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A simple behavioural model for solar module electric characteristics based on the first order system step response for MPPT study and comparison

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ABSTRACT

This paper proposes a simple behavioural model for photovoltaic modules. This model can be used to characterise current–voltage and power–voltage outputs of photovoltaic modules as a function of solar module temperature and solar radiation intensity. Such a model cannot only serve as a tool to study the *I–V* curve and its maximum power point characteristics but also to design photovoltaic power systems and power converters used for PV applications. It can also be used for performance rating. This model has first been developed to study the maximum power point characteristics by exploring the existing similarity between the photovoltaic module *I–V* characteristic and the step response of a first-order system. It has the advantage to use only parameters that are available on the data sheet. To construct the proposed model, measured *I–V* curves at different working conditions (solar radiation intensity and ambient temperature) were used, then other *I–V* characteristics corresponding to different working conditions have been used to validate it. The obtained results show a high degree of correspondence between the real outdoor measured *I–V* characteristics and those given by the developed model.

1. Introduction

Solar energy is considered to be the energy source of the future. It is clean, abundant and renewable. Solar modules are the key component in all photovoltaic power systems. They are used to convert solar energy to electric energy. So, the knowledge of the PV module behaviour and characteristics is crucial and needed for photovoltaic systems and applications design. This knowledge is of a special interest when the maximum power is required from the PV module. This is particularly the case knowing that the power delivered to the load is strongly dependant on the working temperature, solar radiation intensity and aging.

To characterise their products in terms of electrical properties and performance, PV manufacturers generally present some *I–V* curves of the module and some typical values such as short circuit current, open circuit voltage and maximum power point properties (MPP current, MPP voltage and MPP power). These values are usually given at the Standard Test Conditions (STCs) also known as Standard Reporting Conditions (SRC) which correspond to a module temperature equal to 25 °C, a solar radiation intensity (G_{STC}) of 1000 W/m^2 at 1.5 air mass spectral distribution. These module characteristics are also given for the Nominal Operating Cell Temperature (NOCT) also known as the Standard Operating Conditions (SOC). These correspond to a solar radiation intensity (*G*NOCT) of 800 W/m^2 and an ambient temperature of 20 °C with an average wind speed of 1 m/s, furthermore the cell or module is in an electrically open circuit state, the wind orientation is parallel to the plane of the array, and all sides of the array are fully exposed to the wind. To deduce the module electrical characteristics corresponding to working conditions other than STC or NOCT, temperature coefficients are available in the manufacturer data sheet.

Several models were developed in order to describe and explain the PV modules electrical characteristics. These models are generally analytical equations based on a physical description which formulates photovoltaic generated current by means of the working voltage, the ambient temperature and the solar radiation intensity. Some of the used parameters are not available on the corresponding module data sheet, additional work is often necessary to compute them and it is an arduous process to determine their exact values [1,2]. In some other cases, empirical or semi empirical models are used, where the parameters and coefficients are the results of complex fitting procedures and approximations [3,4].

To avoid the parameters approximation problems, this paper presents a new and simple behavioural model based only on data sheet parameters. This model can facilitate photovoltaic power systems study, design and analysis. The developed model is based on the existing shape similarity between the *I–V* photovoltaic module characteristic and the step response of a first order system. The parameters of this system are expressed as a function of those

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Nomenclature

PV	photovoltaic	G	solar radiation intensity (W/m^2)
PVG	photovoltaic generator	R_s	series resistance (Ω)
P	power (W)	R_{sh}	shunt resistance (Ω)
P_{max}	maximum power (W)	T	temperature (°C)
MPP	maximum power point	T_m	PV module's temperature (°C)
V	voltage (V)	T_a	ambient temperature (°C)
V_{oc}	open circuit voltage (V)	τ_v	rate of change for the voltage (V)
V_{mpp}	maximum power point voltage (V)	τ_i	rate of change for the current (A)
I	current (A)	FF	the fill factor
I_{sc}	short circuit current (A)	NOCT	Nominal Operating Cell Temperature (°C)
I_{mpp}	maximum power point current (A)	α	the percentage of the effective solar radiation intensity
k	Boltzmann' constant (JK^{-1})	γ	the shading linear factor
k_i	current proportional constant	TC_v	open circuit voltage temperature coefficient (V/°C or %/°C)
q	the elementary charge (C)		
n_1, n_2	ideality factors	TC_i	short circuit current temperature coefficient (V/°C or %/°C)
I_D	diode reverse saturation current (A)		
I_{ph}	photogenerated current (A)	TC_{Vmpp}	MPP voltage temperature coefficient (V/°C or %/°C)

given in the module data sheet and which the corresponding expressions were evaluated by considering measured *I–V* curves for different working temperatures and solar irradiation intensity levels.

The developed modelling procedure is fully explained, it can easily be used to construct a model corresponding to some measured *I–V* characteristics. This kind of model can be used to simulate the studied photovoltaic modules and arrays for eventual parameters rating, performance, behaviour and functioning analysis.

2. Existing models

Several models have been presented in order to explain and describe the photovoltaic conversion. The most famous of them are:

2.1. The one-diode analytical model

The one diode model is the most widely used equivalent circuit for PV cells and modules. This model, shown in Fig. 1, a, consists of a lumped series resistance, a shunt resistance and one diode. The analytical formulation of this model, called the five parameter model, is expressed as follow:

$$I = I_{ph} - I_D \cdot \left(e^{\frac{q(V+R_S \cdot I)}{n \cdot k \cdot T}} - 1\right) - \frac{V + R_S \cdot I}{R_{sh}} \qquad (1)$$

2.2. The two-diodes analytical model

A second diode shown in Fig. 1b is added to the one-diode based model in order to better fit the *I–V* curves characterising the photovoltaic cells and modules output characteristics. This is achieved by taking into account the recombination characteristics of the charge carriers in the space-charge zone. The two diode based model expression is given by:

$$I = I_{ph} - I_{D1} \cdot \left(e^{\frac{q(V+R_S \cdot I)}{n_1 \cdot k \cdot T}} - 1\right) - I_{D2} \cdot \left(e^{\frac{q(V+R_S \cdot I)}{n_2 \cdot k \cdot T}} - 1\right) - \frac{V + R_S \cdot I}{R_{sh}} \qquad (2)$$

The models mentioned previously require several parameters, but only a few of these (temperature coefficients, short circuit current and open circuit voltage) are available from the manufacturers' data sheets. Unfortunately other parameters required by these models are not available, among these are the photo current, the ideality factor, the diode reverse saturation current, the series and shunt resistances, etc. To calculate these parameters, two approaches are basically used: a numerical one, in which the parameters are calculated iteratively, the second involves the extraction of the parameters analytically [5–8]. In order to overcome this problem and to simplify some photovoltaic application analysis, behavioural models have been developed. The advantage of those models is the use of the electrical characteristics provided by the solar module data sheet. As an example we have the next two models.

2.3. Behavioural models

In [9], the proposed model takes into account the temperature and the percentage of effective intensity of the light over the solar module, a shading linear factor, the short circuit current and the open circuit voltage. The *I–V* characteristic of the presented solar module is described as:

$$I(V) = \alpha \cdot I_{\max} \cdot \tau_i - \alpha \cdot I_{\max} \cdot \tau_i \cdot \exp\left(\frac{V}{b \cdot (\gamma \cdot \alpha + 1 - \gamma) \cdot (V_{\max} + \tau_V)} - \frac{1}{b}\right) \qquad (3)$$

With α the percentage of the effective solar radiation intensity and γ the shading linear factor defined as the percentage of voltage loss from a maximum to a minimum intensity of solar radiation as indicated in (4) and (5) respectively. $I_{\max}$, $V_{\max}$ are the ideal maximum current and voltage at 25 °C and 1000 W/m^2, while $I_{\min}$ and $V_{\min}$ are the ideal maximum current and voltage at 25 °C and 200 W/m^2.

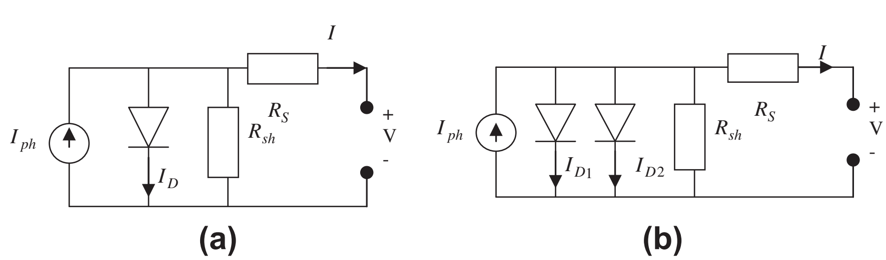


Fig. 1. Diode based solar cell models, (a) ideal model, (b) one diode model, and (c) two diodes model.

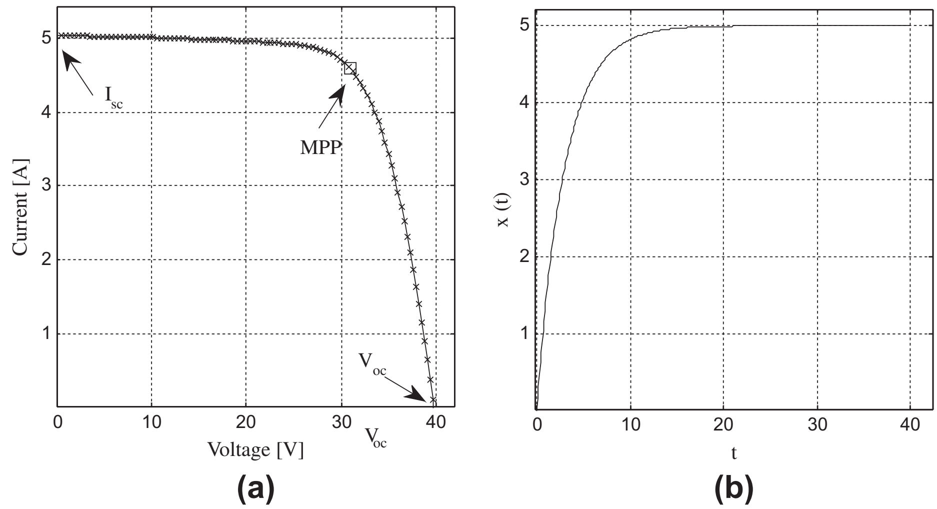


Fig. 2. Shape similarity between (a) I–V PV module characteristic and (b) the first order system step response.

$$\alpha = \frac{G}{G_{STC}} \tag{4}$$

$$\gamma = 1 - \frac{V_{\min}}{V_{\max} + \tau_V} \tag{5}$$

However, according to [10], this model has a drawback as it requires the calculation of decreasing module voltages with increasing solar radiation for cell temperatures above 60 °C; this is dictated by the definition of the shading linear factor. To overcome this problem, the author has presented another behavioural model for PV modules, for which the electric characteristics are described by the following equation:

$$I(G,T,V) = \frac{G}{1000} \cdot I_{sc} \cdot \tau_i(T) \cdot \left[\frac{1 - \exp\left(\frac{V}{b \cdot \left(1 + \frac{V_{\max} - V_{\min}}{V_{\max}} \cdot \frac{G - G_{\max}}{G_{\max} - G_{\min}}\right) \cdot (V_{\max} + \tau_V(T))} - \frac{1}{b} \right)}{1 - \exp(-\frac{1}{b})} \right] \tag{6}$$

The parameter b is a fitting parameter for the model. It acts on the maximum power point of the I–V curve. To determine this parameter, the author suggests to employ a guess value, e.g. $b = 0.09$ and then calculate V_{mpp} at STC by solving Eq. (8) obtained by using the MPP condition $\frac{dP}{dV} = 0$ from Eq. (7). Then Eqs. (6) and (7) are used to calculate I_{mpp} and P_{mpp} at STC. These values have to be compared with those available on the data sheet and the fitting parameter b is then adjusted iteratively to minimise the error of P_{mpp} at STC.

$$P(G,T,V) = V.I(G,T,V) \tag{7}$$

$$0 = 1 - \left[1 + \frac{V_{mpp}}{b \cdot \left(1 + \frac{V_{\max} - V_{\min}}{V_{\max}} \cdot \frac{G - G_{\max}}{G_{\max} - G_{\min}}\right) \cdot (V_{\max} + \tau_V(T))} \right] . \exp\left(\frac{V_{mpp}}{b \cdot \left(1 + \frac{V_{\max} - V_{\min}}{V_{\max}} \cdot \frac{G - G_{\max}}{G_{\max} - G_{\min}}\right) \cdot (V_{\max} + \tau_V(T))} - \frac{1}{b} \right) \tag{8}$$

It is important to note that both the behavioural models presented here use a constant curve parameter named b. If the method by which this parameter is calculated is not mentioned in [9] for the first model, its iterative adjustment for the second model is expensive in terms of computing time, knowing that Eq. (8) cannot be solved analytically. Furthermore, a study of the outdoor measured I–V module characteristics showed that the fitting parameter value is strongly dependent on the working conditions. Thus the best fitting parameter value corresponding to STC is not adequate for other I–V characteristic. That is why the translation of the I–V characteristic from a working condition to another is so complicated.

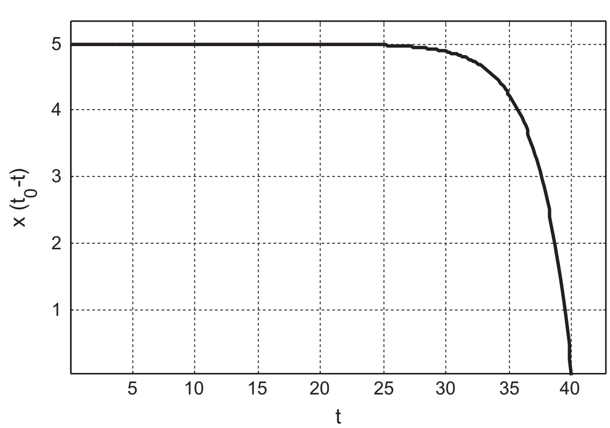


Fig. 3. The first order system step response with linear abscise variable transformation.

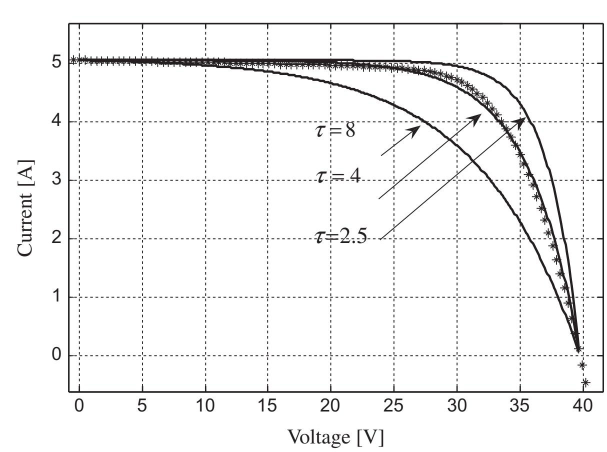


Fig. 4. Influence of the voltage constant value on the I–V model curve.

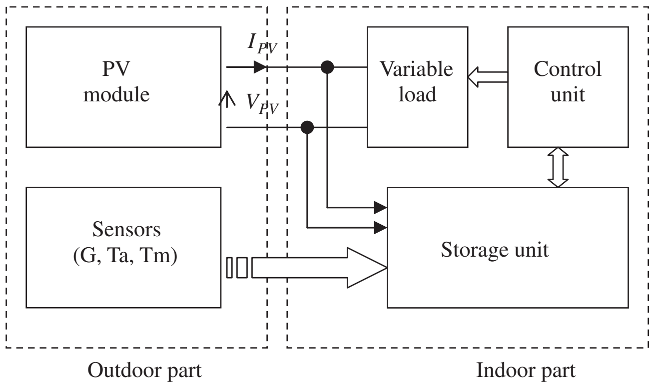


Fig. 5. Diagram of the experimental device.

To exploit these behavioural models, manufacturers must give more information about the *I–V* module characteristics corresponding to other operating conditions than those corresponding to 200 W/m^2 solar radiation intensity and 25 °C ambient temperature. That is why a new behavioural model for photovoltaic module has been developed.

3. The developed model

3.1. The basic idea of the proposed modelling method

It is well known that for a given working condition, ambient temperature and solar radiation intensity, there exists only one *I–V* curve with specific points (I_{sc}, MPP, V_{oc}). The basic idea of our modelling task is to formulate the I-V curve equation for a specific working condition by means of those specific points and the well known module characteristics at Standard Test Conditions available on its data sheet. It is another way to tackle the sliding I-V curves problem. By using the well known Eqs. (9) and (10) [9,10], the corresponding (I_{sc}, V_{oc}) to the new working condition can easily be determined according to Eqs. (11) and (12).

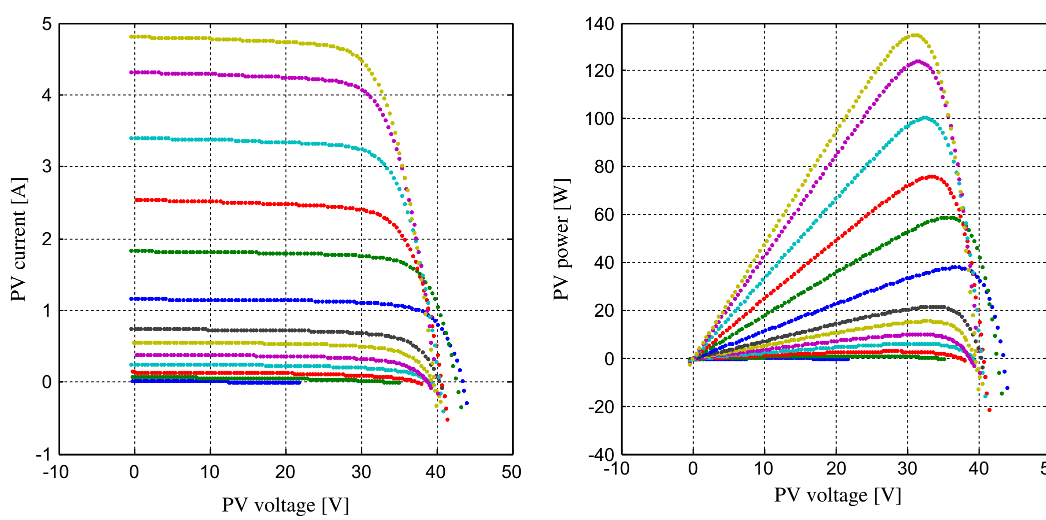


Fig. 6. Example of some measured *I–V* and *P–V* curves.

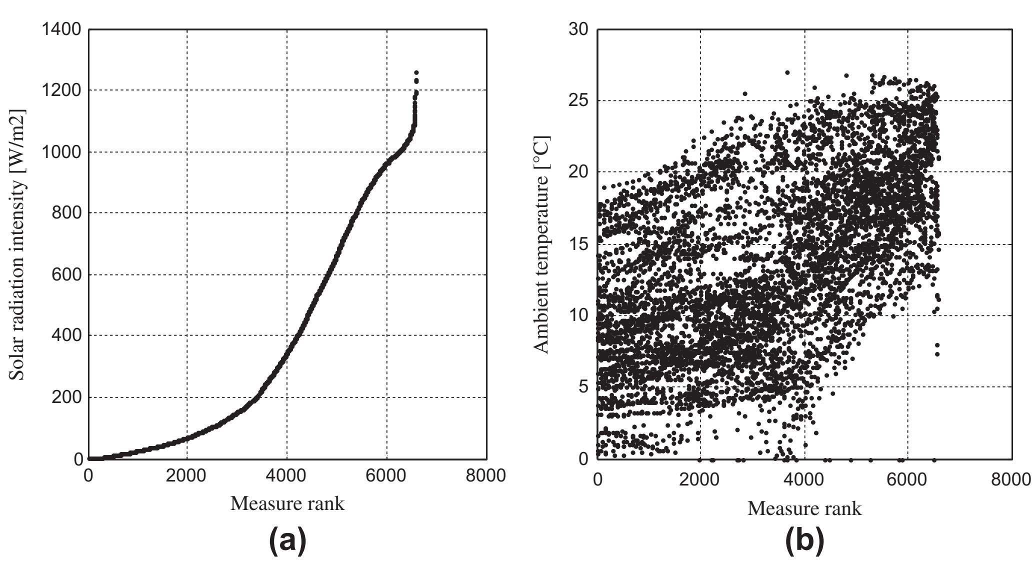


Fig. 7. The measured variations of the working conditions.

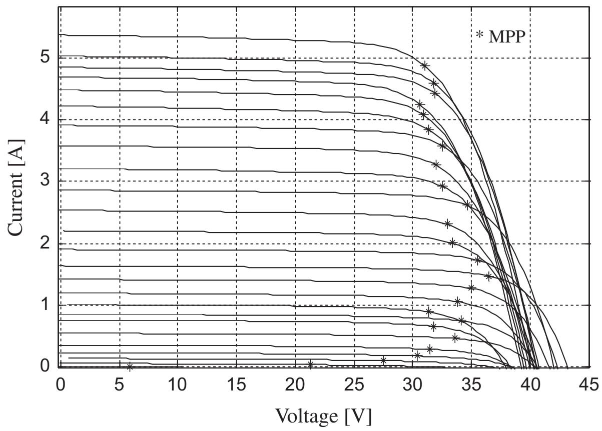


Fig. 8. The selected *I–V* characteristic curves for the constant voltage analysis and study.

$$\tau_i(T) = 1 + \frac{TC_i}{100\%}(T - \mathrm{NOCT}) \tag{9}$$

$$\tau_V(T) = TC_V \cdot (T - \mathrm{NOCT}) \tag{10}$$

$$I_{sc} = \frac{G}{G_{STC}} \cdot I_{sc\_STC} \cdot \tau_i \tag{11}$$

$$V_{oc} = V_{oc\_STC} + \tau_V \tag{12}$$

To develop the *I–V* curve model for a specific working condition corresponding to particular (I_{sc}, V_{oc}) points, the existing similarity between the *I–V* characteristic and the first order system step response shapes (Fig. 2) has been exploited. This feature is more obvious by considering a linear transformation in the abscise variable (Eq. (14)) for the mathematical expression of the first order system step response (Eq. (13)) as illustrated in Fig. 3.

$$x = E \cdot (1 - e^{-t/\tau}) \tag{13}$$

$$x = E \cdot (1 - e^{(t'-t_0)/\tau}) \tag{14}$$

By using condition $I(V_{oc}) = 0$, we obtain:

$$t_0 = V_{oc} \tag{15}$$

The model equation becomes:

$$I = E \cdot (1 - e^{(V - V_{oc})/\tau}) \tag{16}$$

The model parameter E is the maximum current value corresponding to $V = -\infty$. It must not be confused with the short circuit current value. By using the condition $I(0) = I_{sc}$, the maximum current value can be determined as follows:

$$E = I_{\max} = \frac{I_{sc}}{1 - e^{(-V_{oc}/\tau)}} \tag{17}$$

By substituting E and t_0 by their respective expressions, the model can be formulated by relation (18). The parameter τ defined as a voltage constant. It determines how the current evolves from $I = I_{sc}$ to $I = 0$. It influences the *I–V* curve slopes near I_{sc} and V_{oc}. It also determines the position of the maximum power point and the *I–V* curve behaviour around it as described by Eqs. (19)–(21) and shown in Fig. 4

$$I(V) = \frac{I_{sc}}{1 - e^{(-V_{oc}/\tau)}} \cdot (1 - e^{(V - V_{oc})/\tau}) \tag{18}$$

$$\left.\frac{dI}{dV}\right|_{V=V_{mpp}} = \frac{-I_{sc}}{\tau(1 - e^{(-V_{oc}/\tau)})} e^{(V_{mpp} - V_{oc})/\tau} \tag{19}$$

$$\left.\frac{dI}{dV}\right|_{V=V_{oc}} = \frac{-I_{sc}}{\tau(1 - e^{(-V_{oc}/\tau)})} \tag{20}$$

$$\left.\frac{dI}{dV}\right|_{V=0} = \frac{-I_{sc}}{\tau(1 - e^{(-V_{oc}/\tau)})} e^{(-V_{oc})/\tau} \tag{21}$$

3.2. Experimental and results

To determine the constant voltage mathematical expression, some outdoor measured *I–V* characteristics were considered and studied. The identification procedure was based on the sets of data (voltage, current, temperature and irradiance intensity) obtained in real working conditions from the characterisation bench of INES (Institut National de l'énergie solaire, CEA, France). As illustrated in Fig. 5, a data acquisitions system and the corresponding software were operated to retrieve for the studied PV module the experimental voltages and currents at different meteorological conditions when the working point was changed through a variable load.

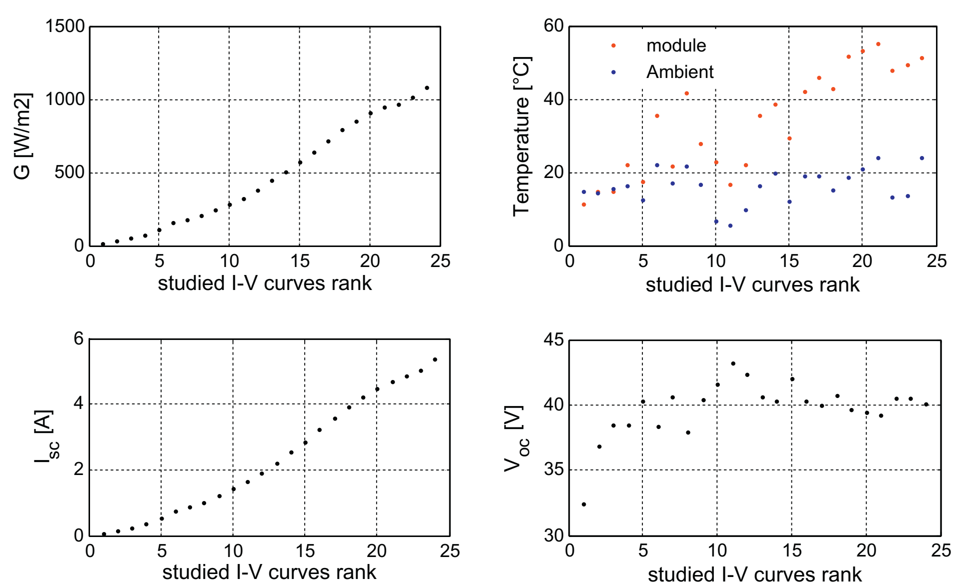


Fig. 9. The selected *I–V* characteristic curves' working conditions and the corresponding short circuit current and open circuit voltage values.

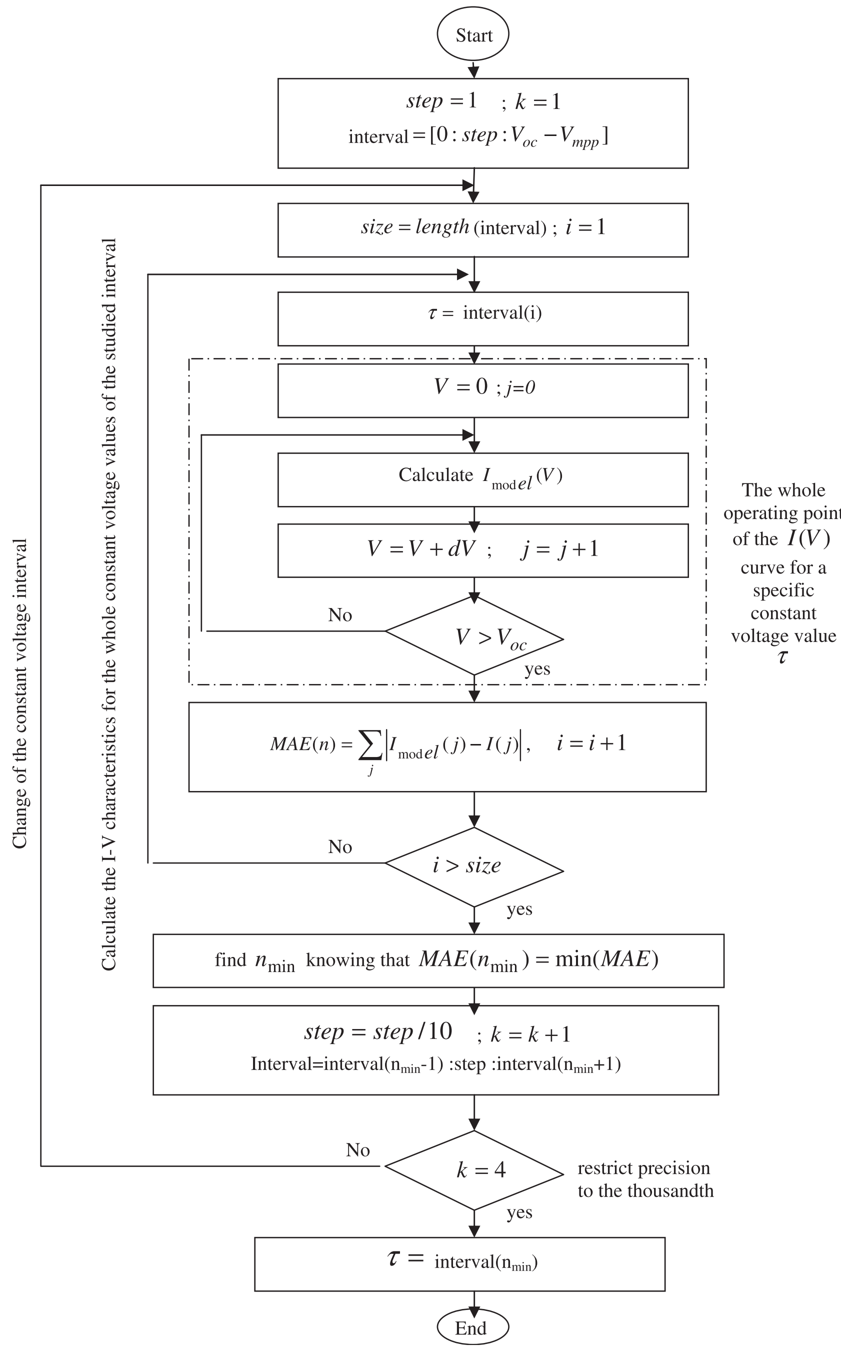


Fig. 10. Flowchart for determining the best constant value.

One characteristic is recorded every 5 min and is represented by one hundred points as shown by Fig. 6. The experimental data sets were then analysed and classified according to different irradiance and temperature in order to obtain homogeneous current–voltage characteristics covering a large interval of working conditions' variations as illustrated in Fig. 7a and b.

To study the existing correlation between the constant voltage and the working conditions, some measured *I–V* characteristics were chosen to represent a large variation interval for the solar radiation intensity and ambient temperature, this leads to a large variation interval for the short circuit current and open circuit voltage as illustrated by Figs. 8 and 9.

The best constant voltage value was calculated by iteration for each *I–V* curve in order to minimise the Mean Absolute Error (MAE) between the actual *I–V* characteristic and that given by the developed model according to the flowchart represented by Fig. 10. The MAE was calculated according to relation (22), with *N* the number of measures for the studied *I–V* characteristics. Fig. 11 shows an example of the MAE evolution during the identification phase of the best constant voltage value in the search interval. As illustrated in Fig. 12, the constant voltage value varies from one working condition to another. It is clear that this constant voltage value depends on the working condition and thereafter is a function of their image, i.e. the (I_{sc}, V_{oc}) couple. These values are close to those determined by Eq. (23) as shown in the same figure.

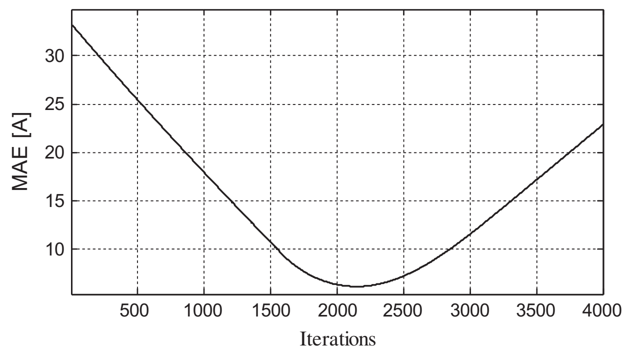


Fig. 11. An example of MAE evolution during the search procedure of the best constant voltage value.

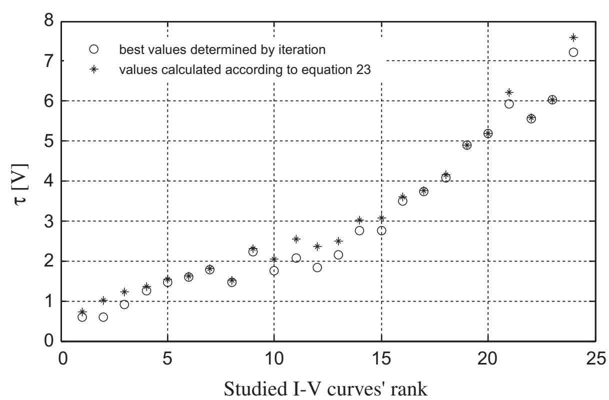


Fig. 12. The constant voltage evolution according to the working condition variation.

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|I_{\text{module}} - I_{\text{model}}| \tag{22}$$

Using Eq. (14) and the maximum voltage coefficient temperature TC_{Vmpp}, the constant voltage expression can be calculated according to Eq. (24). And then for every working condition, the $I(V)$ curve evolution can be expressed using Eq. (25)

$$\tau = \frac{V_{oc} - V_{mpp}}{2,16} \tag{23}$$

$$\tau = \frac{(V_{oc\_STC} - V_{mpp\_STC}) + (T - T_N)\cdot(TC_V - TC_{Vmpp})}{2,16} \tag{24}$$

$$I = \frac{\frac{G}{G_{STC}}\cdot I_{sc\_STC}\cdot\tau_i}{1 - e^{\left(\frac{-2.16\cdot(V_{oc\_STC}+\tau_V)}{(V_{oc\_-STC}-V_{mpp\_STC})+(T-T_N)\cdot(TC_V-TC_{Vmpp})}\right)}}\cdot\left[1 - e^{\left(\frac{2.16\cdot(V-V_{oc\_STC}-\tau_V)}{(V_{oc\_-STC}-V_{mpp\_STC})+(T-T_N)\cdot(TC_V-TC_{Vmpp})}\right)}\right] \tag{25}$$

The use of the MPP voltage temperature coefficient (TC_{Vmpp}) for the constant voltage determination in Eq. (23) can be substituted by the Fill Factor (FF) parameter as noted in Eq. (26). This is achieved by combining Eq. (28) which determines the Fill Factor expression and Eq. (29) describing the existing proportional linearity between the short circuit current and the MPP current as illustrated in Fig. 13.

$$\tau = \frac{1 - k'\cdot FF}{2.16} \tag{26}$$

where

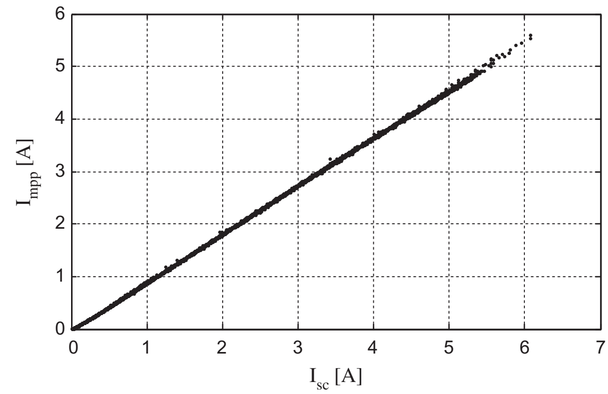


Fig. 13. The MPP current versus the short circuit current.

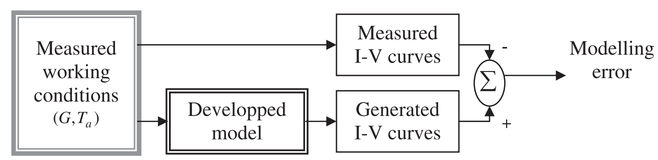


Fig. 14. The schematic diagram of the validation procedure.

$$k' = \frac{1}{k} \tag{27}$$

$$FF = \frac{V_{mpp}\cdot I_{mpp}}{V_{oc}\cdot I_{sc}} \tag{28}$$

$$k = \frac{I_{mpp}}{I_{sc}} = \frac{I_{mpp\_STC}}{I_{sc\_STC}} \tag{29}$$

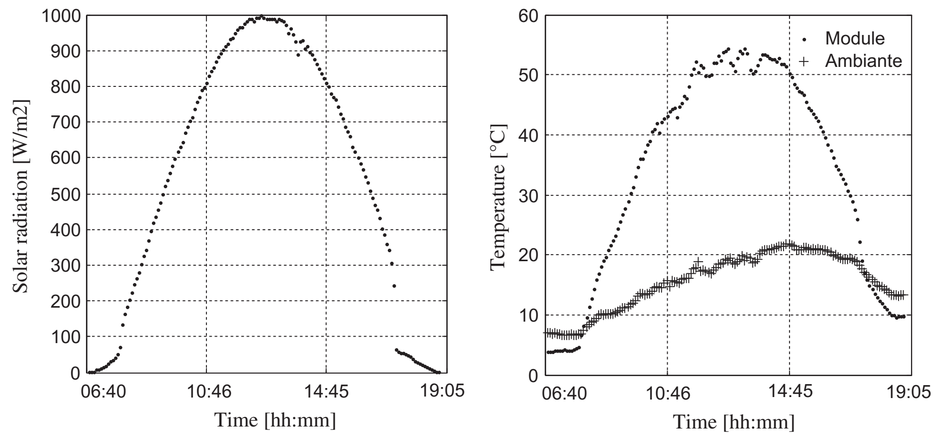
4. Model validation and discussion

To discuss the developed model efficiency; we considered several tests corresponding to different working conditions from those used in the precedent section. Those working conditions were used as inputs to the developed PV module's model, and its outputs was then compared to the real outputs of the studied PV module which were measured and stored using the previously described experimental setup. The schematic diagram of the comparison method is illustrated in Fig. 14 while Fig. 15 illustrates the daily collected data by the experimental setup used for the validation test, in which the solar radiation intensity, ambient temperature, module temperature and the evolution of I–V curves are all plotted.

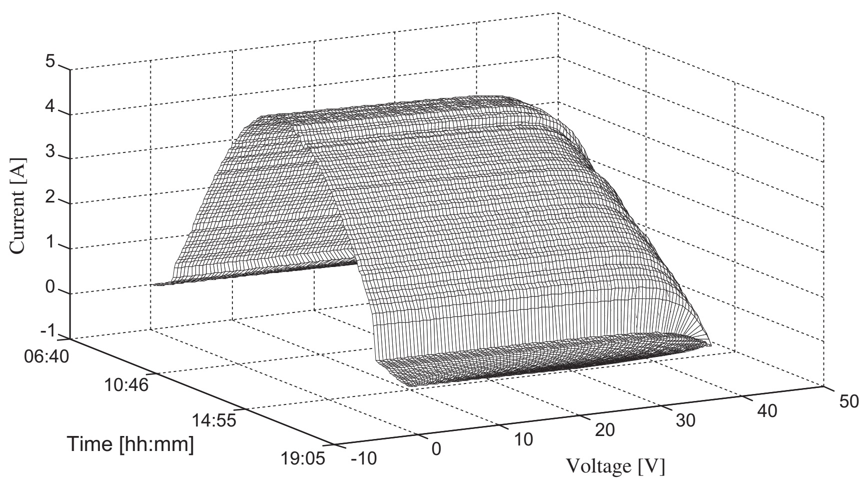
Fig. 16 illustrates the evolution of the constant voltage during the test day time. The resulting modelling error is shown in Fig. 17. For better visualisation and comparison of the previous results, some measured I–V curves and modelled ones are illustrated in 2D shapes in Fig. 18 with the corresponding modelling error.

As we can see, the evolution of the modelling error shows a maximum difference around the maximum power point. This error has two origins: firstly, the tolerance of the electrical parameters available on the manufacturer datasheet which influence the model parameters values, and thus its precision. Secondly, the intrinsic proposed model limitation. In fact, the best constant voltage values determined by a fitting process present a similar behaviour around the MPP.

In order to overcome the new model limitation, we plan to investigate an extended model based on the step response of a second order system. In this model a second exponential term is added with a second voltage constant that will allow a better fit of the PV module characteristic around the maximum power point.



(a) Working conditions evolution.



(b): I-V curves evolution.

Fig. 15. Evolution of the working conditions and the measured and stored *I–V* characteristics of the studied polycrystalline PV module, period from 06 h:40 to 18 h:50 of the day 18/03/2009.

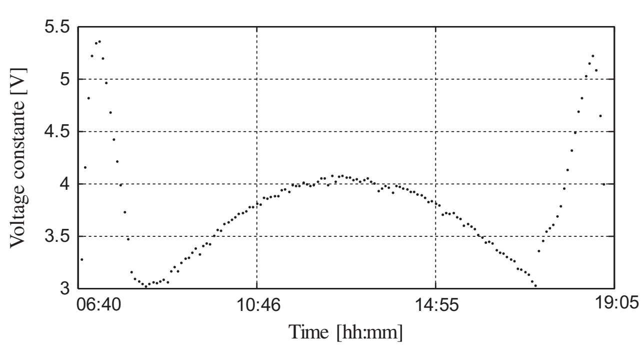


Fig. 16. the evolution of the constant voltage during the test day according to the working conditions' changes.

To summarise this section, we can highlight those two points:

– Firstly, the presented model is not perfect but simple, it is easy to program, to simulate and use for PV systems analysis and conception.
– Secondly, this modelling study and the existing likeness between the final expression of the developed model and those presented in [9,10] permitted us to understand the fundaments of those last ones, to know the limitation of the model and to find the solution that consists in adding a second exponential aiming to refine the model's outputs around the MPP, and especially to discover that contrary to what has been evoked in [9,10], the constant voltage cannot have the same value for all possible working conditions.

5. Conclusion and perspectives

A new and simple behavioural model for photovoltaic module was developed and presented in this paper. Based on the step response of a first order system, the new model exploits only the parameters available on the manufacturer's data sheet. No fitting and no approximation is needed to model the PV module characteristics at any working condition (ambient temperature, solar radiation intensity). The model simplicity greatly simplifies its implementation and reduces considerably the programme time execution; it then facilitates the photovoltaic systems design, study, analysis and rating.

This study shows the importance of the existing correlation between the PV module behavioural models precision and the parameters provided by the manufacturers describing the MPP of the *I–V* characteristic, the Fill Factor and the maximum voltage temperature coefficient. It's clear that those parameters are not constant and change with solar radiation and temperature variations. It will be more useful to generalise their availability for the whole modules datasheets and to precise their variation over wider working conditions intervals.

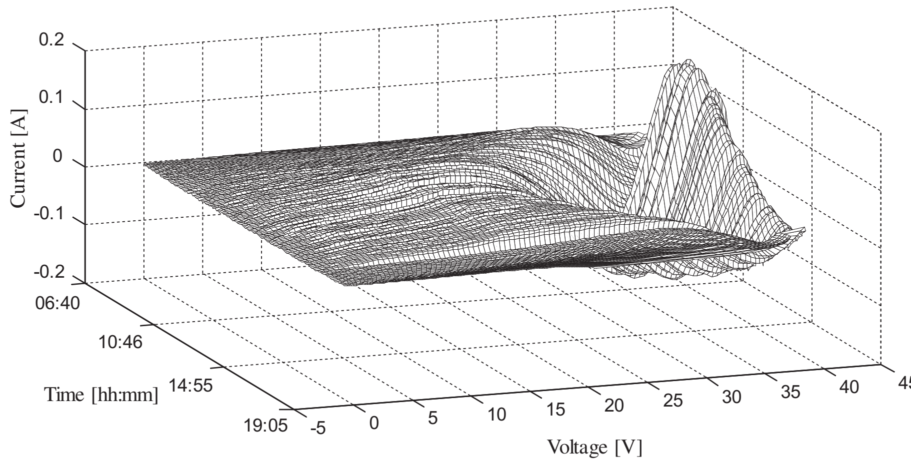


Fig. 17. The modelling error.

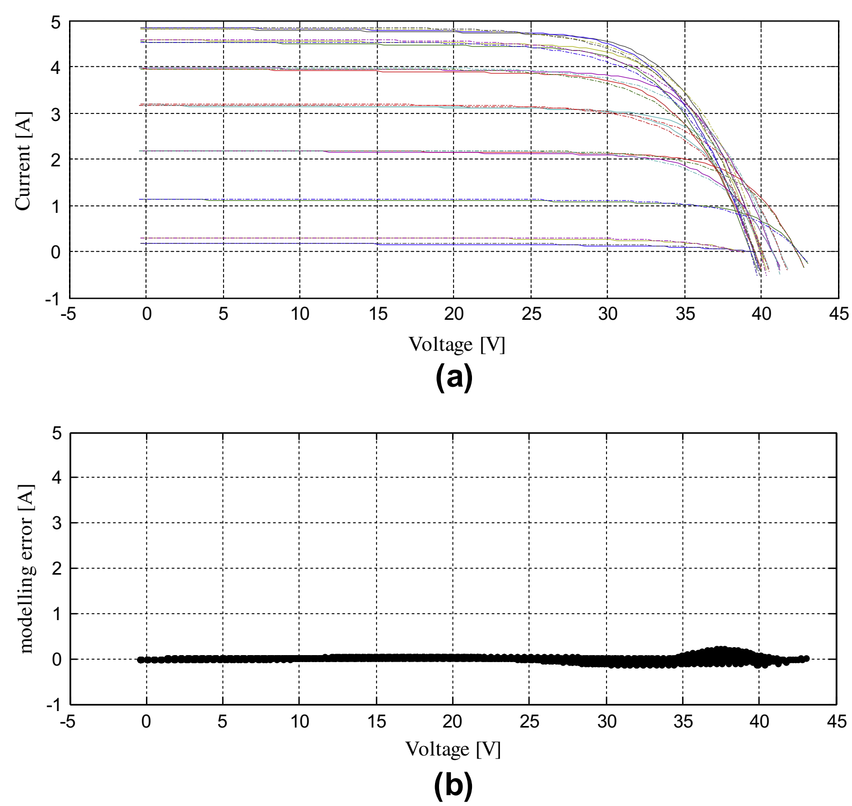


Fig. 18. Some examples of validation results: (a) Measured and modelled *I–V* curve and (b) modelling error.

The validation tests shows a variable modelling error which is at its maximum around the maximum power point. Its analysis showed that it's caused by the model's expression limitation. In order to improve the presented module model we plan to:

– Present an analysis study about the correlation existing between the developed model's constant voltage and its corresponding modelling error location, which allow to justify the use of a second exponential inspired from the step response of a second order system as a solution.
– Work on the irradiance influence on the open circuit voltage and the temperature influence of the short circuit current for more precision on the *I–V* characteristics modelling.
– Validate the model for other existing PV technologies as thin film PV modules.

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