Comparative study of the three equivalent models' response of solar cell

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Abstract. The photovoltaic cell is the main part of the solar energy conversion. The analysis of the response of the solar cell becomes a necessity. In the literature the solar cell is generally modeled by three equivalent electrical circuits. There are single diode, double diode and triple diodes model. the aim of this paper is to study the accuracy of each model. Therefore, by comparing the generated errors between each model and those obtained by measured data from RTC France solar cell, it was proven that the triple diodes model is the most precise among the three models. errors functions like RMSE and IAE were used to demonstrate this outcome.

Keywords— Equivalent electrical circuit, solar cell, accuracy, triple diode, modeling, $I_{PV}(V_{PV})$ characteristic.

1 Introduction

The optimization of photovoltaic cells yields is ensured by modeling the intrinsic physical phenomena governing the device. However, there are several electrical andmathematical models presenting the behavior of the solar cellby using characteristic parameters. In the literature, we distinguish the model based on: Single diode, double diodeand three diodes [1-3]. These equivalent presentations of the solar cell are the commonly used by most researchers inthe field. The three equivalent designs are defined mainly byintrinsic electrical parameters namely: Series resistance, shunt resistance, photocurrent, saturation current and diode ideality factor. The more the number of diodes increases in themodel, the more the pair (saturation current - ideality factor)increases.

This work is focused on the comparison between the three models in terms of accuracy. In this context, a well-determined approach has been adopted. First, the electrical parameters were taken from [4] for the three models. The chosen reference presents the most accurate parameters in theliterature which are identified from the experimental data cited in [5]. In the second step, a characterization of the photovoltaic current and voltage has been carried out

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carefully by varying the values of the resistance placed at theoutput. Then calculations are performed using statisticalfunctions to shed light on the accuracy of each model. As result, the triple diode equivalent model of solar cell is found the most precise among the three models. In order to demonstrate the high accuracy of the triple diodemodel, a 3D presentation of the individual absolute error function according to the photovoltaic voltage has beenperformed. This paper is arranged as follows: Section 2 illustrates the structure of the solar cell of single diode, double diode and triple diode model. Section 3 presents the different obtained outcomes and the related discussions. Section 4 gives the conclusion of the paper.

2 Equivalent models of solar cell

2.1 Single diode model

The model of the solar cell based on a single diode ispresented in the form of an electrical circuit as shown in Fig.1. Several physical processes define the internal environment ofthe cell, each of which is modeled by an electrical component. Indeed, the series resistance R_s presents the losses due to thevarious metallic contacts and connections covering the cell, the shunt resistance R_{sh} is the set of defects marking the semiconductor material. On the other hand, the saturation current I_s and the diode ideality factor n are the two parameters specific to the diode. The photocurrent I_{ph} is simply the current generated during the conversion of light photons to electrical energy. This parameter is modeled by a current source.

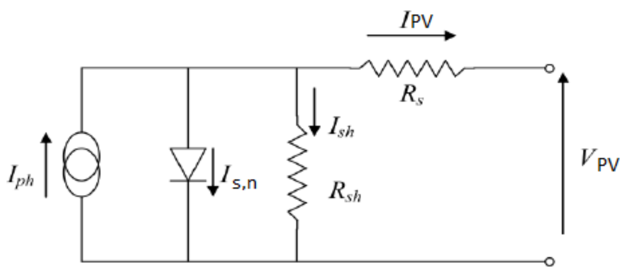

Fig. 1: Equivalent single diode model of solar cell

The characteristic mathematical equation is deduced in adirect way by applying Kirchhoff's law:

$$I_{PV} = I_{ph} - I_s \left[exp \left(\frac{q(V_{PV}+R_s I_{PV})}{nKT}\right) - 1\right] - \frac{V_{PV}+R_s I_{PV}}{R_{sh}} \qquad (1)$$

Where:

K: The Boltzmann constant (1.3806503 × 10–23 J/°K),
q: The charge of the electron (1.60217646 × 10–19 C),
T: The temperature of the cell in Kelvin.

2.2 Double diode model

The double diode model is based on two diodes. The first one describes the diffusion current flowing in the material, characterized by an ideality factor n_1 and a saturation current I_{s1}. The second diode represents the current due to recombination in the depletion region. It is electrically modeled by the ideality factor n_2 and the saturation current I_{s2}.

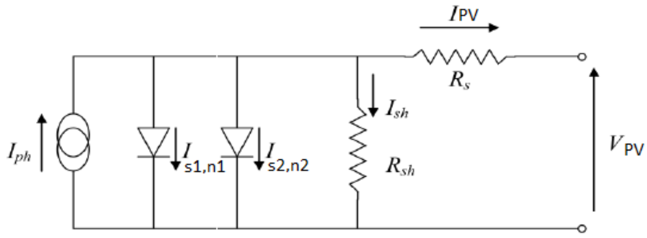

Fig. 2: Equivalent double diode model of solar cell

This electrical circuit shown in Fig. 2 can be presented as the following mathematical equation:

$$I_{PV} = I_{ph} - I_{s1}\left[exp\left(\frac{q(V_{PV}+R_sI_{PV})}{n_1KT}\right) - 1\right] - I_{s2}\left[exp\left(\frac{q(V_{PV}+R_sI_{PV})}{n_2KT} - 1\right)\right] - \frac{(V_{PV}+R_sI_{PV})}{R_{sh}} \quad (2)$$

2.3 Triple diode model

The photovoltaic cell can also be modeled as an electrical circuit based on three diodes. Such that each diode is modeled by its own two parameters (I_{si}, n_i), whose index i is the number of the diode in question.

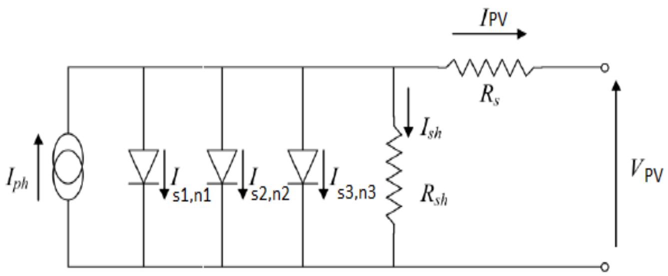

Fig. 3: Equivalent triple diode model of solar cell

The corresponding mathematical equation is as follows:

$$I_{PV} = I_{ph} - I_{s1}\left[exp\left(\frac{q(V_{PV}+R_sI_{PV})}{n_1KT}\right) - 1\right] - I_{s2}\left[exp\left(\frac{q(V_{PV}+R_sI_{PV})}{n_2KT} - 1\right)\right] - I_{s3}\left[exp\left(\frac{q(V_{PV}+R_sI_{PV})}{n_3KT} - 1\right)\right] - \frac{(V_{PV}+R_sI_{PV})}{R_{sh}} \quad (3)$$

3 The solar cell response

The solar cell generates a precise value of current and voltage depending on the value of a variable resistance connected to its terminals.

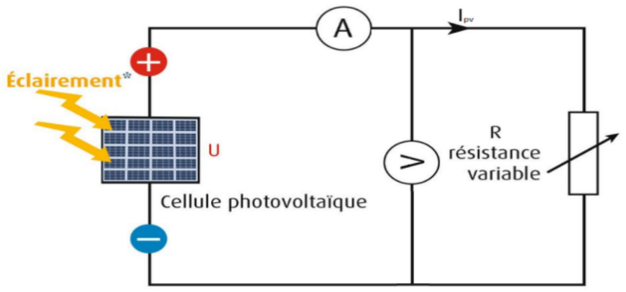

Fig. 4: Electrical circuit of solar cell with a resistive load

The set of measurements obtained from the current and the voltage allow to obtain a characteristic describing the response of the solar cell. The power can also be plotted according to voltage

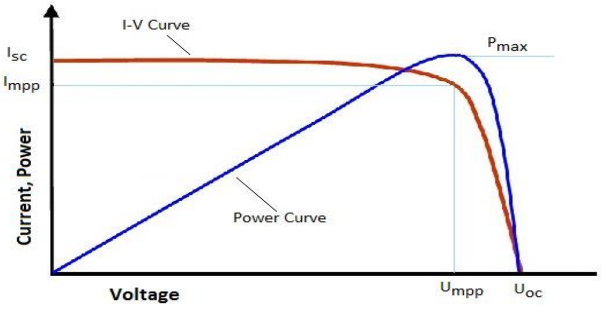

Fig. 5: Electrical characteristics $I_{PV}(V_{PV})$ and $P_{PV}(V_{PV})$ curves under an irradiance of 1000W/m² and a temperature of 25°C.

4 Results and discussions

The study discussed in this paper consists at comparing the accuracy of the three equivalent models of the solar cell based on: One diode, double diodes and three diodes. All the results obtained are compared with the measurements of I_{PV}-V_{PV} of commercial cell RTC France, under a temperature of 33°C and an irradiance of 1000W/m². The electrical parameters used in this paper are taken from [4]. The results of this work are simulated and obtained under MATLAB/Simulink

4.1 Statistical functions for accuracy calculation

In order to highlight the difference in the accuracy of the three equivalent models of the solar cell studied in this paper, some error functions (RMSE and IAE) have been used.

Root Mean Squared Errors (RMSE)

$$RMSE = \sqrt{\frac{1}{n}\sum_{0}^{n}(y_{mes}(i) - y_{cal}(i))^2} \quad (4)$$

Individual Absolute Errors (IAE)

$$IAE = |y_{mes}(i) - y_{cal}(i)| \quad (5)$$

4.2 The solar cell modeling under Simulink

4.2.1 Single diode model

The sampling of the different points of $I_{PV}(V_{PV})$ during the simulation of the scheme shown in Fig. 6, was ensured by setting up a variable resistance of 10Ω at the terminals of the equivalent electrical circuit based on a single diode.

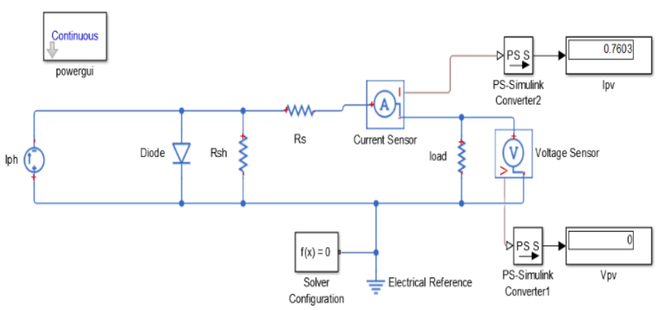

Fig. 6 : Equivalent Single diode model of solar cell

The generated characteristic from the above model simulation is shown in Fig. 7.

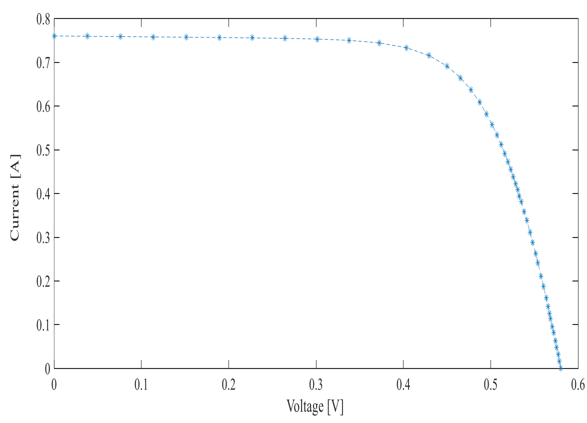

Fig. 7: $I_{PV}(V_{PV})$ characteristic of single diode model of solar cell.

4.2.2 Double diode model

The model of the solar cell based on two diodes is the same as the one based on a single diode plus a second diode in parallel as shown in Fig. 8, In order to plot the characteristic curves, a variable resistance around 10 Ω is connected to the terminals of the electrical circuit.

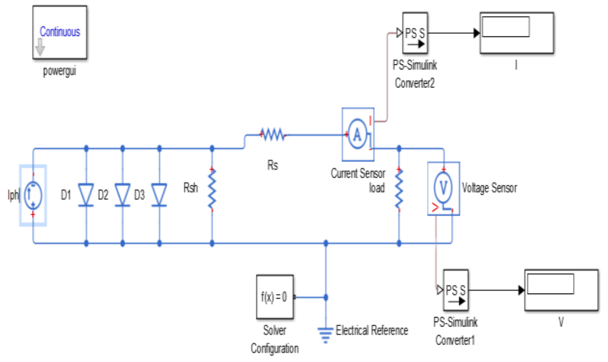

Fig. 8: Equivalent double diode model of solar cell

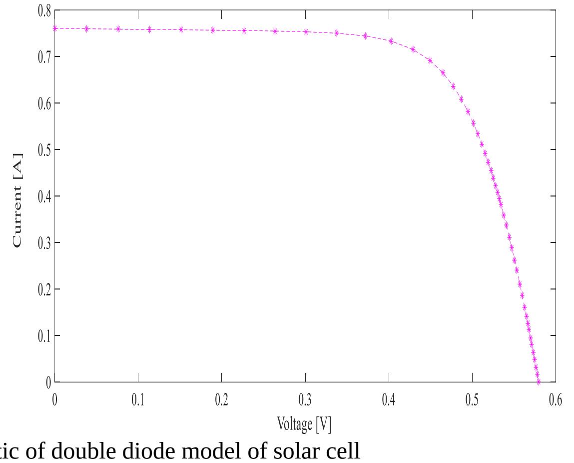

Fig. 9: $I_{PV}(V_{PV})$ characteristic of double diode model of solar cell

4.2.3 Triple diode model

In order to obtain the $I_{PV}(V_{PV})$ response (Fig. 11) we follow the same approach as in the two previous sections. The three-diode circuit to be simulated is shown in Fig. 10.

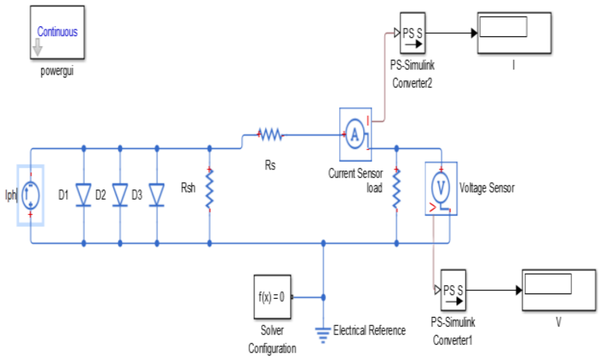

Fig. 10: Equivalent triple diode model of solar cell

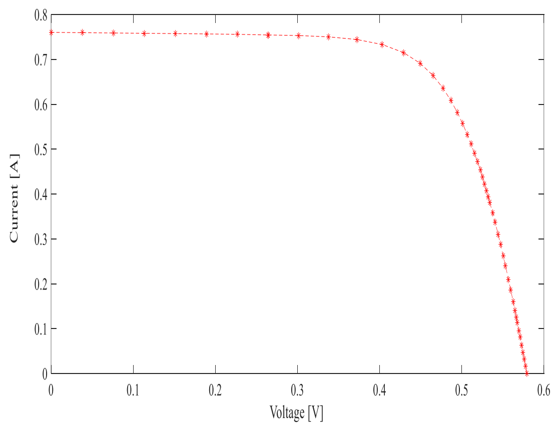

Fig. 11: $I_{PV}(V_{PV})$ characteristic of triple diode model of solar cell

4.3 Study of the three models' accuracy

Accuracy is an important criterion to judge the quality of the equivalent model of a solar cell. In our case the accuracy is evaluated on the calculated value of the error functions. A comparison is established between the calculated value of the error function of the model in question and that calculated from the experimental points listed in the table (Table I).

Table 1. Experimental data of RTC france solar cell.

Item	I_{PV}	V_{PV}	Item	I_{PV}	V_{PV}
1	0,662069	0,005556	11	0,633706	0,413318
2	0,662069	0,063889	12	0,613751	0,436761
3	0,662069	0,118056	13	0,585481	0,458864
4	0,660313	0,167503	14	0,54557	0,478288
5	0,660313	0,213049	15	0,490693	0,495703
6	0,65865	0,253906	16	0,424175	0,511778
7	0,656987	0,292085	17	0,344354	0,526513
8	0,653661	0,326914	18	0,159767	0,551965
9	0,650335	0,358394	19	0,088261	0,563352
10	0,643683	0,387196	20	-0,04311	0,573399

Table 2. Obtained I_{PV} and V_{PV} simulated values under Simulink of the three models of solar cell.

Item	Single diode model			Double diode model			Three diodes model		
	V_{PV}	I_{PV}	IAE1	V_{PV}	I_{PV}	IAE2	V_{PV}	I_{PV}	IAE3
1	0,063657	0,662069	0	0,005144	0,665259	0.00319	0,006649	0,662308	0.000239
2	0,118056	0,662069	0	0,064622	0,664094	0.002025	0,065436	0,662308	0.000239
3	0,167824	0,659195	0.002874	0,118474	0,662913	0.000844	0,119745	0,660313	0.001756
4	0,167824	0,659195	0.001118	0,167503	0,661713	0.001400	0,169013	0,660313	0
5	0,212963	0,659195	0.001118	0,213317	0,660497	0.000184	0,214363	0,660313	0
6	0,291415	0,656987	0.001663	0,254308	0,660656	0.002006	0,255795	0,658317	0.000333
7	0,326914	0,653661	0.003326	0,292085	0,658022	0.001035	0,293865	0,656322	0.000665
8	0,358394	0,650335	0.003326	0,326646	0,656765	0.003104	0,328576	0,654326	0.000665
9	0,387196	0,643683	0.006652	0,357993	0,652718	0.002383	0,360485	0,650335	0
10	0,413318	0,633706	0.009977	0,386928	0,645877	0.002194	0,389031	0,644349	0.000666
11	0,436761	0,613751	0.019955	0,413452	0,636247	0.002541	0,415333	0,634371	0.000665
12	0,458864	0,585481	0.028270	0,437021	0,615487	0.001736	0,439382	0,614266	0.000515
13	0,478288	0,545570	0.039911	0,458727	0,587046	0.001565	0,461312	0,585396	0.000085
14	0,495628	0,496282	0.049288	0,478496	0,548685	0.003115	0,480613	0,545939	0.000369
15	0,511908	0,432767	0.057926	0,495551	0,496438	0.005745	0,497908	0,496860	0.006167
16	0,526327	0,363478	0.060697	0,511830	0,433109	0.008934	0,513953	0,429495	0.005320
17	0,551755	0,200456	0.143898	0,526172	0,359766	0.015412	0,528641	0,361168	0.016814
18	0,539351	0,286105	0.126338	0,539351	0,281413	0.121646	0,541979	0,282255	0.122488
19	0,563383	0,114806	0.026545	0,551755	0,193046	0.104785	0,553961	0,197569	0.109308
20	0,573461	0,028195	0.071305	0,563383	0,108010	0.151120	0,564603	0,108070	0.151180
Sum IAE			0.654187			0.434964			0.417474
RMSE			0.052390			0.050080			0.049512

From Table 2, it is clear that the three-diodes equivalent solar cell model is more accurate than the other two studied models. Indeed, the calculated values of RMSE = 0.049512 and IAE = 0.417474 of the three-diodes model present the lowest values compared to those found for the one- and two-diode model. The $I_{PV}(V_{PV})$ characteristics of the three models and the experimental points extracted from the RTC France solar cell are plotted and presented in Fig. 12.

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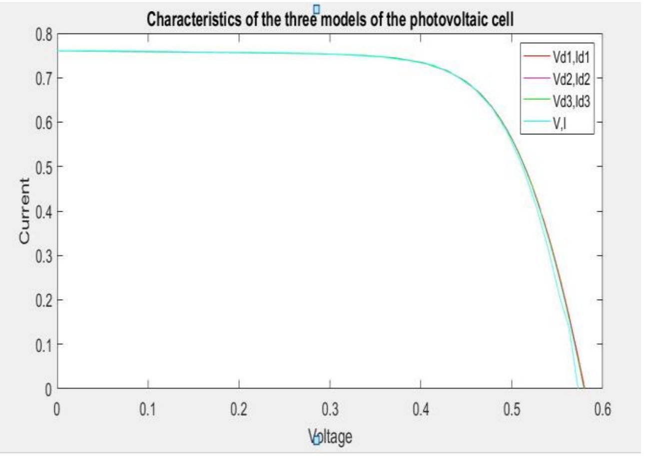

Fig. 12: $I_{PV}(V_{PV})$ characteristic of the three models of solar cell.

The difference between the three models is clearer after zooming an area in the curve plane.

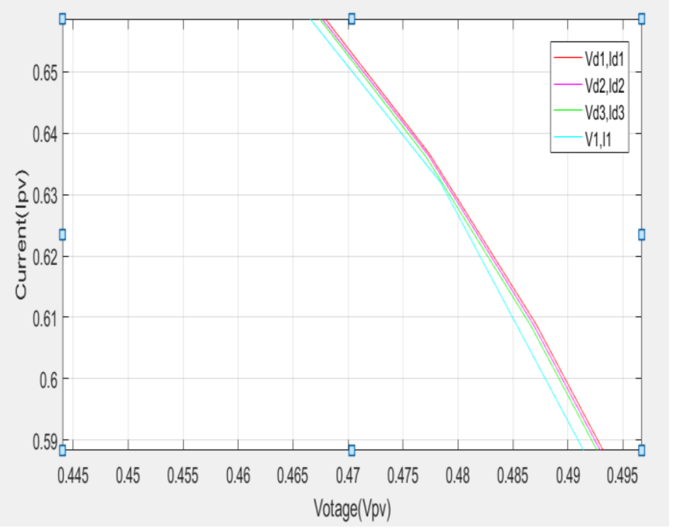

Fig. 13: zooming of the $I_{PV}(V_{PV})$ characteristic of the three models of solar cell.

We observe from the three models, translated by three characteristic curves $I_{PV}(V_{PV})$ a significant shift between the three characteristics and the curve of experimental data. This shift is minimized when the number of diodes in the model increases. Indeed, the two-diode model is more accurate than the one-diode model and the three-diode model is more accurate than the two-diode model.

To demonstrate the outstanding of the three-diodes model in terms of accuracy, we have presented in 3D the characteristic function IAE as according to voltage for each of the three models as shown in Fig. 14.

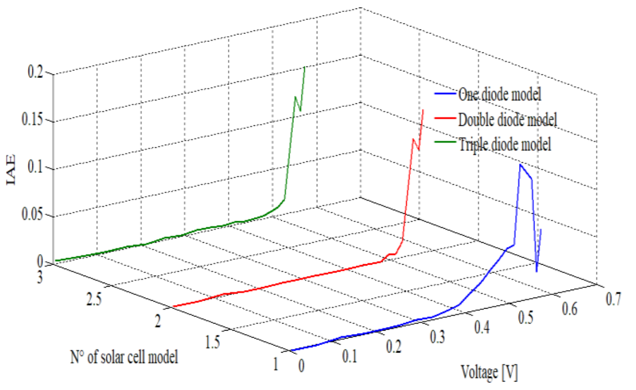

Fig. 14: $I_{PV}(V_{PV})$ characteristic of the three models of solar cell

5 Conclusion

This paper closely studies the accuracy of three models (single diode, double diode and triple diodes). The analysis of the behavior of these models was done using the experimental points (IPV-VPV) of the RTC France solar cell. These values were called to calculate the offset witnessed.

This paper closely examines the accuracy of three models (single diode, double diode and triple diodes). The analysis of the behavior of these models was carried out using the experimental points (IPV-VPV) of the RTC France solar cell. These values were called up to calculate the control difference in the current generated in each circuit of each model and then compare the difference values calculated for the three models. As a result, the three diodes model shows a high accuracy through the calculation of some error functions such as RMSE and IAE which have the lowest values compared to those of one and two models.

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