Development of a photovoltaic characteristics generator based on mathematical models for four PV panel technologies

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Article Info	ABSTRACT
	A good study of photovoltaic system requests to have very precise current-voltage characteristic curves of photovoltaic modules for different technologies. The photovoltaic emulator provides an efficient solution to maintain the same current-voltage output of photovoltaic module. It includes three parts: the PV model, the control strategy, and the power converter. This paper provides three classes of modeling and simulation of photovoltaic arrays and presents the synthesis results of the current-voltage characteristic performances obtained by the modeling approaches. The models of the first class are based on electrical circuit model, those of the second class are based on multiple straight lines model, and for the third class, it is based on the look up table. The mathematical model is built using MATLAB/ Simulink, and an experimental bench was carried out to acquire an up-to-date and representative experimental database of four PV panels. This database is used for the validation of these models for the different PV panel technologies under Moroccan meteorological conditions. Following this comparative study, we came to a high agreement between the experimental and simulated current-voltage characteristics for the emulator under study.

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1. INTRODUCTION

In recent years, Morocco has faced major challenges regarding the future of its energy system, economic growth and demographic growth [1]. Consequently, Morocco has implemented a national energy policy favorable to the development of renewable energies [2], to secure its energy supply, to control the future costs of energy services compared to the future costs of petroleum products and finally to preserve the environment by mitigating greenhouse gas emissions [3]. Photovoltaic solar energy represents an inexhaustible source of green energy and an alternative to fossil fuels [4]. The very high rate of growth of the energy industry means that the availability of specialized equipment for laboratory tests becomes crucial [5], in particular for manufacturers and laboratories working in the field of power electronics linked to PV installations. The obtained results require validation by appropriate experiments [6].

The photovoltaic emulator allows the validation of these tests by the modeling of the photovoltaic sources [7-9]. These mathematical models have a great effect on the proper functioning of these systems. It directly affects the static and dynamic performance of the photovoltaic emulator. The objective of this paper is the development of models that allows to better emulate the electrical characteristics of photovoltaic (PV) panels. This work is done on different technologies (Amorphous, CIS, Mono-Si, and CdTe) [10], and

for different temperature and irradiation conditions [11]. These developed models will serve as the real-time control part of the photovoltaic emulators [12].

In this paper, we present in the first part of the studied methods to develop the generator of PV characteristics. The first method is deduced from the theory of semiconductors [13]; it takes the physical properties of PV cells as unknown. The second method uses models based on linear interpolation [8] and the third uses look up tables [14]. In the second part we describe the experimental system carried out and installed at Green Energy Park of Bengrire to have an updated and real experimental database of the meteorological conditions of Morocco then we present the collected database. The third part shows the results of the current-voltage characteristic obtained for the different technologies and based on the experimental system carried out which would be compared with the simulated results of the models proposed to confirm their validity.

2.   RESEARCH METHOD

The modeling of the photovoltaic modules must represent their behavior with precision, without complicated mathematical operations that make the solutions difficult to obtain [15, 16]. For this objective, three different models of PV are presented: The first is a classic model based on the electrical diagram of the photovoltaic cell. The second uses linear interpolation to reproduces the characteristics of PV panels, while the last is a purely experimental model, based on the LUT arrays.

2.1. Electrical circuit model

The electrical behavior of a PV module can be represented, according to the semiconductor theory, by a mathematical model with two exponentials or one exponential [7, 17-19]. In this work we used a single exponential model [20], allowing to obtain the models with five, four or two parameters.

2.1.1. Five parameters model

It is called a five parameters model, because the number of parameters necessary for the characterization and identification of the PV module is equal to 5: (I_{sc}, V_{oc}, A, R_s and R_p). This model can be represented by the equivalent diagram in Figure 1, includes a current source I_{ph} associated with a diode in parallel, modeling the P-N junction formed within the semiconductor making up the PV cell. To this association are added two resistances; one parallel R_p and the other series Rs [21, 22].
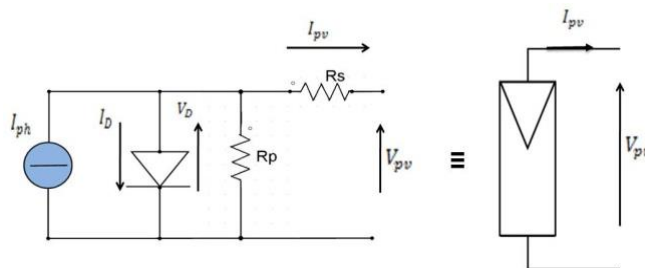

Figure 1. Equivalent circuit of a solar cell

According to Figure 1, the output current of the model is described as follows:

$$I_{ph} - I_0 \left[\exp\left(\frac{V_{pv} + R_s I_{pv}}{AV_t} \right) - 1 \right] - \frac{V_{pv} + R_s I_{pv}}{R_p} - I_{pv} = 0 \tag{1}$$

where:
Iph	: Photocurrent.
I_0	: Reverse saturation current for an ideal pn-junction diode.
A	: Ideality factor of the solar cell.
$V_t = NsKT / q$	: thermal voltage.
Ns	: Number of cells connected in series.
K	: Boltzmann's constant (1.38 10-23 J / K).
T	: Real junction temperature (K).

Q   : Elementary charge.
R_s : Series resistance (Ω).
R_p : Shunt resistance (Ω).
     The identification of these five parameters requires the resolution of the following:

$$
\begin{cases}
I = I_{ph} - I_0 \left[exp\left(\dfrac{V + R_s\,I}{A V_t} \right) - 1 \right] - \dfrac{V + R_s\,I}{R_p} \\[4mm]
I_0 = \dfrac{I_{sc}}{exp\left(\dfrac{V_{oc}}{A V_t} \right) - 1} \\[4mm]
I_{ph} = \dfrac{R_p + R_s}{R_p} I_{sc}
\end{cases}
\tag{2}
$$

where:
I_{sc}: short-circuit current (A).
V_{oc}: open circuit voltage (V).

2.1.2. Two parameters model
     The idea in this model is based on the fact that under standard conditions, the current of a PV module can be expressed as a function of the voltage, by an expression containing a single simplified exponential as shown in (3):

$$
I_n = I_{scn}\left\{ 1 - C_1 \left(exp\left(\frac{V_n}{C_2 V_{oc}} \right) - 1 \right) \right\}
\tag{3}
$$

     The two parameters C_1 and C_2 are calculated as a function of I_{mpn}, V_{mpn}, V_{ocn} and I_{scn} under standard conditions:

$$
C_1 = \left(1 - \frac{I_{mpn}}{I_{scn}} \right) exp\left(\frac{-V_{mpn}}{C_2 V_{ocn}} \right)
\tag{4}
$$

$$
C_2 = \frac{\dfrac{V_{mpn}}{V_{ocn}} - 1}{log\left(1 - \dfrac{I_{mpn}}{I_{scn}} \right)}
\tag{5}
$$

where:
I_{mpn} : maximum power current into (STC) (A).
V_{mpn} : maximum power voltage into (STC) (A).
     In (3) allows to calculate the electrical characteristic $I_n(V_n)$ of the PV panel under standard conditions. The system of (6) allows the translating of the curve $I_n(V_n)$ to generate the characteristic I (V) corresponding to the new values of temperature and irradiation.

$$
\begin{cases}
V = V_n \dfrac{ln(G)}{ln(G_n)} \big(1 + K_v\,(T_c - T_{cn}) \big) \\[4mm]
I = I_n \dfrac{G\,ln(G_n)}{G_n\,ln(G)} \dfrac{\big(1 + K_{mp}\,(T_c - T_{cn}) \big)}{\big(1 + K_v\,(T_c - T_{cn}) \big)}
\end{cases}
\tag{6}
$$

where:
G   : real illumination (W / m^2).
G_n : Illumination in nominal STC (W / m^2).
K_v : voltage temperature coefficient of the open circuit (= 80 ± 10 mV / °C).
T_{cn} : Nominal temperature of the PV cell.

2.2. Piecewise linear model

Interpolation is a mathematical operation allowing to replace a curve or a function by a simpler one that coincides with the first curve in a finite number of points given at the start. In this work we the linear interpolation [23], which consists of "joining the points" given by straight lines to subsequently estimate the rest of the points on the curve.

2.2.1. Two lines approach

This model is determined by adjusting the two lines to the three main points that characterize the I(V) characteristic: open circuit point, maximum power point and short-circuit point, as shown in Figure 2 [8, 17], it is represented by the following system of:

$$
\begin{cases}
V_{mp} = V_{mp,n} + V_t \times \log\left(\dfrac{G}{G_n}\right) + Kv \times (T - T_n) \\[2ex]
I_{sc} = I_{sc,n} \times \left(\dfrac{G}{G_n}\right) + K(ci \times (T - T_n)) \\[2ex]
I_{mp} = I_{mp,n} \times \left(\dfrac{G}{G_n}\right) + (Ki \times (T - T_n))
\end{cases}
\tag{7}
$$

The two-line model is based on the knowledge of the four data items I_{mp}, V_{mp}, V_{oc} and I_{sc}. Despite its lack of precision, the two-lines model is simple and allows the main appearance of I(V) characteristic to be represented.

2.2.2. Four lines approach

The objective of this model is to improve the accuracy [12], by selecting two other points: $((V_{oc} + V_{mp}) / 2, I_2)$ and $(V_{oc} / 2, I_1)$. As a result, we will have five points and four lines as shown in Figure 3.
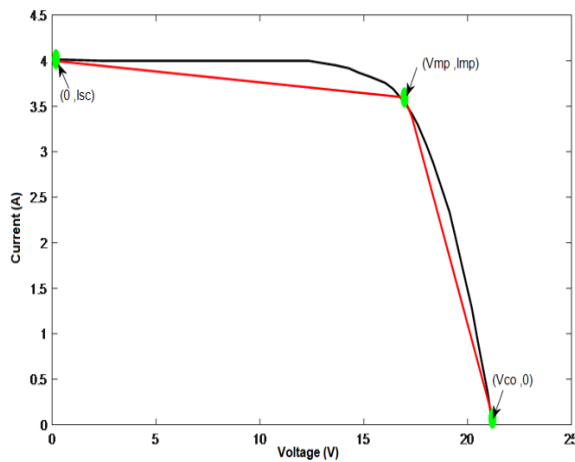

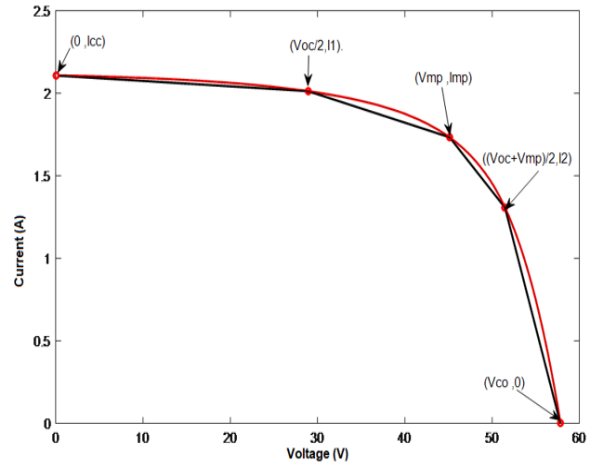Figure 2. Two-lines interpolation model   Figure 3. Four-lines interpolation model

The four equations representing the four lines are given by:

$$
\begin{cases}
I = I_2 - I_2 \dfrac{V - V_2}{V_{OC} - V_2} & ; \quad if \quad V_2 \leq V \leq V_{oc} \\[2ex]
I = I_{mp} + (I_2 - I_{mp})\left(\dfrac{V - V_{mp}}{V_2 - V_{mp}}\right) & ; \quad if \quad V_{mp} \leq V \leq V_2 \\[2ex]
I = I_1 + (I_{mp} - I_1)\left(\dfrac{V - V_1}{V_{mp} - V_1}\right) & ; \quad if \quad V_1 \leq V \leq V_{mp} \\[2ex]
I = I_{sc} + (I_1 - I_{sc})\left(\dfrac{V}{V_1}\right) & ; \quad if \quad 0 \leq V \leq V_1
\end{cases}
\tag{8}
$$

where: $V_1 = \dfrac{V_{oc}}{2}$ and $V_2 = \dfrac{V_{oc} + V_{mp}}{2}$

2.3. Look up table model

The look up table (LUT) approach, is based on the acquisition of all possible I(V) data of a real PV field under different climatic conditions (temperature, illumination, etc.), and on the storage of these data in appropriate unit. This method avoids any mathematical link between current and voltage. The I(V) characteristic is generated by a direct linear interpolation of the experimental data tables. The generator of I(V) characteristics in our PV emulator is a look-up-table with four dimensions (V, I, G, T), as shown in Figure 4. The current I is a function of the illumination G, temperature of module T and voltage V of PV module.
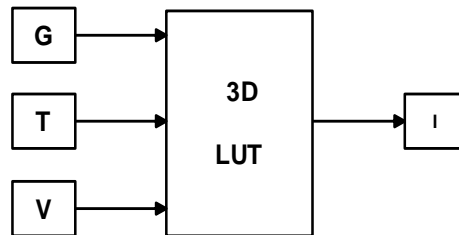

Figure 4. Look up table model in Matlab/Simulink

3.   RESULTS AND DISCUSSION
3.1. Experimental bench

The validation of the proposed models requires an up-to-date experimental database that represents the meteorological conditions of Morocco. For thus, we have located the experimental bench at Green Energy Park in Benguerir City, allowing the recording of the I(V) characteristics corresponding to a duration of 56 days. These registrations concerned four PV modules of different technologies: monocrystalline silicon, microcrystalline amorphous, cadmium telluride and CIS.

Data is captured with a 10 minutes sampling period throughout the day. It contains the illumination, module temperature, current and voltage data provided by the PV modules. The data is collected using an active load, a temperature sensor (pt 1000), a sun sensor (hemispherical solar radiation), and a data acquisition server (PV Analyzer - SQL Connect Center, as illustrated in Figure 5. The results are validated by four PV technologies. Table 1 summarizes the electrical characteristics of the PV technologies studied.
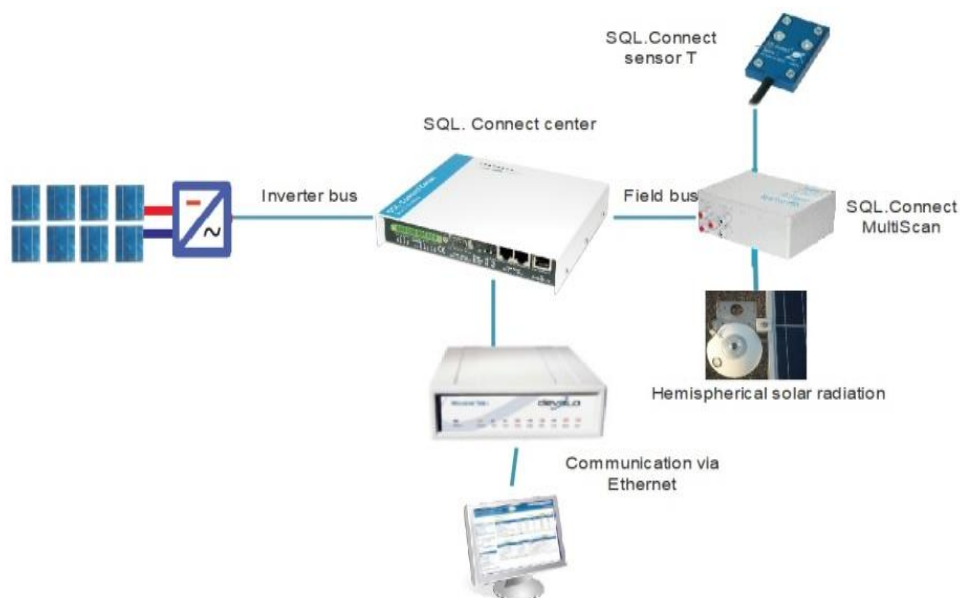

Figure 5. The experimental bench at Green Energy Park in Benguerir City

Table 1. Typical electrical characteristics of solar modules studied

Module PV	SHARP NS-F135G5 [24]	Power Max STRONG 120 [25]	TSM-DC01A [26]	CALYXO CX3 [27]
Material	Amorphe/Microcrystalline	CIS	Mono-Si	Cdte
Voc (V)	61.3	58.3	45.1	62
Isc (A)	3.41	3.22	5.52	1.92
Vmp (V)	47	42.8	36.8	46.6
Imp (A)	2.88	2.81	5.18	1.68
Pmax (W)	135	120	190	77.5
Ns	--		72	--
Kv %/°C	-0.3	-170 mV/°C	-0.35	-0.24
Ki	0.07%/°C	0.1 mA/°C	0.05%/°C	0.02%/°K
Kmp (%/°C)	-0.24	-0.39 %/°C	-0.45	-0.25
NOCT(°C)	--	--	46	45

3.2. Evaluation criteria

The coefficient of determination R_d and the mean square error RMSE, are calculated to evaluate the precision of the parameters for each technology studied [28]. R_d is a quality indicator of linear regression. It describes the effect of the independent variable on the dependent variable. The value of this coefficient is taken between 0 and 1. It is calculated according to (9).

$$R_d = 1 - \frac{\sum_{i=1}^{N}\left(G_{mes}(i) - G(i)\right)^2}{\sum_{i=1}^{N}\left(G_{mes}(i) - \overline{G_{mes}}\right)^2} \tag{9}$$

where: $\overline{G_{mes}} = \dfrac{\sum_{i=1}^{N} G_{mes}(i)}{N}$ is the arithmetic mean of the measured quantity G.

The RMSE mean square error describes the difference between the values predicted by a model and the values actually observed. It is calculated according to the formula in (10).

$$RMSE = \sqrt{\sum_{i=1}^{N} \frac{\left(G_{i\ mes} - G_{i\ cal}\right)^2}{N}} \tag{10}$$

Furthermore, we calculated the average computation time t_{CPU}, to estimate the speed execution of each processed models.

3.3. Results and discussion

Based on the experimental data collected from the Green Energy Park in Benguerir City, for each PV technology studied, the experimental characteristics are compared to the simulation results of models that have been developed. The results obtained, allow finding the most efficient model, which gives the best correlation compared to the experimental I(V) curves, for the four PV technologies. Figures 6, 7, 8, 9 and 10 respectively show the results of applying the 5-parameters, 2-parameters, 2-lines, 4-lines and LUT model for the four PV panel technologies. The I(V) characteristics are given for different values of illumination and temperatures.

In all studied cases, we clearly notice that the simulated values agree with the experimental measurements. At some power range, they are literally identical. To evaluate the accuracy of each model, Table 2 summarizes the values calculated for the coefficient of determination R_d and the mean square error RMSE. The comparison of the different models' performances requires the calculation of the average values of the different criteria as shown in Table 3.

The analysis of the results presented on Tables 2 and 3, shows a high compromise in precision and speed of execution by the 5-parameters model (R_d=0.993, t_{CPU} =0.16s), and 4-lines model (R_d=0.989, t_{CPU} =0.03s). The LUT model is less precise but it still the fastest (R_d=0.96, t_{CPU} =0.01s). As an economic study is required for the design of photovoltaic emulator, and since the low-cost micro-controllers has memory limitation issues, the four lines approach is the most appropriate for modeling I(V) curves of the PV panel.
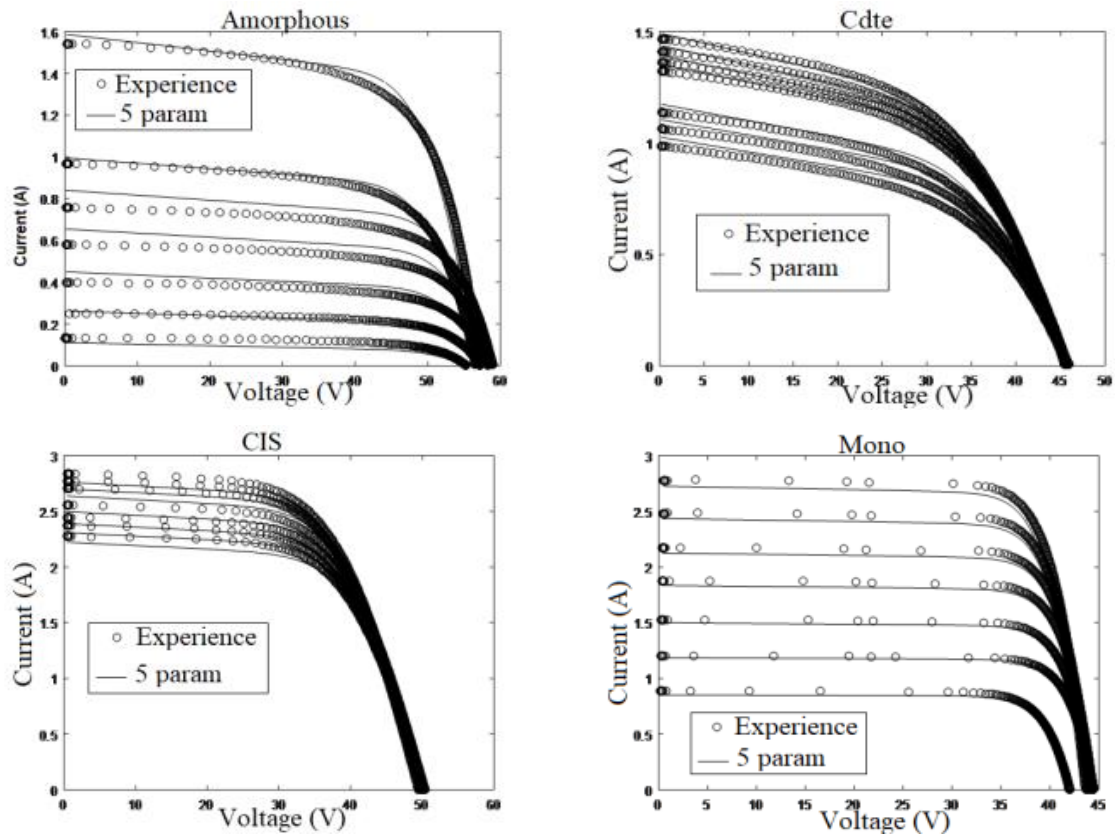
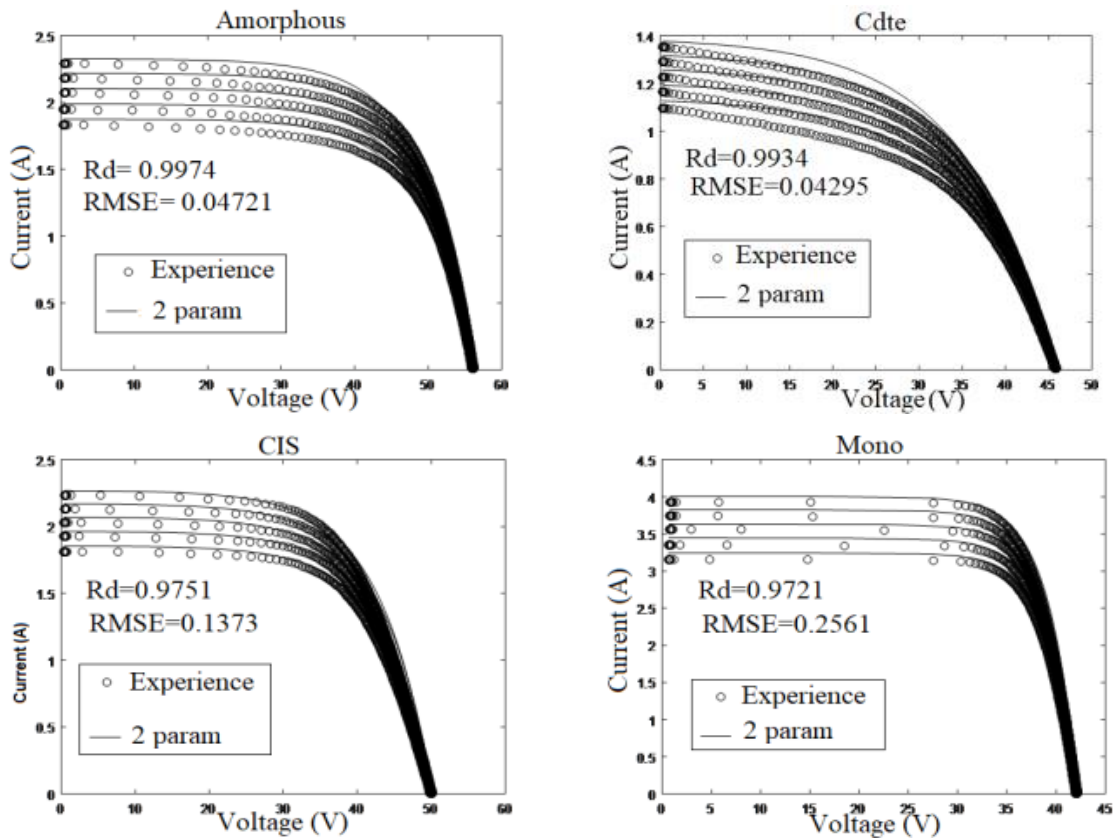Figure 6. Comparison between experimental and simulated I(V) characteristics of the five-parameters model

Figure 7. Comparison between experimental and simulated I(V) characteristics of the two-parameters model
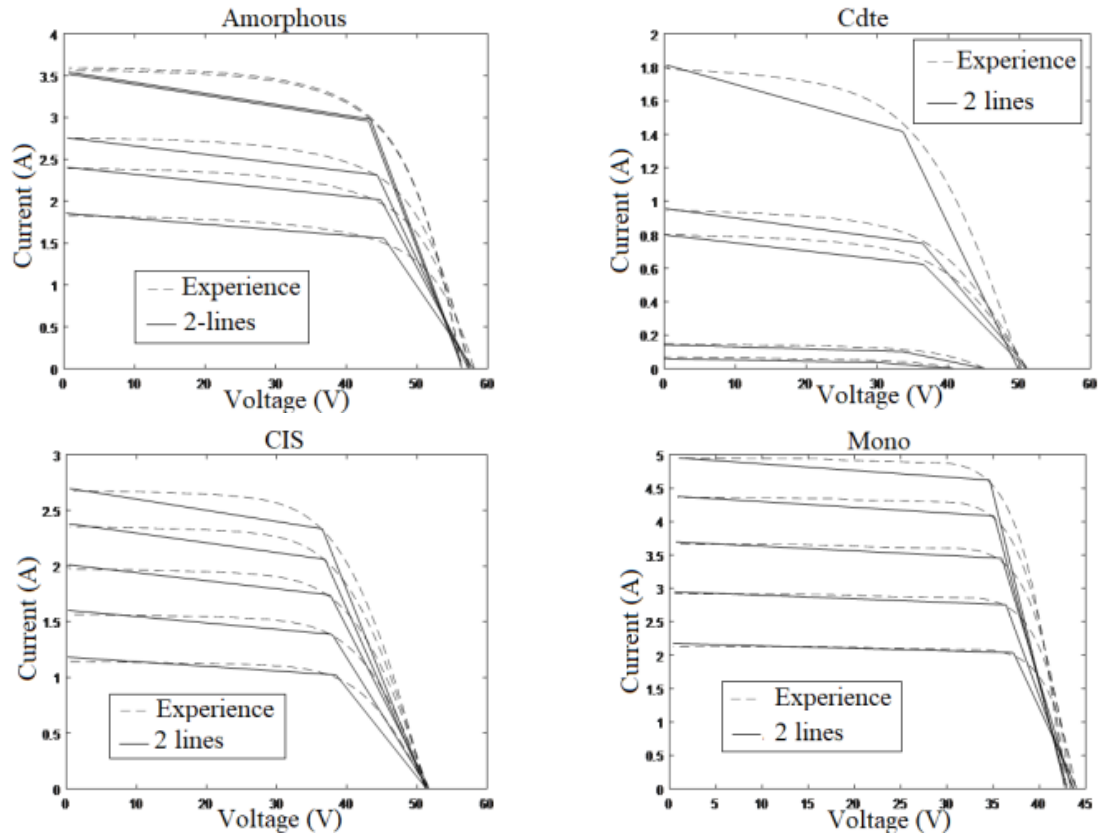
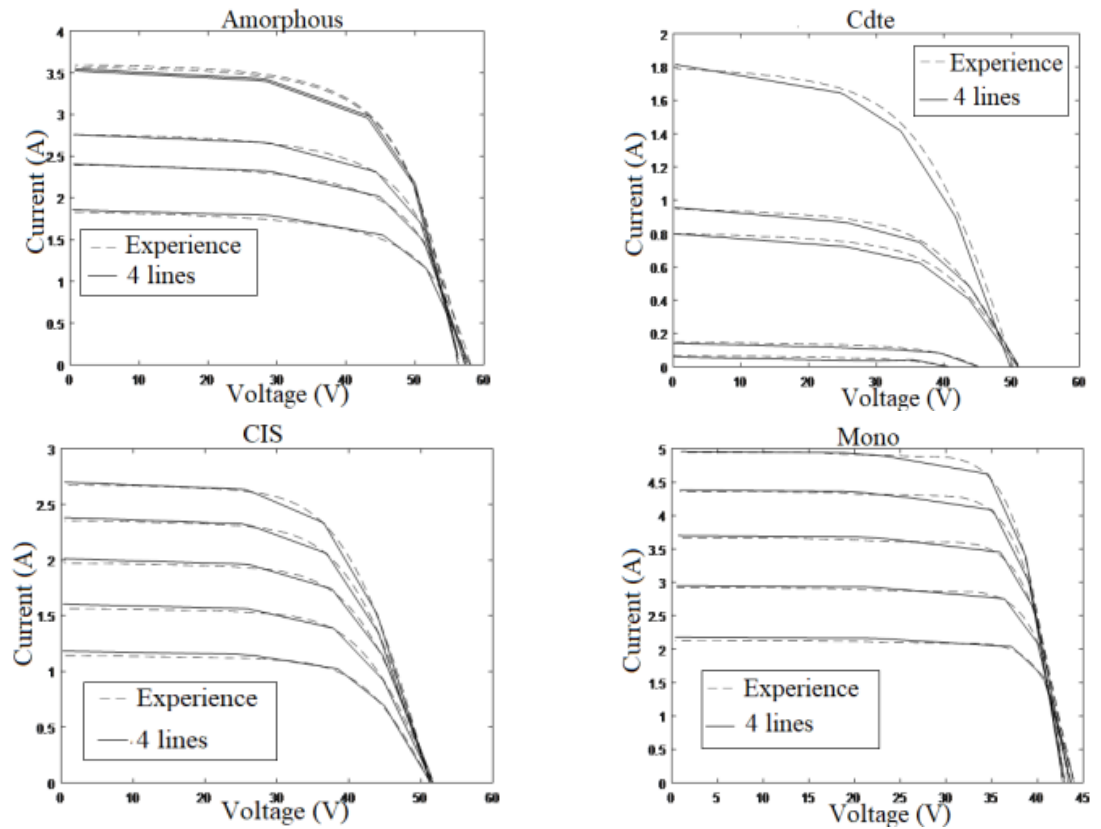Figure 8. Comparison between experimental and simulated I(V) characteristics of the two-lines model

Figure 9. Comparison between experimental and simulated I(V) characteristics of the Four-lines model
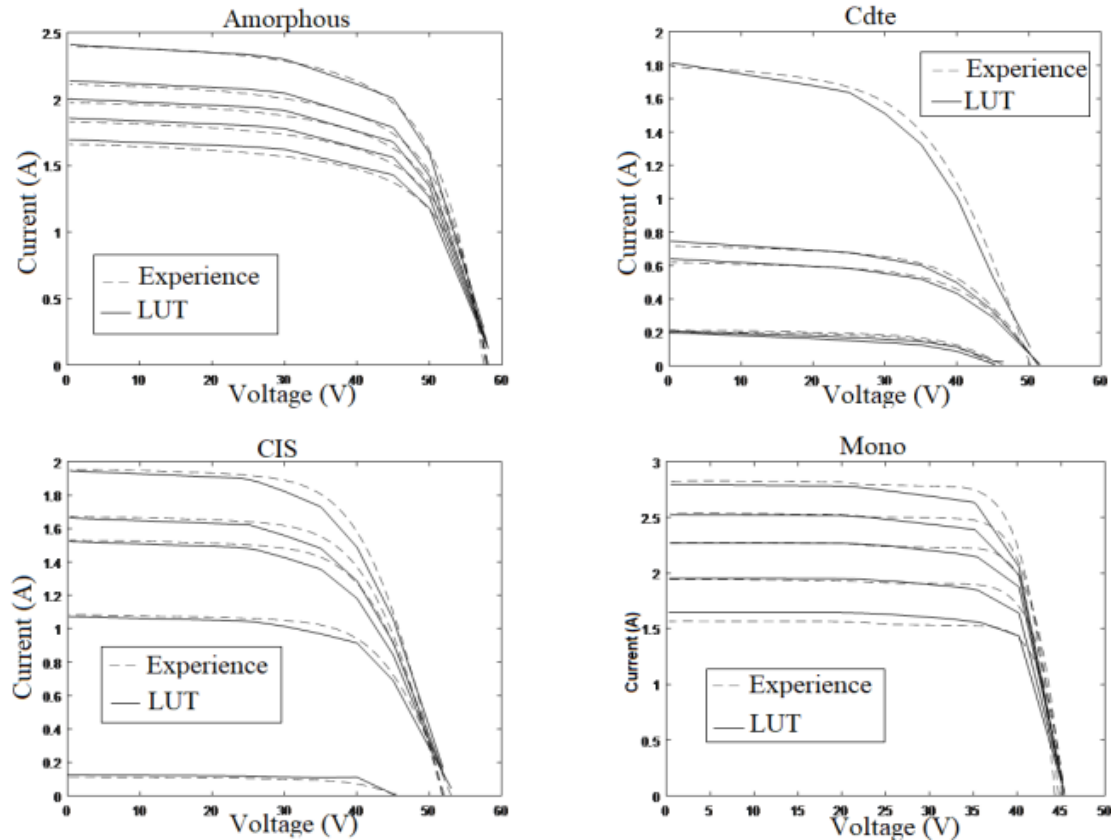
Figure 10. Comparison between experimental and simulated I(V) characteristics of the LUT model

Table 2. Summary of the performance of models studied

Technology	Criterion	5 parameters	2 parameters	2 lines	4 lines	LUT
SHARP	R_d	0.9887	0.9974	0.8771	0.9864	0.9643
NS-F135G5 Amorphe	RMSE	0.0982	0.0472	0.3235	0.9864	0.1743
	t_{CPU} (s)	0.1654	0.0370	0.0369	0.0398	0.0081
Calyxo	R_d	0.9973	0.9934	0.9580	0.9966	0.9952
Cx3	RMSE	0.0277	0.0429	0.1087	0.0308	0.0368
Cdte	t_{CPU} (s)	0.3581	0.0445	0.0385	0.0366	0.0081
Power Max STRONG 120 CIS	R_d	0.9980	0.9751	0.9390	0.9948	0.9770
	RMSE	0.0389	0.1373	0.2151	0.0626	0.1320
	t_{CPU} (s)	0.1643	0.0399	0.0372	0.0369	0.0101
TSM-DC01A	R_d	0.9950	0.9721	0.8251	0.9834	0.9322
Mono-Si	RMSE	0.1080	0.2561	0.6406	0.1974	0.3989
	t_{CPU} (s)	0.0677	0.0370	0.0302	0.0372	0.0082

Table 3. Summary of the average criteria for the four technologies

Average criteria	5 parameters	2 parameters	2 lines	4 lines	LUT
R_d	0.99382	0.98292	0.90666	0.98942	0.96258
RMSE	0.10726	0.17782	0.3936	0.31832	0.26954
t_{CPU} (s)	0.1632	0.05138	0.0385	0.03908	0.0102

4. CONCLUSION

The aim of this article is the development of a photovoltaic characteristic generators based on mathematical models. The parameters estimation problem is solved using a system of equations determined using the electrical circuit method, the linear interpolation method, and the LUT model. The experimental validation of these models is done for four technologies: monocrystalline silicon (TSM-DC01A), microcrystalline amorphous (SHARP NS-F135G5), CIS (Power Max STRONG 120) and CdTe (Calyxo Cx3 Cdte). The test bench has been located at Green Energy Park in Benguerir City, Morocco, allowing the recording of the I(V) characteristics of PV panels. The results show that the proposed models are very precise and agree with the experimental measurements. A comparative study is performed in order to find

the high accuracy model and it have demonstrated that the 4-lines model is fast, accurate and straight-forward (R_d=0.989, RMSE=0.318, t_{CPU}=0.03s). Otherwise, it is planned as a future perspective, to realize this emulator in order to apply these models as well as develop other methods of emulation.

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