly affects the maximum power. However, any value of  $R_p$  below the optimal value leads to a significant decrease in maximum power.

Finally, considering the variation of  $n$ , Figures 4(a) and (b), there is a significant influence on both I-V and P-V characteristic curves, which translates into MPP displacement, either by increasing or decreasing  $n$ . Contrary to resistances  $R_s$  and  $R_p$ , the diode ideality factor  $n$  does not affect the I-V and P-V characteristic curves before or after MPP. Instead, an increase or decrease of  $n$  causes the area around MPP to be longer. This area around the MPP can be increased by adding another diode in parallel, which

leads to the double-diode model also used in the literature. For an even larger increase, several diodes can be added in parallel or series which leads to the multidimension diode model [8].

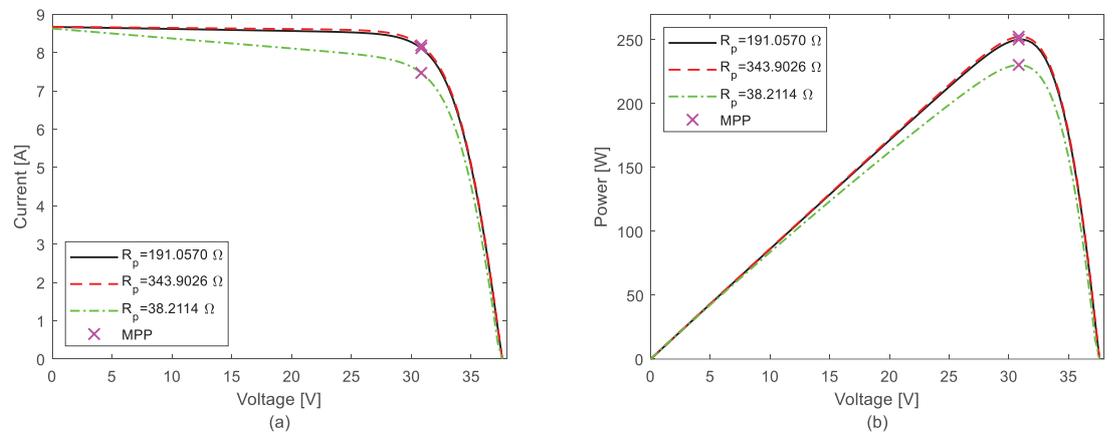


Figure 3: Characteristic curves obtained by the variation of  $R_p$ : (a) I-V; (b) P-V.

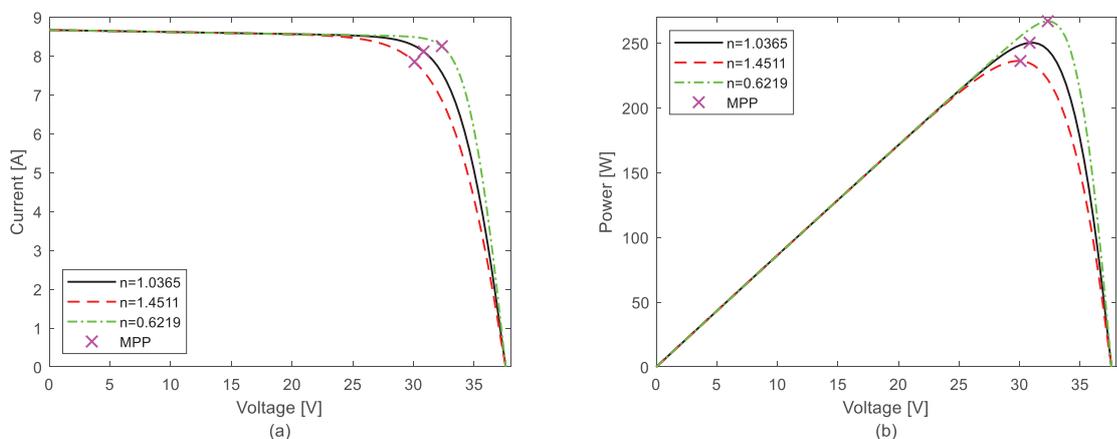


Figure 4: Characteristic curves obtained by the variation of  $n$ : (a) I-V; (b) P-V.

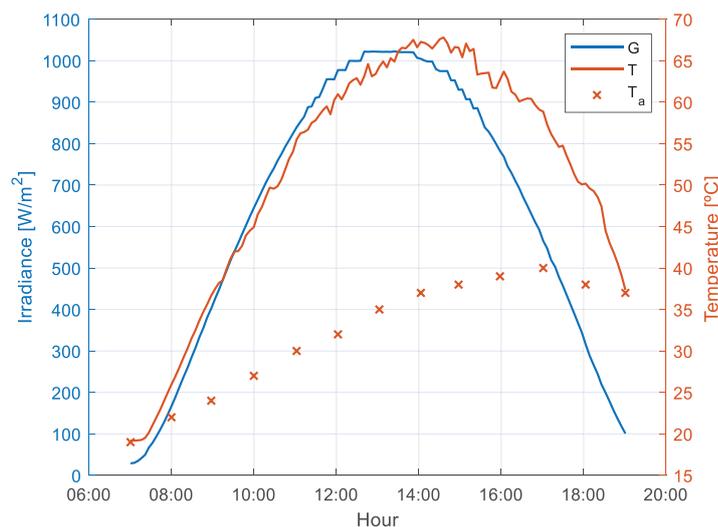
In short, the variation of  $R_s$  and  $R_p$  allows to adjust the slope of the characteristic curve to the right and left of the MPP, respectively. If the I-V or P-V characteristic curves are not within the coverage region of the PV model, the variation of  $n$  can be used as another degree of freedom to adjust the respective curves [8].

## 6. Variation with Irradiance and Temperature

Understanding how PV parameters vary with respect to irradiance and temperature levels is fundamental when it is intended to estimate the current of PV modules. In this sense, a study of the variation of the single-diode model parameters, under different operating conditions, was conducted in a similar fashion to the one performed in [10].

In contrast to the study presented in the previous section, in this case experimental data were used (outside the STC), i.e., 130 characteristic curves were experimentally measured over a typical day, between 7 am and 7 pm on July 15, to take into account the most diverse operating conditions, especially low irradiance and high temperatures. The respective experimental curves were obtained with an interval of 5 minutes, between the end and the beginning of each measurement using a programmable electronic load and an irradiance and temperature sensor. The experimental data comprise an irradiance range between the  $29 \text{ W/m}^2$  and  $1023 \text{ W/m}^2$ , and a temperature range between the  $19 \text{ }^\circ\text{C}$  and  $68 \text{ }^\circ\text{C}$ . It should be noted that during the measurement of the several curves both irradiance and temperature remained stable, with an average variation of  $4.4 \text{ W/m}^2$  and  $0.24 \text{ }^\circ\text{C}$ , respectively.

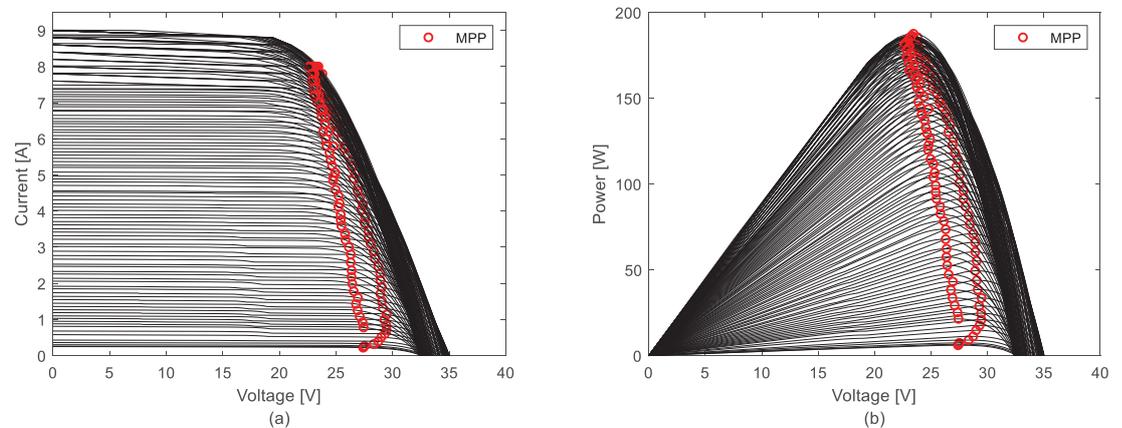
Figure 5 shows the time series of  $G$  and  $T$  recorded during the experimental acquisition test of the several characteristic curves, from the PV module installation site. However, the ambient temperature data,  $T_a$ , shown in this figure are an approximation for every hour of that day, since it was not possible to obtain a complete record, which in itself is not relevant since they are not used in the extraction of PV parameters.



**Figure 5:** Incident irradiance ( $G$ ), PV module temperature ( $T$ ) and ambient temperature ( $T_a$ ) throughout the day.

Having said that, Figures 6(a) and (b), respectively, present the several I-V and P-V characteristic curves. The MPP is marked in each of the curves, thus allowing to make some observations. We can verify that the first acquired curve reached a maximum power of  $6.05 \text{ W}$ , which increased at a slower pace at the beginning due to the irradiance intensity. The highest power curve recorded a value of  $187.44 \text{ W}$  and the last measured curve recorded a value of  $21.4 \text{ W}$ . However, it is important to note that the MPP has started to shift left after the peak power having been reached; this displacement is a

result of the voltage drop due to the PV module temperature increase, i.e., because the temperature has been considerably higher in the afternoon. Consequently, the maximum power is affected by this voltage drop. The slightly slanting of MPP points to the left is due to the slight influence of irradiance on voltage.



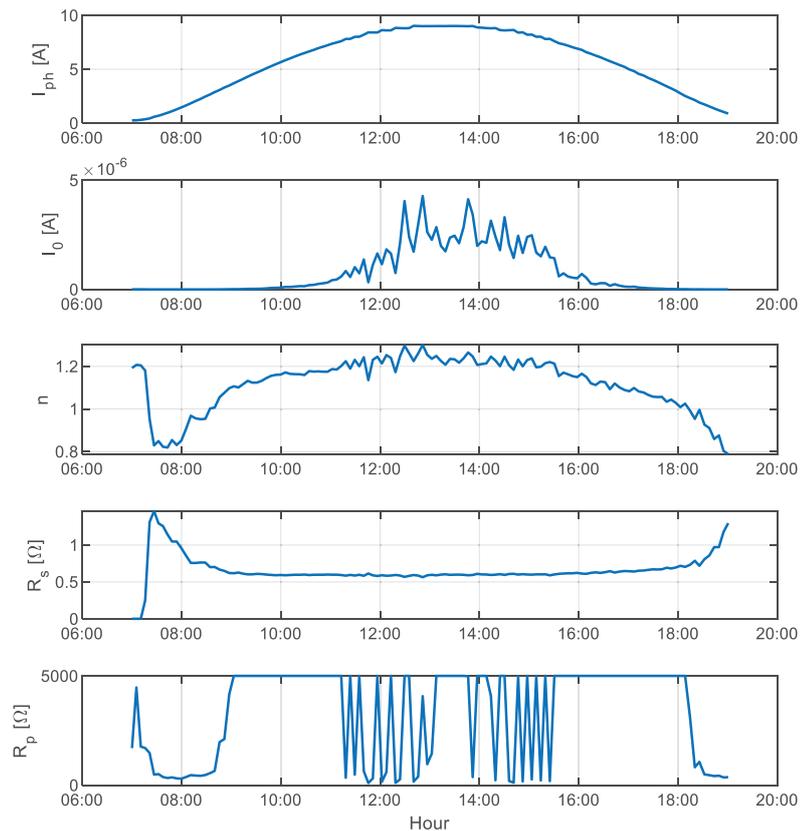
**Figure 6:** Characteristic curves throughout the day: (a) I-V; (b) P-V.

After acquiring the experimental data, and in order to make it possible to study the variation of the parameters  $\{I_{ph}, I_0, n, R_s, R_p\}$  with irradiance and temperature, the optimal values were extracted for each of the measured curves by minimizing the root mean square error (RMSE) between experimental and estimated data, using the guaranteed convergence particle swarm optimization (GCPSO) algorithm proposed in [2].

The optimal parameters of the single-diode model obtained for each curve are shown in Figure 7. The variation of these parameters throughout the day reflects the dynamics of the considered PV module under different operating conditions to which it was subjected. This fact could not be visible from the static I-V characteristic curves.

Concretely, regarding the variation of PV parameters throughout the day, we can notice that the current value measured at the beginning of the assay is lower than the measured at the end; an analysis of Figure 7 shows that:

- $I_{ph}$  presents a proportional variation with the irradiance, i.e., it increases and decreases according to its intensity;
- $I_0$  almost does not vary during periods of low temperature, but it increases significantly and varies greatly when the temperature is high (10 am to 17 pm);
- $n$  initially decreases with increasing irradiance within a relatively short range, from which, it maintains a tendency to increase with its intensity;



**Figure 7:** Single-diode model parameters for the Sharp ND-R250A5 PV module throughout the day.

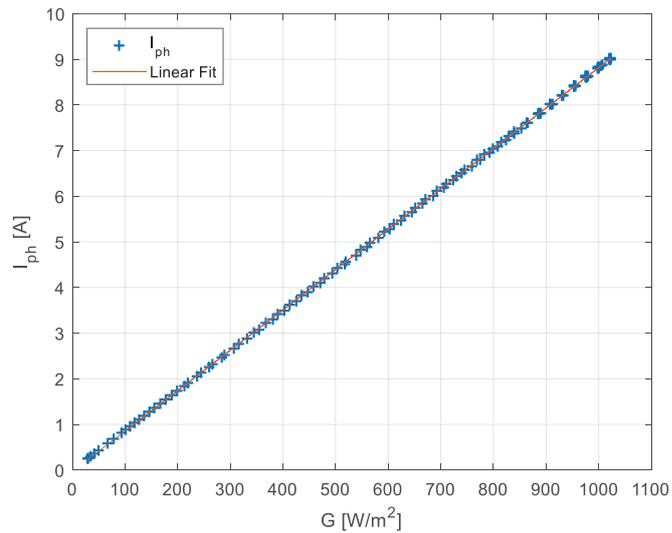
- $R_s$  presents a uniform variation except for periods of lower irradiance, where its value is higher;
- $R_p$  presented an unstable variation, settling mostly in maximum values, but for the lowest and sometimes the highest irradiance levels it was set at minimum values.

Moreover, it should be noted that if the test had finished a little later presumably the symmetric initial profile of the curves would have occurred.

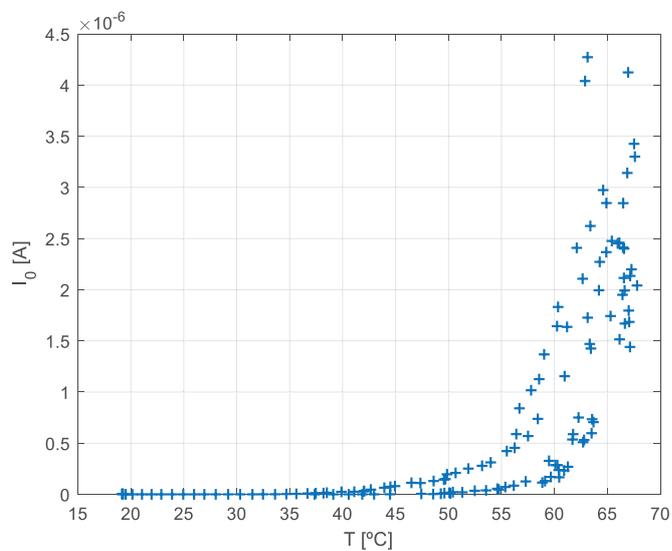
A more consistent analysis of the PV parameter variation with irradiance and temperature can be performed by looking at Figures 8 to 11.

Thus, Figure 8 shows that the proportional variation between  $I_{ph}$  and the irradiance intensity  $G$  has a linear distribution.

From Figure 9 we can conclude that  $I_0$  maintains a constant value up to about 40 °C, increasing slightly up to 60 °C. From this temperature there is a sharp increase; highlighting an increasing trend of  $I_0$  value with the PV module temperature increase, and is consistent with previous literature findings [10], [11].



**Figure 8:** Proportional variation between  $I_{ph}$  and  $G$ .



**Figure 9:** Variation of  $I_0$  as a function of  $T$ .

Regarding the variation of  $n$ , Figure 10, we found a decrease in its value with the irradiance increase up to the  $100 \text{ W/m}^2$ , from this point a growing trend is maintained. This initial decrease followed by an increase has been mentioned in the literature [10].

Contrary to what has been verified by some authors [12] for poly-Si technology, in this particular case, we inferred that  $R_s$  decreases with increasing irradiance, as shown in Figure 11(a).

Finally, in relation to the variation of  $R_p$ , Figure 11(b) does not always allow a clear conclusion, since in the vast majority of irradiance levels the solution found coincides with the defined upper bound, while in the lower and higher irradiance levels the solution of  $R_p$  pointed to minimum values. However, this difference between the  $R_p$

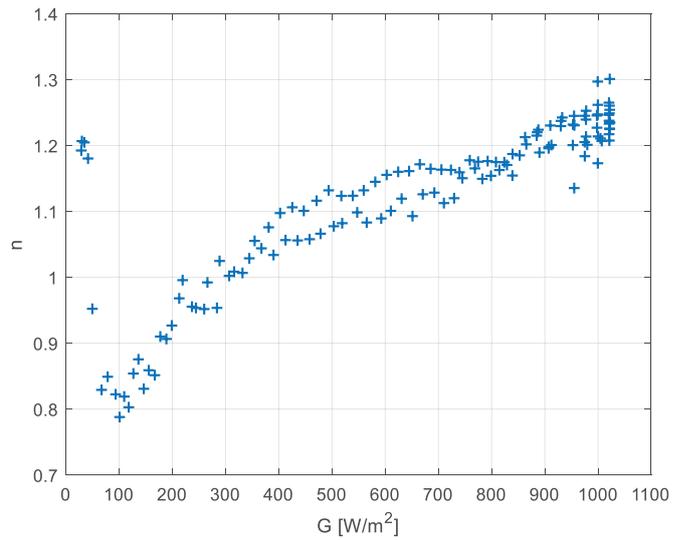


Figure 10: Variation of  $n$  as a function of  $G$ .

values shows that the common literature practice of assuming an infinite  $R_p$  value may be wrong, since for some irradiance values (in this case higher and lower) its optimal value tends to approach the lower bound. Therefore,  $R_p$  may assume smaller or larger values depending on the incident irradiance.

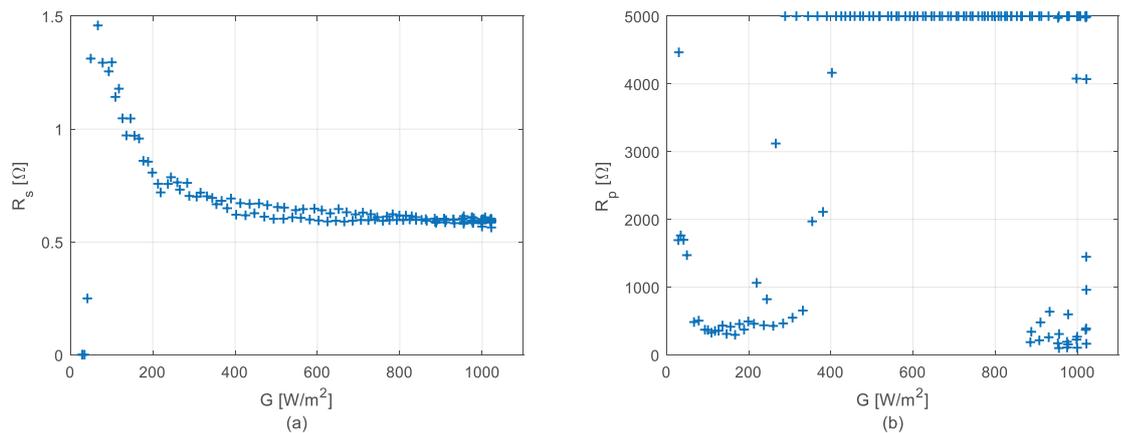


Figure 11: Variation of  $R_s$  as a function of  $G$  (a); Variation of  $R_p$  as a function of  $G$  (b).

In summary, according to the analysis performed, we concluded that all parameters  $\{I_{ph}, I_0, n, R_s, R_p\}$  vary considerably over an operating range consistent with other approaches in the literature, whether in relation to the incident irradiance or temperature to which PV modules are subjected.

## 7. Conclusion

This paper presented an experimental analysis of the PV parameter variation of the single-diode model with irradiance and temperature. The experiment was performed using a poly-Si PV module and the main purpose was to study the variation of the parameters  $\{I_{ph}, I_0, n, R_s, R_p\}$  with irradiance and temperature levels. This study allowed us to conclude that: (i) the current  $I_{ph}$  presents a proportional variation with the irradiance; (ii) the inverse saturation current  $I_0$  increases significantly when the temperature is high; (iii) the ideality factor  $n$  increases with increasing irradiance from 100 W/m<sup>2</sup>; (iv) the resistance  $R_s$  decreased with increasing irradiance contrary to that verified by other authors; (v) the resistance  $R_p$  presented an unstable variation, settling mostly in maximum values. In short, for poly-Si technology the PV parameters vary considerably with irradiance and temperature levels within a range consistent with other approaches in the literature, therefore reinforcing the importance and need to determine reliable values to accurately model I-V characteristics.

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