Simulation Study of a Photovoltaic Cell with Increasing Levels of Model Complexity

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***Abstract*—In this paper, different complexity levels are analyzed for modeling photovoltaic cells. The electrical circuit approach is the technique mostly used to describe photovoltaic cell behavior. Single and double diode models are two typical representations for this purpose. The parameters number necessary to represent photovoltaic cells in single and double diode models are studied in this paper and its impact on characterizing I-P and P-V curves is explored to discuss parameters role in providing more accuracy. The modeling approach allows to adequately simulate photovoltaic array systems taking into account the compromise between the accuracy and simplicity. The mathematical models are implemented in Matlab/Simulink by using the Newton–Raphson method.**

Keywords—Photovoltaic cells; sustainable energy; electrical circuit; mathematical models; Newton–Raphson.

I. Introduction

Photovoltaic (PV) energy is a promising source of renewable energy. The clearest advantage of the PV energy conversion systems is the almost total absence of anthropogenic greenhouse gas (GHG) emissions during their operation. Other important advantages are: they have no moving parts; they do not produce any noise; they require little maintenance and work quite satisfactorily, posing no health or environmental hazards [1]. In addition, One of the most important aspects of the remarkable progress of the PV market is the observed decrease of the PV generation associated costs and the evolution of the performance and quality of their internal electronic elements [2]. Presently, PV energy conversion systems are still expensive, but it is expected that future developments can significantly mitigate the price, and also increase the efficiency of solar panels in converting sunlight to electrical energy. Therefore, the rise of future high-power PV facilities, connected to the electric grid, is very likely [3].

Within the European Union (EU), Portugal is, after Greece and Spain, the country with the highest potential for solar energy exploitation: over 2300 hours per year of sunshine in the north region, and about 3000 hours per year in the Algarve region. So, Portugal displays an advantageous position to develop this type of renewable energy [4].

In the design of power generation facilities based on photovoltaic technology, solar cell model is an important tool to find an optimal size of the power to be installed. With regard to the project a previous knowledge how the solar cell will behave by experiencing several alternative weather conditions provides valuable information to right-size their power rating [5].

In this context, achieving high efficiency in PV energy conversion systems is mandatory to match the photovoltaic source and load impedance properly for any weather condition, thus obtaining maximum power generation [6]. Simulations are provided for assessing the temperature dependence, diode ideality factor variation, solar radiation change, and internal losses through parasitic resistances on modeling by comparison the single-diode model to double-diode model.

This paper is organized as follows: Section II discusses single and double-diode models. Section III presents the results of modeling the cell by varying their parameters with a special emphasis on solar cell temperature and incident solar radiation amplitude effect in the two type of models from the perspective of parameter variation. Finally, Section IV summarizes the work.

II. PV Cell Models

The conversion of PV energy into electrical energy involves distinct energy forms: light, electricity and heat. The energy conversion processes involving these energy forms may be modeled using an equivalent electrical circuit with growing complexity.

A. Single-diode circuit

It is actually the easiest representation for the solar cell model. It comprises a current source in parallel with a p-n junction. The equation is formulated as:

$$I = I_s - I_{is}\left[e^{\frac{qV}{mkT}} - 1\right] \qquad (1)$$

where I_s the photo-electric current, I_{is} is the diode saturation current, q is the electron charge, m is the diode ideality factor, k is the Boltzman's constant, and T is the cell temperature,

B. Single-diode circuit with series resistance

Its use is abundant in the literature because it requires low computational resources [7]. The model is built with additional parameter (four parameters circuit) that takes into account the power losses by Joule effect using a series resistance as depicted in Fig. 1.

And expressed according to:

$$I = I_s - I_{is}\left[e^{\frac{q(V+R_s I)}{mkT}} - 1\right] \qquad (2)$$

This work was supported by FEDER funds through COMPETE 2020 and by Portuguese funds through FCT, under Projects SAICT-PAC/0004/2015 - POCI-01-0145-FEDER-016434, POCI-01-0145-FEDER-006961, UID/EEA/50014/2013, UID/CEC/50021/2013, and UID/EMS/00151/2013. Also, the research leading to these results has received funding from the EU 7th Framework Programme FP7/2007-2013 under GA no. 309048.

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where G is the solar radiance modeled as current source I_s, R_s is the internal series resistance, I_d is the p-n junction current, I is the output current, and V is the terminal voltage.

C. Single-diode circuit with series resistance and parallel resistance

A more useful model includes an additional source of inefficiency that happens inside the cell. A parallel resistance serves to reproduce the effect of internal leak currents that prevent the full use of the generated photo-current.

The equivalent circuit diagram of the PV with single diode, series resistance and shunt resistance model is shown in Fig. 2, where Rp is the shunt resistance, and Ip is the shunt current.

The fundamental equation for the PV generator system with single diode, series resistance and shunt resistance model is given by:

$$I = I_s - I_{is}\left[e^{\frac{q(V+R_sI)}{mkT}} - 1\right] - \frac{V+R_sI}{R_p} \qquad (3)$$

D. Double-diode model with series resistance and parallel resistance

Mathematical derivation for single-diode scheme is based on the premise that electrical current is not affected by the recombination of free carrier in the depletion region. However the reality observed in the manufacturing of solar cells doesn't confirm this assumption. In actual fact, carrier recombination is a phenome that happens in p-n junction. It is know that this phenome cannot be totally modeled by using a single-diode model.

In this sense, adding a second diode to the electrical circuit based model the number of modeling parameters offers additional flexibility to describe the aforementioned issue.

The model is called seven parameters equivalent electrical circuit. In this way, there are two saturation currents for D1 and D2 respectively called I_{is1} and I_{is2}. The equivalent circuit diagram is shown in Fig. 3.

The characteristic equation for seven parameters cell is given by:

$$I = I_s - \left[e^{\frac{q(V+R_sI)}{mkT}} - 1\right](I_{is1} + I_{is2}) - \frac{V+R_sI}{R_p} \qquad (4)$$

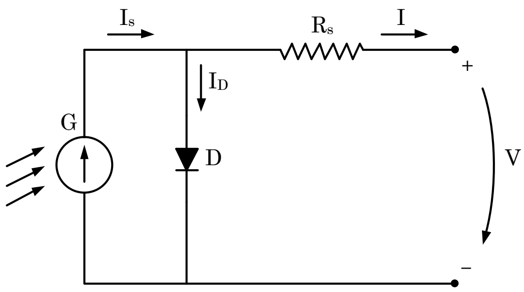


Fig. 1. The equivalent circuit diagram of the PV with single diode and series resistance model.

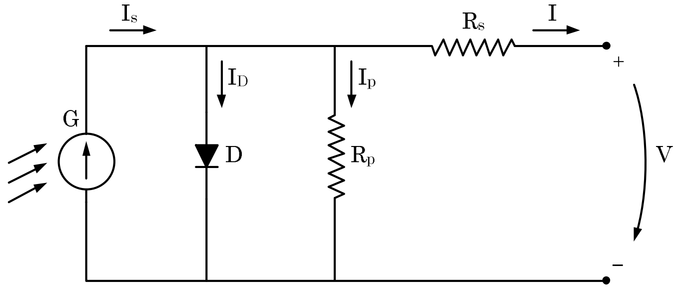


Fig. 2. The equivalent circuit diagram of the PV with single diode, series resistance and shunt resistance model.

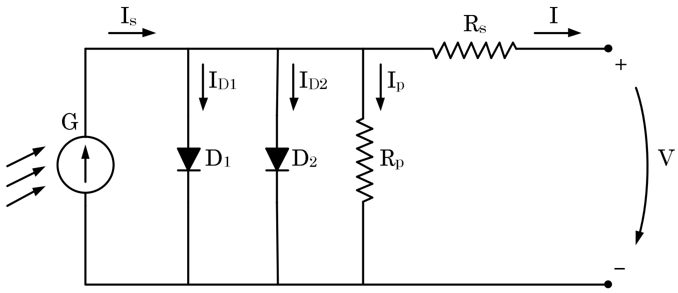


Fig. 3. The equivalent circuit diagram of the PV with a double diode, series resistance and shunt resistance model.

III. Operating Conditions Influence on Model Parameters

All the simulations were carried out on the basis of a solar cell whose electrical specifications are given in Table 1. These data refer to operating conditions under standard test conditions (STC). For models with at least four parameters it means there is no analytic procedure to find I_{cell} as function of V_{cell}. Therefore, the Newton-Raphson algorithm was used for finding the roots of $I_{cell} = f(I_{cell}, V_{cell})$.

A. Single-diode circuit with series resistance

To understand the power losses role due to internal parasitic resistance, the model was simulated with four different variations of R_s as shown in Fig. 4. The meteorological scenario is under STC operating conditions.

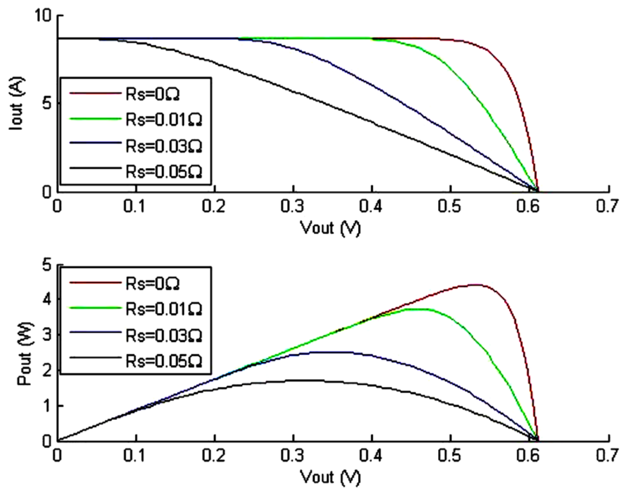


Fig. 4. R_s impact on I-V and P-V curves.

TABLE I. GENERIC PV CELL IN OPERATING CONDITIONS UNDER STC

V_{ca_n} (Open circuit voltage)	0.61 (V)
I_{s_n} (Short-circuit current)	8.7 (A)
$V_{Pmáx\_n}$(Cell maximum voltage)	0.49 (V)
$I_{Pmáx\_n}$(Cell maximum current)	7.8 (A)
$P_{máx\_n}$(Cell peak power)	3.83(W)
$V_{ca_}$temperature coefficient	-0.34%/ºC
I_s temperature coefficient	0.065%/ºC

By observing the Fig. 4 it can be seen that increasing the value of R_s the current delivered to the load is diminished. At the same time since the parasitic resistance is in series with the load a significant part of available power generated in the cell is internally wasted. In an extreme situation like observed with a series resistance of 50mΩ the I-V curve resembles a load connected to a power supply with internal resistance. This view point is supported by the fact of the power curve symmetry – peak power is situated at the middle of solar cell voltage value range.

Four solar radiation levels were injected via the cell model (100 W/m2, 300 W/m2, 700 W/m2 and 1000 W/m2) for a constant temperature at 25ºC. For each radiation level two distinct curves were generated. One refers to consider null the Rs parameter presence and while the other has a series resistance of 10mΩ. The results are shown in Fig. 5.

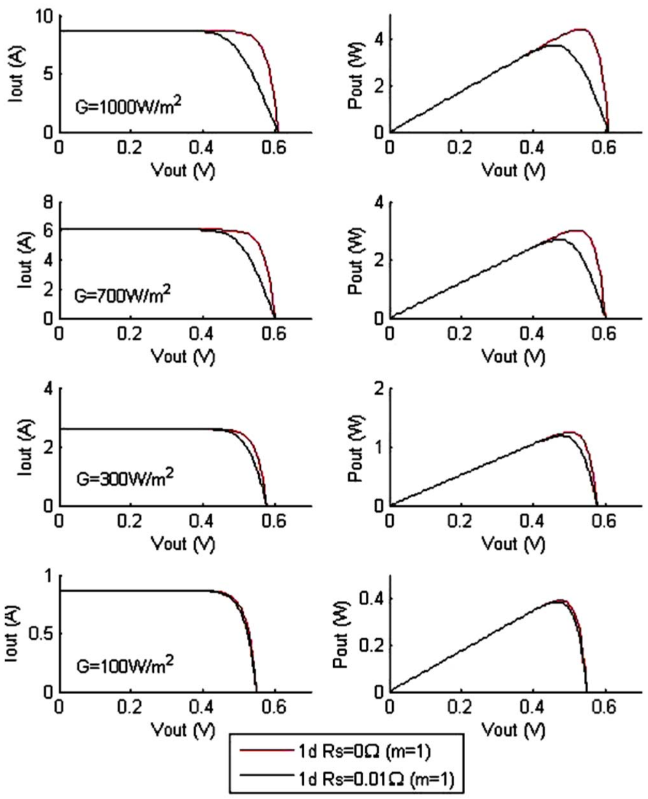


Fig. 5. Combined solar generation and series resistance impact on cell solar curves.

Between 100 W/m^2 and 300 W/m^2 power peak is similar for both models with and without series resistance. That is to say for this level of internal losses (at least until 10mΩ of series resistance) and under the conditions of unity ideality factor for the model diode.

By taking into account the same meteorological conditions the cell solar four parameters model is again evaluated but now exploring the ideality factor m to express its influence on available cell power deterioration. Findings are presented in Fig. 6.

As the parameter m is increased two negative effects stand out. First, V_{OC} is falling significantly compared to the curve obtained with R_s = 10mΩ and m=1. Second, when a higher diode ideality factor is introduced in the model plus the presence of series resistance, the power provided by the cell is further reduced. The combined effect is particularly noticeable in the range of 100 W/m^2 to 300 W/m^2.

In the following scenario Rs and m are combined increasing and decreasing the other at the same time. In other words, both parameters are never in simultaneous low or high. The goal was to verify if one parameter with much higher value has indeed a major role in the formation of the characteristics curves. The cell plots are depicted in Fig. 7.

Some important remarks can be extracted. From 300 W/m2 to 500 W/m2 V_{OC} operating point reveals a strong dependence with respect to m. Series resistance amplitude plays a major role to generate maximum power. Under reduced solar exposition (300 W/m2) playing with both parameters the observed differences are no longer relevant.

B. Single-diode circuit with series resistance and parallel resistance

Two simulation scenarios are provided. The load is first connected to solar cell model dominated by power loses related to R_P. That is to say R_S is null. Then R_s was introduced with a fixed value of 10 mΩ. R_P is initialized with 10Ω, goes to 200Ω and ends with 1000Ω.

Analyzing Fig. 8 is clear that R_p does not interfere in the influence region of p-n junction diode. At left side of the Fig. 8 where is predominant solar cell behavior as a current source for R_P starting at 200 Ω the leakage current in this branch is virtually null. Whereas the R_P signalized with 10 Ω the effect is visible, it is not significant.

With a cell power output view P-V plots regarding internal losses modeled as leak current though R_p the data points are quite identical as can be checked in Fig. 9. As such the R_p is this value band does not compromise the maximum power to be estimated. This conclusion is valid for the external physical parameters used in this simulation context (G=1000 W/m$_2$ and T_{cs} = 25 ºC). Using the same set of values for R_P a scenario of low solar radiation (100 W/m^2) was also tested in this study by exploring a range of solar cell surface temperatures from 10 ºC to 75ºC, Fig. 10. The influence of low R_P is only visible in the lower half of the evaluated temperature range and is decreasing slightly the expected peak power.

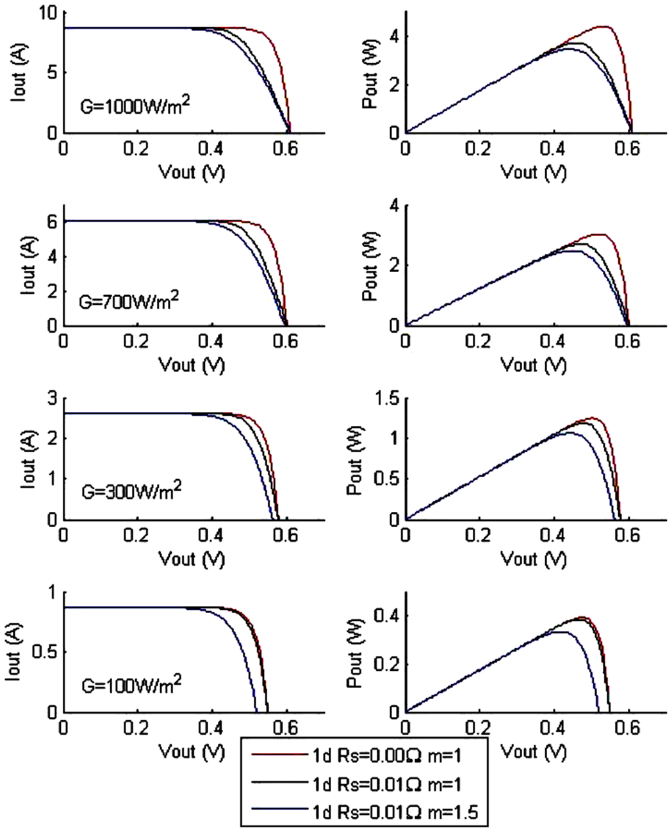


Fig. 6. Combined solar generation and ideality factor m impact on cell solar curves with and without series resistance.

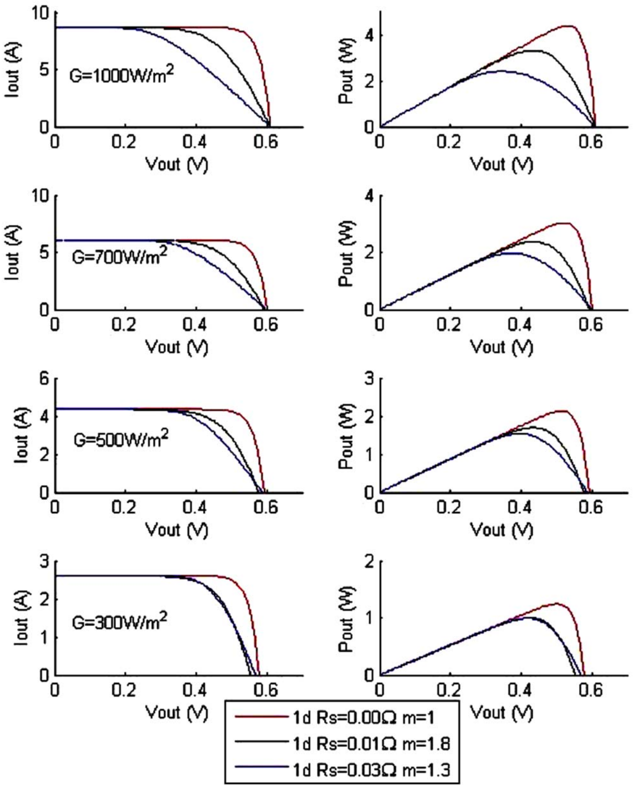


Fig. 7. Combination of R_s and m parameters with opposite evolution.

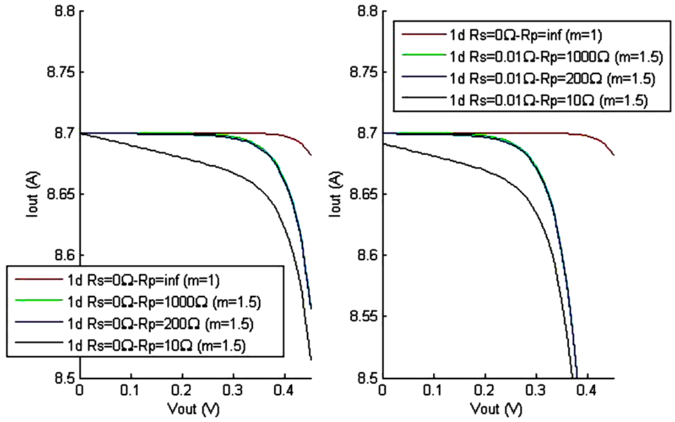
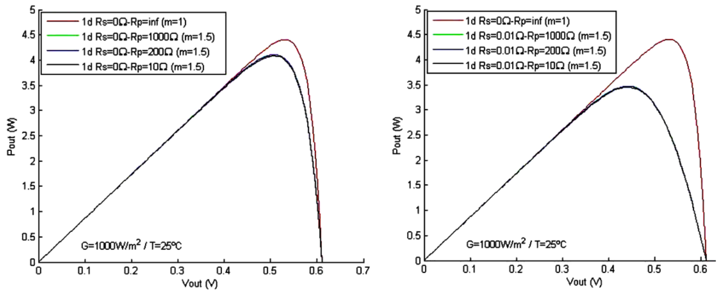


Fig. 8. I-V curves for single-diode model varying R_P as function of R_S: a) 0Ω; b) 10 mΩ.



a) b)

Fig. 9. P-V curves for single-diode model varying R_p as function of R_s: a) 0Ω; b) 10 mΩ.

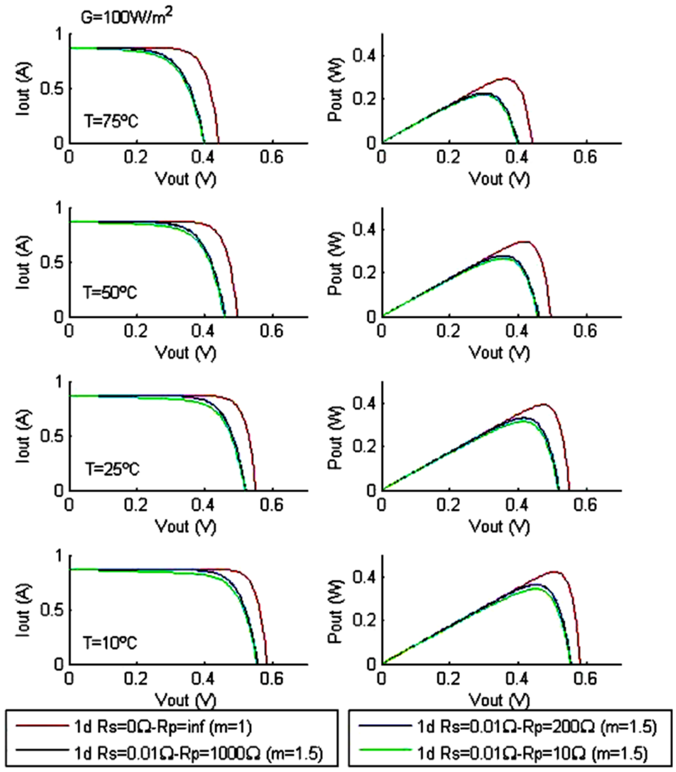


Fig. 10. Characteristic curves as function of solar cell surface temperature and R_p at a solar radiation of 100 W/m^2.

C. *Comparison of single-diode model to double-diode model*

In order to better understand the diode ideality factor effect in the formation of the characteristic curves in the double–diode model two groups of simulations were generated in the study of this paper. In each group three radiation levels and two distinct diode ideality factor m_1 and m_2 combinations are applied. In addition, the double-diode model is compared to ideal single-diode model.

In Fig. 11 choosing $m_1=m_2=2$ generates less sharp I-V curves. If one of the diodes is modeled as ideal (m1=1) the resulting curve has potential to provide a higher power peak. Moreover, by doubling the m parameter the V_{OC} has no longer coincident for both models when solar radiation is equal or lower than 500 W/m^2. As the solar radiation declines the V_{OC} gap tends to increase.

A higher solar cell surface temperature, Fig. 12, has a more pronounced effect on V_{OC}. However, the gap is not so significant if double-diode model is generated with a mixed set of m parameters ($m_1=1$ and $m_2=2$).

The choice of the m_1 and m_2 parameters and their influence on modelling solar cell performance can be better noticed in the generated data organized to plot P-V curves, as shown in Fig. 13 and Fig. 14.

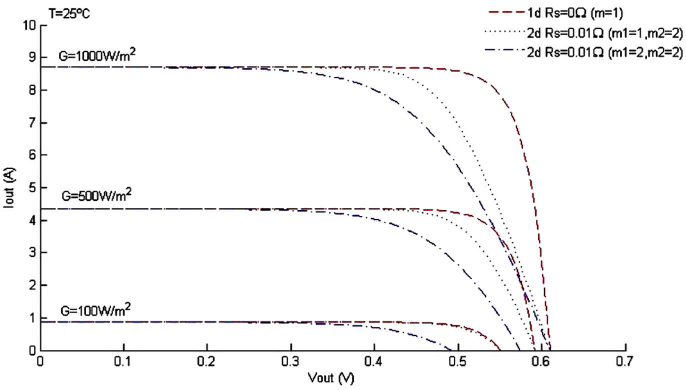


Fig. 11. I-V curves for single and double-diode models at solar cell surface temperature of 25º C.

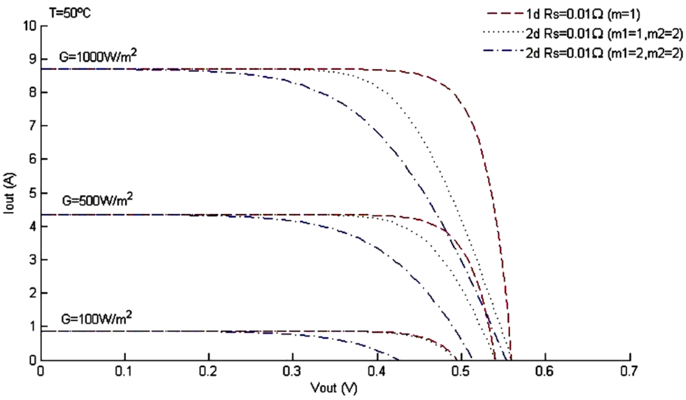


Fig. 12. I-V curves for single and double-diode models at solar cell surface temperature of 50º C.

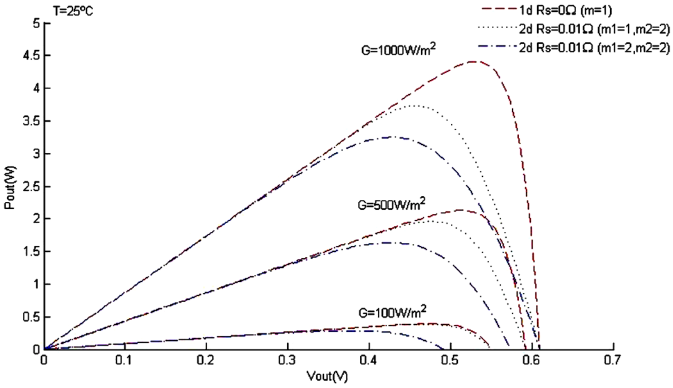


Fig. 13. P-V curves for single and double-diode models at solar cell surface temperature of 25º C.

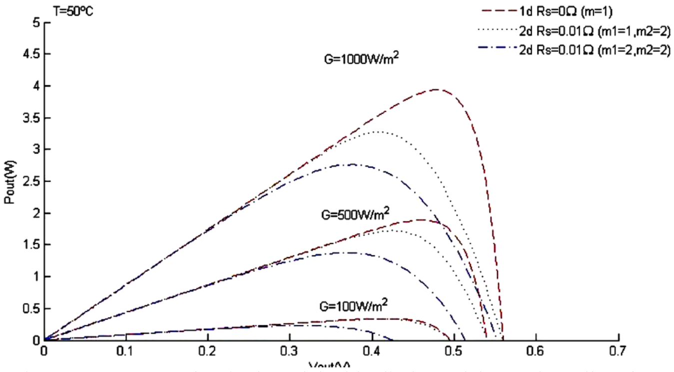


Fig. 14. P-V curves for single and double-diode models at solar cell surface temperature of 50º C.

IV. Conclusions

The rise of future high-power PV facilities, connected to the electric grid, is very likely. Thus, adequate modeling studies are important to capture the most important physical phenomena. Taking into account the comprehensive knowledge acquired in this study, the aim of this work was to comparatively study the different equivalent circuits that represent the PV cell. The single-diode model vs. double-diode version was successfully implemented in Matlab/Simulink.

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