

# Extraction of Monocrystalline Silicon Photovoltaic Panel Parameters Based on Experimental Data

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## Abstract

The aim of this work is to develop models that reproduce highly precise I-V (Current-voltage) curves of photovoltaic (PV) panels, regardless of the temperature and sunlight conditions, using an experimental database installed at the PV PARK of Benguerir city, that allow the record an up to date current-voltage characteristics (I-V) of the PV. This paper presents three modeling approaches that simulate the PV arrays, two are classic models determined by the electrical behavior of the PV cell, while the last is based on experimental modeling using the LUT (Look up tables) arrays and shows the performances results of the current-voltage characteristic obtained by the modeling approaches. To estimate the experimental parameters, we used the robust optimization algorithm Levenberg-Marquardt system, and a model based on the adaptive inference system ANFIS (Neuro-fuzzy adaptive inference systems) is developed to solve the problem of estimating of the experimental voltages  $V_{oc}$  and  $V_{mp}$ . We used MATLAB/SIMULINK to build the mathematical model, and the experimental database is used to validate these models under Moroccan meteorological conditions.

## Keywords

Mathematical modelling, Experimental data, ANFIS, Photovoltaic system

## Introduction

The PV emulator is a programmable power supply designed to facilitate the experimental tests of PV systems. It is used to approve these tests by using the PV sources models [1-3]. These models are crucial to the functioning of PV systems. It simply affects the static performance and the dynamic of the PV emulator.

Parameter identification of PV panels is a crucial step in the process of generating very precise PV characteristics [4, 5]. Several identification approaches have been proposed in the literature [6, 7]. Identification methods can be classified according to the data set used for parameter extraction.

This paper is designed to improve models that allow a better emulating of the electrical characteristics of PV system. In the first part, we present the methods studied in order to develop a PV characteristics generator. The first approach uses unknown physical properties of PV cells. It is deduced from the theory of semiconductors [8]. The second approach uses linear interpolation models [2], while the last one is based on LUT [9]. The experimental system carried out is described in this paper. It is installed at the Park of Bengrrire city, allowing to have an up-to-date and actual experimental database that represent the weather of Morocco. The last part of this paper shows the results of the identifications using the developed models obtained for Monocrystalline technology. The

experimental system was compared with the simulated results obtained, in order to confirm the validity of proposed models.

### Methodology

The PV panels models must perform the panels behavior with high precision, with less complicated mathematical operations [10]. For this objective, three approaches of modeling the PV are presented: Two are classic models based on the electrical behavior of the PV cell, while the last one is an experimental model, that uses LUT arrays. All used materials are nanoscale materials.

#### Five parameters model

According to semiconductor theory, the electrical behavior of a PV panel can be represented by a mathematical model with two or one exponential [11]. In this paper, the single exponential approach is used; it allows obtaining a model with five parameters.

In this approach, the five parameters that are necessary for the characterization and identification of the PV module are: short-circuit current, open circuit voltage, ideality factor of the solar cell, series resistance, and shunt resistance ( $I_{sc}$ ,  $V_{oc}$ ,  $A$ ,  $R_s$ , and  $R_p$ ).

The model is represented by the equivalent circuit in figure 1, A current source  $I_{ph}$  associated with a diode in parallel is used to model the P-N junction making up the PV cell. Two resistances are added to this association; one parallel  $R_p$  and the other series  $R_s$  [12], modeling the voltage drop and leakage current.

According to figure 1, the output current of the five-parameter model is:

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

Where,  $I_0$ : Reverse saturation current for an ideal pn-junction diode,  $R_s$ : Series resistance ( $\Omega$ ),  $R_p$ : Shunt resistance ( $\Omega$ ),  $I_{ph}$ : Photocurrent,  $A$ : Ideality factor of the solar cell,  $V_t = NsKT/q$ ; thermal voltage,  $K$ : Boltzmann's constant ( $1.38 \times 10^{-23}$  J/K),  $T$ : Real junction temperature (K),  $Ns$ : Number of cells connected in series, and  $q$ : Elementary charge ( $1.6 \times 10^{-19}$  C).

In order to identify these five parameters, we need to resolute the following equations:

$$\begin{cases} I = I_{ph} - I_0 \left[ \exp\left(\frac{V + R_s I}{AV_t}\right) - 1 \right] - \frac{V + R_s I}{R_p} \\ I_0 = \frac{I_{sc}}{\exp\left(\frac{V_{oc}}{AV_t}\right) - 1} \\ I_{ph} = \frac{R_p + R_s}{R_p} I_{sc} \end{cases} \quad (2)$$

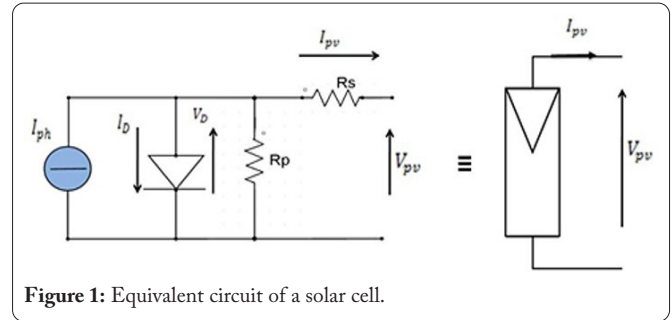


Figure 1: Equivalent circuit of a solar cell.

#### Four lines approach

Interpolation is a mathematical operation that allows replacing a curve by a simpler one, that must coincide with the original curve in a finite number of points given at the start.

The four lines approach is determined by adjusting four lines to five points of the I-V characteristic of the panel: The open circuit point ( $V_{oc}$ , 0), The maximum power point ( $V_{mp}$ ,  $I_{mp}$ ), the short-circuit point ( $0$ ,  $I_{sc}$ ),  $((V_{oc} + V_{mp})/2, I_2)$  and  $(V_{oc}/2, I_1)$ . The results of the five points and the four lines are presented in figure 2.

The equations that represent the four lines are given by:

$$\begin{cases} I = I_2 - I_2 \frac{V - V_2}{V_{oc} - V_2} & ; \text{if } V_2 \leq V \leq V_{oc} \\ I = I_{mp} + (I_2 - I_{mp}) \left( \frac{V - V_{mp}}{V_2 - V_{mp}} \right) & ; \text{if } V_{mp} \leq V \leq V_2 \\ I = I_1 + (I_{mp} - I_1) \left( \frac{V - V_1}{V_{mp} - V_1} \right) & ; \text{if } V_1 \leq V \leq V_{mp} \\ I = I_{sc} + (I_1 - I_{sc}) \left( \frac{V}{V_1} \right) & ; \text{if } 0 \leq V \leq V_1 \end{cases} \quad (3)$$

Where:  $V_1 = \frac{V_o}{2}$  and  $V_2 = \frac{V_o + V_m}{2}$

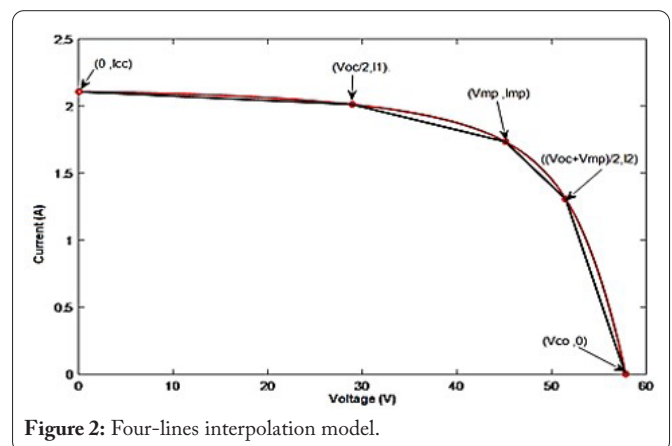


Figure 2: Four-lines interpolation model.

#### Look up table model

The LUT approach, is based on the I-V data of a real PV field under different climatic conditions. It required the acquisition of all possible I-V characteristics and the storage of

these data in appropriate unit. This approach avoids the use of mathematical links between current and voltage. The I-V characteristic is generated using direct linear interpolation of the experimental LUT tables. The generator of I-V characteristics in this paper is a LUT with four dimensions (V, I, G, T) (Figure 3). The current I is a function of the illumination G, temperature of module T and voltage V of PV panel.

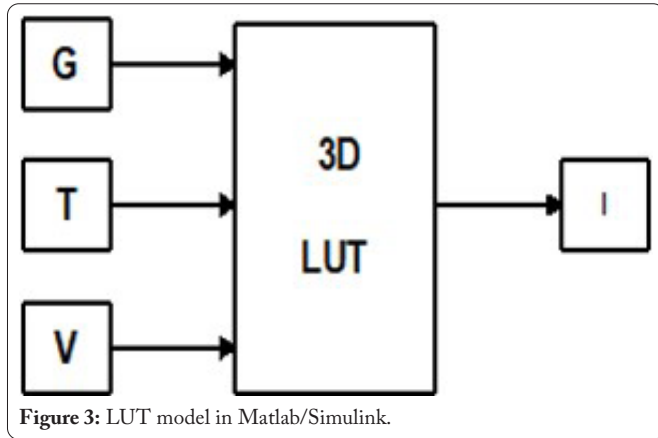


Figure 3: LUT model in Matlab/Simulink.

**Extraction of experimental particular points**

An appropriate exploitation of the models presented, requires a reliable and fast way for the determination of the particular points of the I-V characteristic. These points can be deduced directly from the experimental data base. The values obtained are precise, but the procedure is complex and costly in terms of calculation time [10].

An interesting alternative is to use adjusted equations obtained by smoothing the experimental measurements of the sampling site. These expressions make it possible to calculate the particular points according to the illumination and the temperature with sufficient precision while maintaining a fast execution speed [12].

To extract the parameters of all the models under study, we selected five particular points (Figure 4). These are evenly distributed over the I-V electrical characteristic.

We start by presenting a system of equations for estimating the currents  $I_{sc}$ ,  $I_1$ ,  $I_{mp}$  et  $I_2$ . Then we present an adaptive

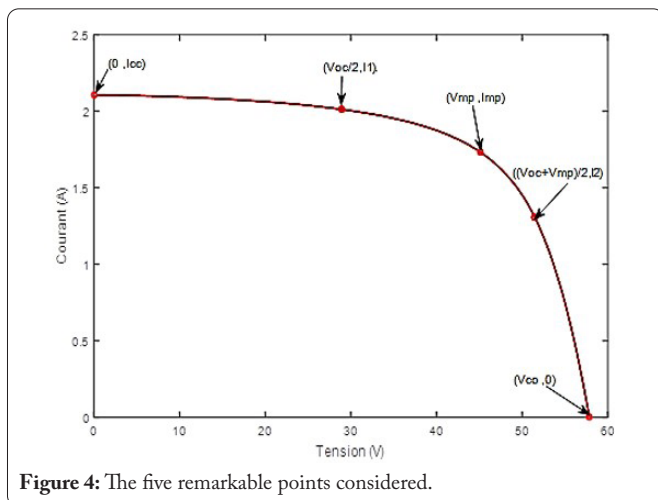


Figure 4: The five remarkable points considered.

neuro-fuzzy model ANFIS for the modeling of the tensions  $V_{mp}$  et  $V_{oc}$ .

**Proposed model for identifying currents  $I_{sc}$ ,  $I_1$ ,  $I_{mp}$ , and  $I_2$**

The linear system (Equation 4) has been developed to estimate these points as a function of the irradiance G and the temperature T of the PV source.

$$\begin{cases} I_{sc} = I_{scn} \left( a_1 + b_1 \frac{G}{G_n} + c_1 (T - T_n) \right) \\ I_{mp} = I_{mpn} \left( a_2 + b_2 \frac{G}{G_n} + c_2 (T - T_n) \right) \\ I_1 = I_{scn} \left( a_3 + b_3 \frac{G}{G_n} + c_3 (T - T_n) \right) \\ I_2 = I_{scn} \left( a_4 + b_4 \frac{G}{G_n} + c_4 (T - T_n) \right) \end{cases} \quad (4)$$

The coefficients ai, bi and ci are determined by the Levenberg-Marquardt algorithm [14] of the Fit function of Matlab.

**Proposed model for identifying tensions  $V_{oc}$  and  $V_{mp}$**

The modeling of the experimental voltages  $V_{oc}$  and  $V_{mp}$  by simple parametric equation 4 gives results that are not in a very good agreement with the experimental values. For that reason, we opted for ANFIS [15]. It is a 4-layer multilayer perceptron. Each layer consists of the realization of an action of the fuzzy inference system (FIS) [16].

$$\begin{cases} V_{oc} = V_{ocn} + a_4 V_t \log \left( \frac{G}{G_n} \right) + b_4 (T - T_n) \\ V_{mp} = V_{mpn} + a_5 V_t \log \left( \frac{G}{G_n} \right) + b_5 (T - T_n) \end{cases} \quad (5)$$

A Matlab code is developed for the generation of the ANFIS model according to the flowchart of figure 5.

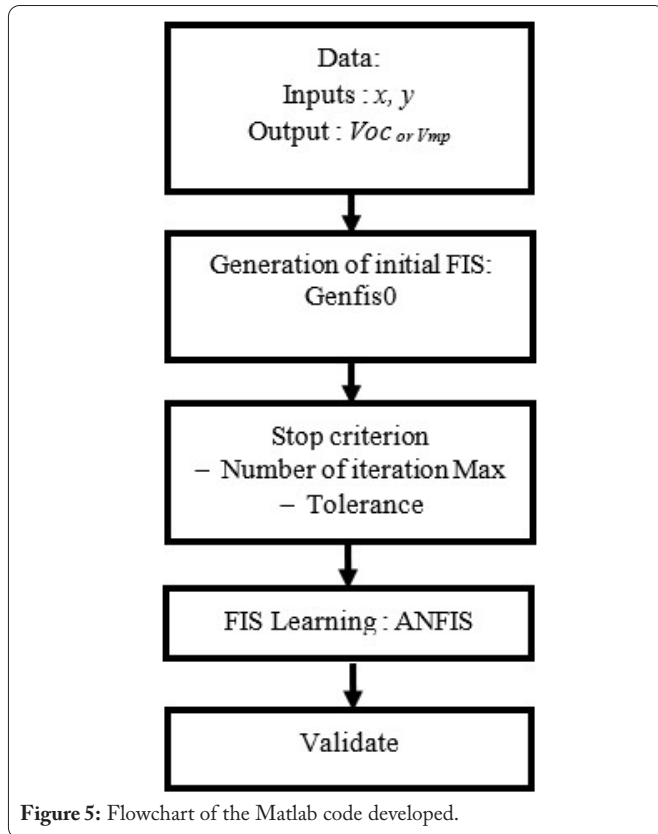
The adopted architecture has two inputs and a polynomial order 1 output, every input constitutes with two fuzzy sets of Gaussian type. The inputs x and y are expressed as functions of the irradiance G and of the temperature T of the PV panel according to the system of equation (6).

$$\begin{cases} x = \frac{G}{G_n} + T - T_n \\ y = (T + 273.15) \log \left( \frac{G}{(T + 273.15) G_n} \right) \end{cases} \quad (6)$$

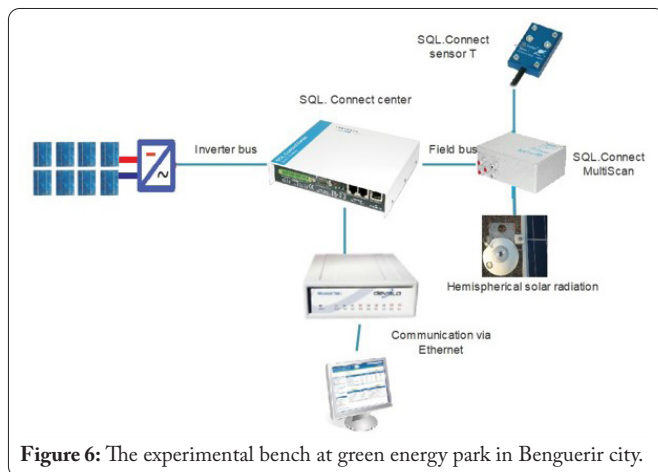
**Experimental validation and results**

**Experimental bench**

In this work, we used an up-to-date experimental database that represents the meteorological conditions of Morocco. This database is required for the validation of the proposed models. The experimental bench is located at green energy park in Benguerir city, allowing the recording of the I-V characteristics.



Data is captured with a sampling period throughout the day. It contains the temperature, illumination, voltage, and current data provided by the PV panels. The data is collected using a data acquisition server, a temperature sensor, an active load, and a sun sensor, as illustrated in figure 6.



For the experimental validation we used the I-V characteristics data for monocrystalline silicon technology. Table 1 summarizes the electrical characteristics of the PV technology studied.

**Evaluation criteria**

In order to evaluate the precision of the identified parameters of the studied panel, we calculated the coefficient of determination  $R_d$  and the root mean squared error (RMSE) [13].  $R_d$  allows to calculate the quality of linear regression according

**Table 1:** Typical electrical characteristics of solar module studied.

Module PV	TSM-DC01A [16]
Material	Mono-Si
$V_{oc}$ (V)	45.1
$I_{sc}$ (A)	5.52
$V_{mp}$ (V)	36.8
$I_{mp}$ (A)	5.18
$P_{max}$ (W)	190
$N_s$	72
$K_v$ %/°C	-0.35
$K_i$	0.05%/°C
$K_{mp}$ (%/°C)	-0.45
$N_{OCT}$ (°C)	46

to equation 7. It describes the effect of the independent variable on the dependent variable.  $R_d$  is taken between 0 and 1.

$$R_d = 1 - \frac{\sum_{i=1}^N (G_{mes}(i) - G(i))^2}{\sum_{i=1}^N (G_{mes}(i) - \overline{G_{mes}})^2} \tag{7}$$

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

The RMSE describes the difference between the values measured and the values predicted by a developed model. It is calculated according to equation 8.

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (G_{i\ mes} - G_{i\ cal})^2}{N}} \tag{8}$$

Finally, the average computation time ( $t_{CPU}$ ) is calculated in order to estimate the speed execution of each processed approach.

**Results and Discussion**

**Results of the identification of the I-V curve's five points**

**Identification of currents**

Figure 7 shows a comparison between the experimental values of currents and the values predicted by the system of equations (3) for the TSM-DC01A solar module.

The results of the figure 7 clearly show a very good agreement between the parameters predicted by the models (3) proposed and the experimental values.

**Identification of Tensions  $V_{oc}$  and  $V_{mp}$**

The values predicted by the ANFIS model, and the simple parametric equations (4) are compared with the experimental values in figure 8.



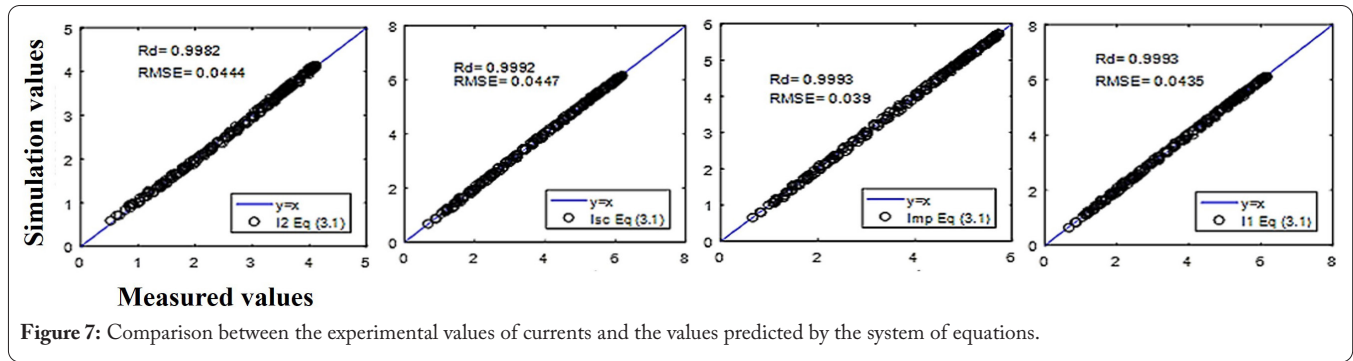


Figure 7: Comparison between the experimental values of currents and the values predicted by the system of equations.

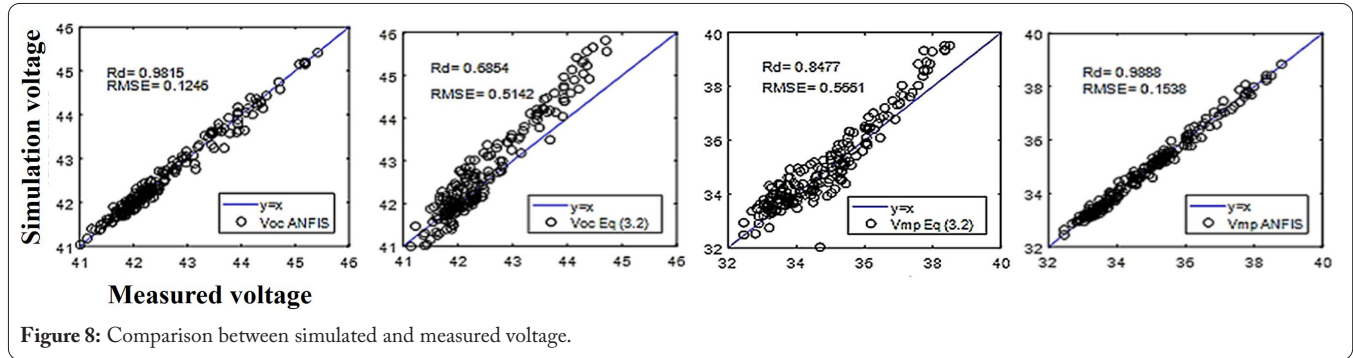


Figure 8: Comparison between simulated and measured voltage.

The results of figure 8 show that the performance of ANFIS model is higher at the level of accuracy and the concordance between measurement and modeling for the two voltages  $V_{oc}$  and  $V_{mp}$ .

To confirm the quality of the predictions of the proposed ANFIS system, we calculated in table 2, the coefficient  $R_d$  and the error RMSE.

**Table 2:** Coefficient of determination ( $R_d$ ) and the RMSE.

Parameter	Model ANFIS		Model (Equation 4)	
	$R_d$	RMSE	$R_d$	RMSE
$V_{oc}$	0.9815	0.1246	0.6854	0.5142
$V_{mp}$	0.9888	0.1538	0.8477	0.5661

**Results of the characteristic I-V**

The experimental characteristics, based on the experimental data collected from the green energy park in Benguerir city, are compared to the simulation results of models that have been developed. The results obtained shows the most efficient model, which gives the best correlation compared to the experimental data, for the monocrystalline technology.

Figure 9, figure 10, and figure 11 show the results of I-V curves of PV panels, using the 5-parameters, 4-lines, and LUT approaches, respectively. The results are given for different levels of temperature and illumination.

For all developed models, it is clearly shown that the simulated values agree with the experimental measurements. They are literally identical in some power range. Table 3 summarizes the calculated values of the  $R_d$ , RMSE, and the average computation time  $t_{CPU}$ , in order to evaluate the performance of each model.

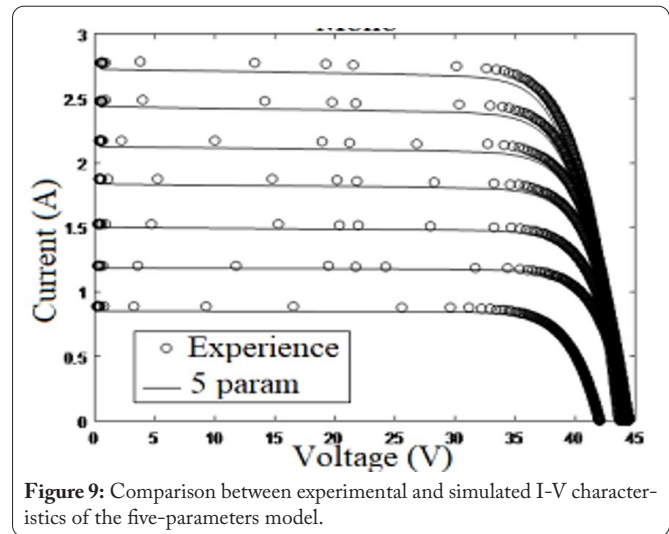


Figure 9: Comparison between experimental and simulated I-V characteristics of the five-parameters model.

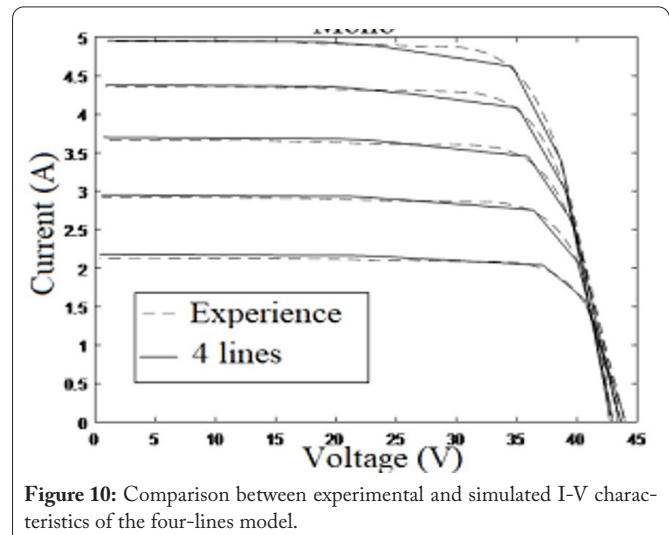
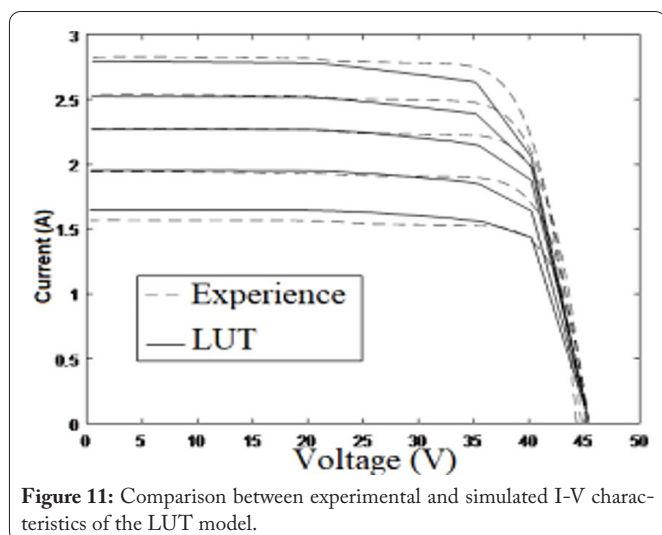


Figure 10: Comparison between experimental and simulated I-V characteristics of the four-lines model.



**Figure 11:** Comparison between experimental and simulated I-V characteristics of the LUT model.

The analysis of table 3, shows a high compromise in precision and computation time by the five parameters approach ( $R_d = 0.9950$ ,  $t_{CPU} = 0.0677$  s), and 4-lines model ( $R_d = 0.9834$ ,  $t_{CPU} = 0.0372$  s). The LUT model is less precise, but it has the best computation time ( $R_d = 0.9322$ ,  $t_{CPU} = 0.0082$  s).

**Table 3:** Summary of the performance of models studied.

Technology	Criterion	5 parameters	4 lines	LUT
TSM-DC01A	$R_d$	0.9950	0.9834	0.9322
	RMSE	0.1080	0.1974	0.3989
Mono-Si	$t_{CPU}$ (s)	0.0677	0.0372	0.0082

## Conclusion

The aim of this paper is the experimental validation applied to PV panel models. Three modeling approaches are developed in order to solve the parameters estimation problem. The developed approaches are based on the electrical circuit method, the linear interpolation method, and the LUT model. The identification of the currents  $I_{sc}$ ,  $I_1$ ,  $I_{mp}$ , and  $I_2$  is estimated by using a system of equations based on the adjusting of experimental data. The problem of estimating  $V_{oc}$  and  $V_{mp}$  voltages is solved by a developed ANFIS neuro-fuzzy model. The results show the high accuracy and the concordance between the measurement and the modeling by the neuro-fuzzy system ANFIS. This confirms the efficiency and the capacity of identification of this model. In order to find the high accuracy approach, a comparative study has been performed. The results have demonstrated that the five parameters approach and the four-lines model are fast, accurate, and straight-forward. Since the low-cost microcontrollers has memory and calculating limitation issues, the four lines approach is considered the most appropriate for modeling I-V curves of the PV panel with low-cost microcontrollers.

## Acknowledgements

None.

## Conflict of Interest

None.

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