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Low cost management for photovoltaic systems in isolated site with new IV characterization model proposed

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ABSTRACT

The control and the follow-up of the operational photovoltaic (PV) systems in isolated sites allow the mystery of this type of installation.

In this context, we set up an experimental manipulation based on microcontroller in order to acquire the data issued from a PV installation in isolated site. Then transmit these data by using high frequency (HF) wireless connection to a central computer which manipulates the information. This work presents the design of a universal data acquisition system with available components and is easily accessible with a central server. The contribution of this work is to control the functioning of PV system and also to give the current–voltage (*I*–*V*) curve of PV modules in real conditions. The transmission of the data by using HF connection, reduce considerably the cost of the system management. This work allows us to study the performances of the PV system in real time. Also, we present in this article a new model for IV characterization as well as the system realized and the obtained results.

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1. Introduction

The photovoltaic solar electricity is an example of renewable source of energy having reached the technological maturity. Its characteristics make it interesting in many areas of applications where traditional solutions of generating electricity are almost impossible to construct. Mainly it finds wide use in isolated sites such as desert regions [1].

From an economic point of view the follow-up of these systems is of an extreme importance. The researchers, the installers of the photovoltaic (PV) systems as well as those who are using the photovoltaic electricity wish that there is an optimization in the sizing of the PV systems [2]. In fact, the estimation of PV system sizing is very useful to conceive an optimal and economic stand-alone PV system. Several studies elaborated on the performance of PV systems [3–7] for an optimal sizing. All these methods allow estimating the sizing of PV system but they require control of the functioning of PV system in site. In fact, the measurements allow verifying experimentally the quality of the sizing and studying the performances of the PV system as well as the constitution of a data bank relative to the studied site [8,9]. We have used the most common models to simulate the current–voltage (*I*–*V*) characteristic of PV modules. Some of these models [10–13] require many parameters as input (e.g. the short circuit current, the open circuit voltage, the maximum current and the maximum voltage delivered by the PV module) and still give a considerable error in the simulation. A statistical test was used [14] to evaluate the accuracy of the models studied. Our aim is to simulate the *I*–*V* curve with few parameters as input and to give an *I*–*V* curve with more precision compared with the experimental data.

Recently, many investigations were done to estimate the performance of PV systems. As an example the data-acquisition system used for monitoring both meteorological data and PV system [15], the grid connected photovoltaic system in Northern Ireland [16] and a creation of a mobile stand-alone photovoltaic generator that can be easily relocated in remote areas to evaluate the feasibility of photovoltaic energy applications [17].

The aim of our work is to control the functioning of PV system and to estimate the performance of stand alone PV systems in real time and also to test the IV characterization curve for each type of PV module in real conditions.

This work presents a new management technique for controlling the PV system with low cost, by using a microcontroller to acquire the data on site (remote areas) and then transmit the information via high frequency (HF) wireless connection to personal computer (PC) for analysis and interpretation.

In addition, after installation of the PV system, we are always brought to analyze the performances of the installation by studying a real case which means the adaptation of different components constituting the PV system with the real load profile and the effect of their ageing. The next section presents a description of the experimental work. Section 3 describes the IV models and presents a new model proposed. Section 4 gives a comparison between the explicit model proposed and experimental data.

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The control and experimental validation are presented in the final section.

2. Description of the experimental work

We have subdivided our experimental work into two parts:

The first experimental part is to make acquisition of the data issued from a PV system in isolated site (Fig. 1). The PV system is constituted by a photovoltaic generator grouping together a combination series/parallel of PV modules, a regulator which controls the state of charge of the batteries (Energy system).

The measured parameters (e.g. the temperature, the solar irradiation as well as the currents and the voltages in the releases of the various components of the PV system) are acquired on-site then passed on HF connection to a transmitter/receiver (T/R). The operation of reception is made by an identical post T/R via central computer which consist the unit of the treatment and the command.

The second experimental part allows to get the current–voltage characteristic (*I*–*V* curve) of the photovoltaic generator (Fig. 2). The different components of the proposed measurement system are

- A sensor of solar irradiation (H).
- A sensor of temperature (T).
- An electronic load.
- An electronic card based on a transistor of type MOSFET of power, by using the microcontroller of type Parallel Interface Controller (PIC) 16F877 of Micro chip firm [2].

2.1. The sensors and the interface circuits

2.1.1. The solar radiation sensor

We have used a mono crystalline silicon solar cell to measure a solar irradiation. The solar cell used presents a large spectral response also important than a usual pyranometer [2]. The use of solar cell as measurement system reduces the cost of all system.

Fig. 3a shows the solar cell device conditioning.

The method of measure consists in acquiring the short circuit current I_{SC} which is proportional to the incident solar irradiation. The calibration of the solar cell allows getting the short circuit current according to the incident solar irradiation

$$I_{SC} = K \cdot H_i \qquad (1)$$

Where K is the calibration factor and H_i is the incident solar irradiation [2]. The solar cell used in our case gives a calibration factor of 80 mA/$\frac{\mathrm{KW}}{\mathrm{m}^2}$.

The measure of the short circuit current I_{SC} is realized by measuring the voltage across the shunt resistor (R_{Sh}). For adaptation, we use the first operational amplifier (OPA_1) as follower and in

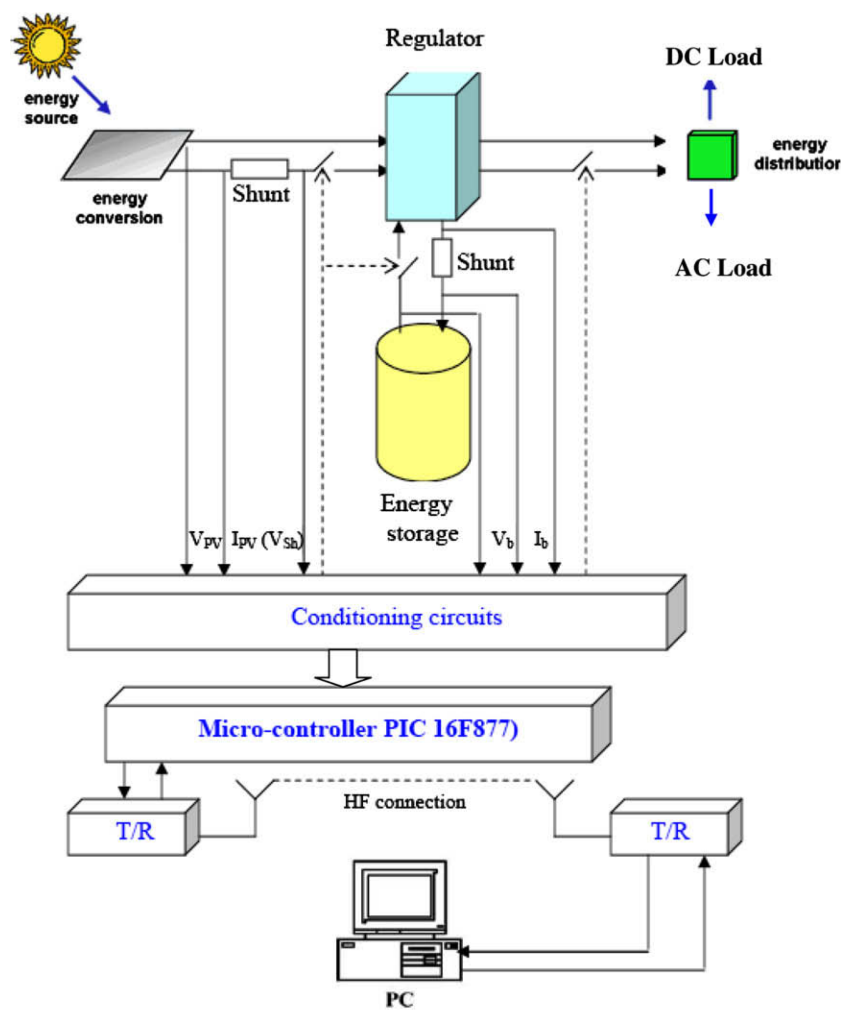

Fig. 1. Microcontroller management system.

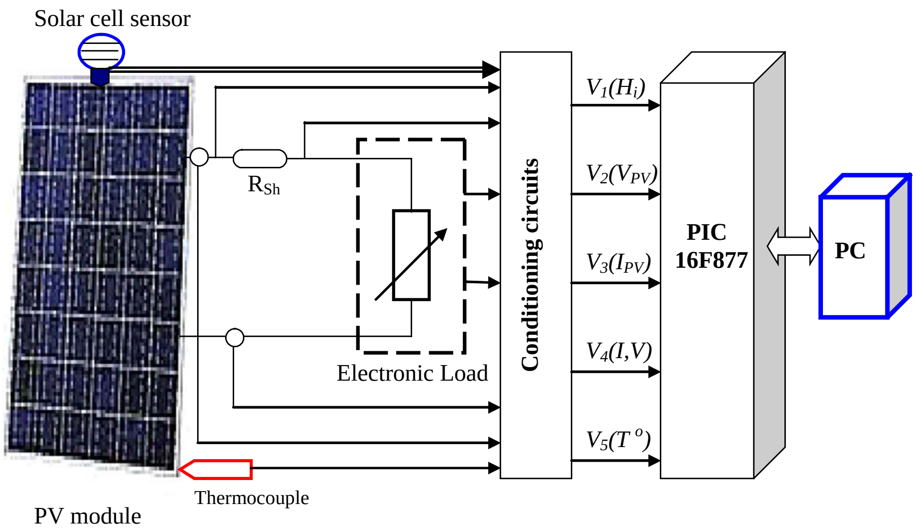

Fig. 2. Experimental *I–V* curve tracer based on microcontroller PIC 16F877.

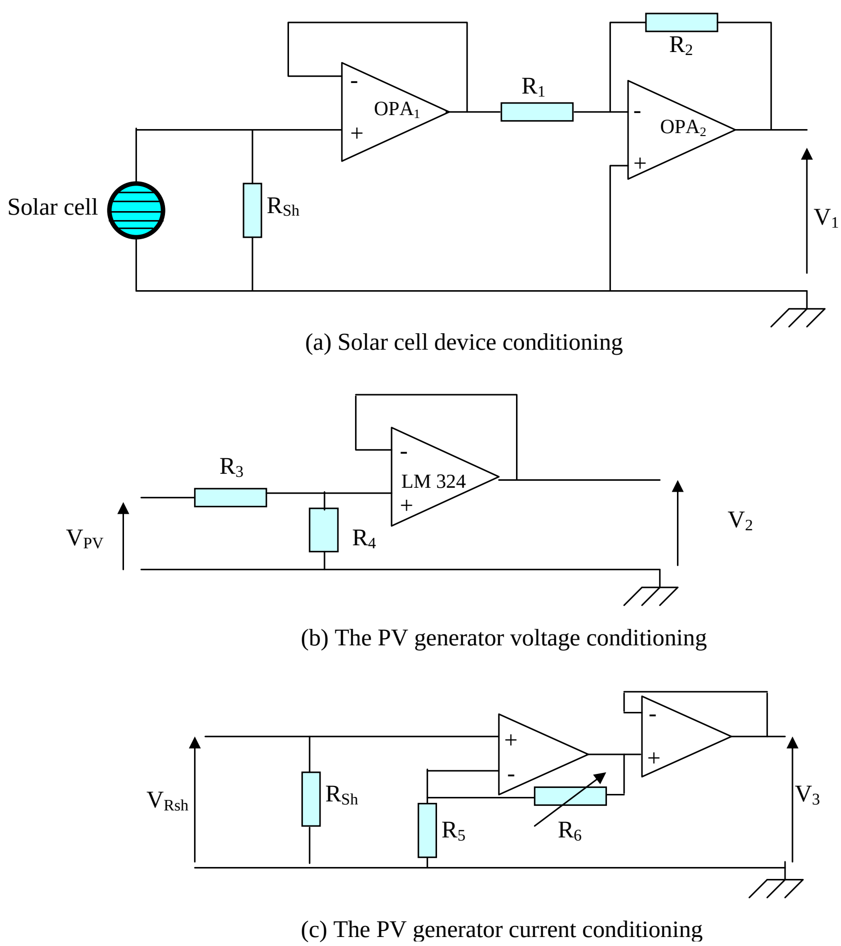

Fig. 3. The interface circuits: (a) solar cell device conditioning, (b) the PV generator voltage conditioning, (c) the PV generator current conditioning.

order to get a large scale measurement we amplify the signal via the resistors R_1, R_2 and the second operational amplifier(OPA_2).We have used the LM 324 series consists of four independent high gain, internally frequency compensated operational amplifiers which were designed specially to operate from a single power supply over a wide range of voltages.

2.1.2. the temperature sensor

The measure of the temperature is dedicated to a sensor based of a thermocouple of type K. Its conditioning and the compensation of its cold weld are realized by the AD595 Analog Devices firm. This sensor presents the advantage to measure directly the temperature of connection by contact on the back face of the PV modules.

The AD595 is a complete instrumentation amplifier and thermocouple cold junction compensator on a monolithic chip. It combines an ice point reference with a precalibrated amplifier to produce a high level (10 mV/°C) output directly from a thermocouple signal [2].

2.1.3. The photovoltaic current and voltage

The current and the voltage data are acquired with a necessary conditioning to adapt the signals to the input of the microcontroller. The acquisition of PV voltage is given by measuring the output voltage of PV generator as shown in the Fig. 3b. The choice of the resistors R_3 and R_4 is conditioning by the maximum voltage value which can be given by the PV generator.

The acquisition of PV current is given by measuring the voltage across the shunt resistor R_{Sh} (0.016 Ω, 5 W), placed in serial with the load. The PV current conditioning circuit is given by the Fig. 3c. In order to get more precisions, we have chosen the precision resistors of 1% for all the conditioning circuits.

2.2. The IV curve tracer

We have conceived an electronic load based on a transistor MOSFET of power. Their advantage is that their command is made by the voltage gate-source (V_{gs}) which is separated with regard to the measure. The variable load allows the measure the couple of the current–voltage (I–V) along the curve. However, this measure must be very quickly made to acquire a large number of points. It is realized by using the microcontroller PIC 16F877 [2,3].

3. Developed models

The obtained IV characteristic is compared with those obtained by using the theoretical models. We have used the most common models to simulate the I–V curve of PV modules.

3.1. Explicit model

This model requires four parameters as input: the short circuit current (I_{SC}), the open circuit voltage (V_{OC}), the maximal current (I_m) and the maximal voltage (V_m) [10].

3.2. Two parameters model

The two parameters of this model [11] are: the maximal current (I_m) and the serial resistance (R_S). These last ones are determined from the short circuit current I_{SC}, the open circuit voltage V_{OC} and the maximal power (P_m).

3.3. Five parameters model

This model uses five parameters [12] of the PV generator definite from the open circuit voltage V_{OC}, the short circuit current I_{SC}, the voltage and the current at the maximum power point (V_m and I_m) and slopes nearest of V_{OC} and I_{SC}.

3.4. Akbaba's model

The model proposed by Akbaba and Alhalawani [13] is explicit. It is based on the choice of arbitrary points of the I–V curve.

3.5. A new explicit model proposed for IV characterization

The purpose of IV characteristic approximation by means of equivalent circuit diagrams lies in the explicit calculability of matching problems between solar generators and several loads. The equivalent circuit diagram for the effective solar cell characteristic is given by Fig. 4.

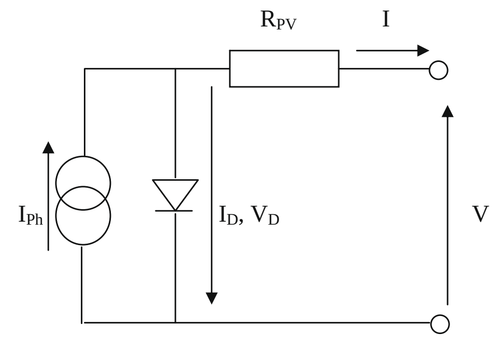

Fig. 4. Equivalent circuit diagram for effective solar cell characteristic.

Where I is the load current, V the output voltage, I_{Ph} is the photo-generated current and R_{PV} is the photovoltaic resistance.

The effective solar cell characteristic is given by the following model:

$$I = I_{ph} - I_0\left(e^{\frac{V+R_{PV}\cdot I}{V_T}} - 1\right) \tag{2}$$

The explicit version is

$$V = V_T \cdot Ln\left(\frac{I_{ph} - I + I_0}{I_0}\right) - R_{PV}\cdot I \tag{3}$$

We need to determine the following parameters: R_{PV}, V_T, I_0 and I_{Ph}.- By using the following simplification:

$$Exp\left(\frac{V+R_{PV}\cdot I}{V_T}\right) \gg 1 \quad \text{and} \quad I_{Ph} = I_{SC}$$

The I–V curve can be expressed as

$$I = I_{SC}\left[1 - \left(\frac{I_0}{I_{SC}}\right)\cdot Exp\left(\frac{V+R_{PV}\cdot I}{V_T}\right)\right] \tag{4}$$

then

$$V = V_T \cdot Ln\left(\frac{I_{CS} - I}{I_0}\right) - R_{PV}\cdot I \tag{5}$$

Since I_0, V_T and R_{PV} are unknown, three conditions are required to enable use of this fit:

1. If $I = 0$, then $V = V_{OC}$.
2. At the maximum power point the fit is tangent to the hyperbola $P_m = V{\cdot}I$.
3. The slope S at the open circuit voltage (V_{OC}) is to be considered.

The condition (1) yields:

$$V_{OC} = V|_{I=0} = V_T \cdot Ln\left(\frac{I_{SC}}{I_0}\right)$$

or

$$V_T = \frac{V_{OC}}{Ln\left(\frac{I_{SC}}{I_0}\right)} \tag{6}$$

and then

$$I_0 = I_{SC}\cdot e^{-\frac{V_{OC}}{V_T}} \tag{7}$$

The condition (2) can be expressed as

$$V|_{I=I_m} = \frac{P_m}{I_m} \tag{8}$$

$$\left.\frac{\partial V}{\partial I}\right|_{I=I_m} = \frac{\partial}{\partial I}\left(\frac{P_m}{I}\right)\bigg| = -\frac{P_m}{I_m^2} \tag{9}$$

Differentiating Eq. (9) according to Eq. (5), we get:

$$\frac{\partial V}{\partial I} = -\frac{V_T}{(I_{Sc} - I)} - R_{PV}$$

For $I = I_m$, we get

$$\left.\frac{\partial V}{\partial I}\right|_{I=I_m} = -\frac{V_T}{(I_{SC} - I_m)} - R_{PV} = -\frac{P_m}{I_m^2} \tag{10}$$

then

$$R_{PV} = \frac{V_m}{I_m} - \frac{V_T}{(I_{SC} - I_m)} \tag{11}$$

By substituting Eq. (6) in Eq. (11), we get:

$$R_{PV} = \frac{V_m}{I_m} - \frac{V_{OC}}{(I_{SC} - I_m)\cdot Ln\left(\frac{I_{SC}}{I_0}\right)} \tag{12}$$

It was found that a typical value of the ratio $\left(\frac{I_0}{I_{SC}}\right)$ for a silicon cell at 25 °C and 1000 W/m^2 ranges from approx. 10^{-7} until 10^{-10} [11]. So, in order to reduce the numbers of measurements, we may assume that $\left(\frac{I_0}{I_{SC}}\right) = 10^{-7}$ at less. Substituting this value into Eqs. (4) and (6) then yields:

$$V_T = \frac{V_{OC}}{Ln10^7} = \frac{V_{OC}}{16.11}$$

$$I = I_{SC}\left[1 - 10^{-7}\cdot Exp\frac{16.11}{V_{OC}}(V + R_{PV}\cdot I)\right] \tag{13}$$

And then Eq. (13) yields:

$$V = \left[\frac{V_{OC}}{16.11}\cdot Ln\frac{10^7(I_{SC} - I)}{I_{SC}}\right] - R_{PV}\cdot I$$

The Eq. (12) yields:

$$R_{PV} = \frac{V_m}{I_m} - \frac{V_{OC}}{16.11(I_{SC} - I_m)} \tag{14}$$

The condition (3) yields:

$$S = \left.\frac{dV}{dI}\right|_{I=0} = -\frac{V_T}{(I_{Sc})} - R_{PV}$$

then

$$V_T = -(S + R_{PV})\cdot I_{SC} \tag{15}$$

Substituting Eq. (15) into Eq. (11), we get:

$$R_{PV} = \frac{V_m}{I_m} + \frac{(S + R_{PV})\cdot I_{SC}}{(I_{SC} - I_m)}$$

then

$$R_{PV} = -S\frac{I_{SC}}{I_m} + \frac{V_m}{I_m}\left(1 - \frac{I_{SC}}{I_m}\right) \tag{16}$$

The slope S is then given by the approximate function [18]:

$$S = \frac{V_{OC}}{I_{SC}}\left(\alpha_1\cdot\frac{I_{p\max}\cdot V_{p\max}}{I_{SC}\cdot V_{OC}} + \alpha_2\cdot\frac{V_{p\max}}{V_{OC}} + \alpha_3\cdot\frac{I_{p\max}}{I_{SC}} + \alpha_4\right)$$

With the equation-constants:

$$\alpha = \begin{pmatrix} -5.411 \\ 6.450 \\ 3.417 \\ -4.422 \end{pmatrix}$$

We note that the Eq. (16) is independent of material properties of the solar cell. The photovoltaic resistance R_{PV} is calculated using Eq. (14) for silicon cell or using Eq. (16) for any materials properties of the solar cell. The value of R_{PV} is substituted into Eq. (2) to find the I–V curve of a single solar cell.

4. Comparison between the explicit model proposed and the experimental data

In order to evaluate the accuracy of the models a statistical tests was used [14], root mean square error (RMSE). The RMSE is given as follow:

$$RMSE = \left(\frac{1}{n}\sum_{i=1}^{n}(I_{si} - I_{mi})^2\right)^{1/2} \tag{17}$$

where n is the number of data, I_{si} is the ith simulated current and I_{mi} is the ith measured current.

The RMSE test provides information on the short-term performance of the simulation model. The lower value of RMSE means the more accuracy for the model used.

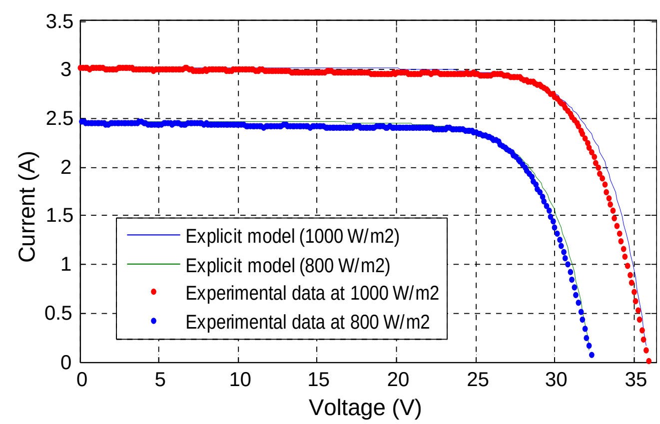

Fig. 5. I–V curve characterization for two illuminations for PV module ISOFOTON.

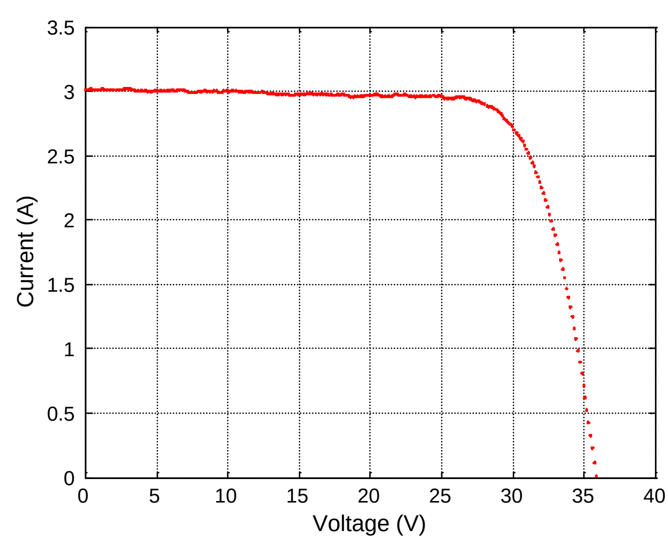

Fig. 6. I–V curve (1000 W/m^2, 25 °C) for PV module of type ISOFOTON.

The RMSE values of the model were calculated. The RMSE average values, which are a measure of the accuracy of estimation, have been found to be the lowest (0.01) at illumination of 800 W/m^2 and 0.03 for the illumination of 1000 W/m^2.

This means the good estimation of *I–V* characterization by using the explicit model proposed for the illumination of 800 W/m^2.

Fig. 5 shows a good agreement between experimental *I–V* curve and those given by the explicit model proposed for different illuminations for PV module ISOFOTON.

5. Control and experimental validation

The follow-up of the PV systems consists in making a series of experimental measures on a beforehand sized system. These measures allow to verify experimentally the quality of the sizing and to study the performances of the PV system as well as the constitution of a data bank relative to the studied site [12,13].

For that purpose, we have conceived and realized a monitoring based on the microcontroller PIC 16F877 allowing to acquire the data on an isolated site and to transmit them by a radio connection HF.

It also allows controlling the functioning of the various constituents of the PV system under the real conditions by acting at distance on these last ones. The use of modules (T/R) grouping together the functions of emission and reception reduces considerably the cost of the system.

We have made the acquisition of the *I–V* characteristic of a module of type ISOFOTON under the following conditions: (1000 W/m^2, 25 °C) and (800 W/m^2, 45 °C).

The obtained experimental curves are given by Figs. 6 and 7. Table 1 presents the electric characteristics of the used module obtained during the test.

Also, we have conceived a software interface under Matlab which allows the acquisition of the *I–V* characteristic and to show at the same time as curves relative to the used theoretical models. Fig. 8–11 illustrate curves obtained by using these models.

We can summarize the results of calculation of errors in Table 2. We have proceeded to the calculation of the standard deviation of the values of the current along the curve.

According to the comparison made between the experimental results and the theoretical curves, we can say that every model presents its advantages and inconveniences. We conclude on the following points:

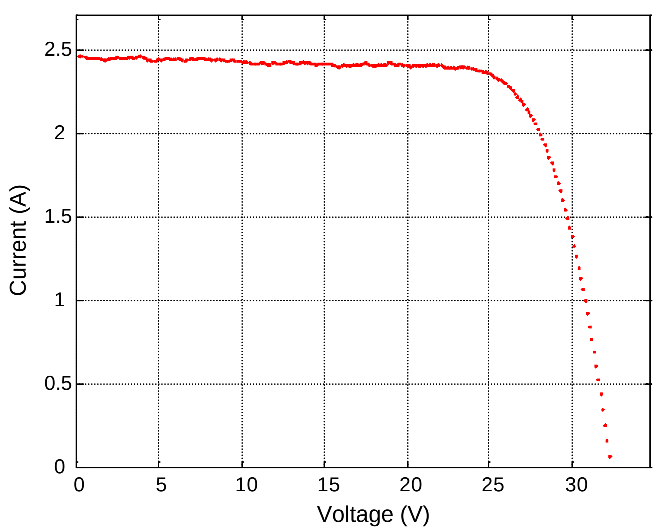

Fig. 7. *I–V* curve (800 W/m^2, 45 °C) for PV module of type ISOFOTON.

Table 1
Characterization of PV module ISOFOTON obtained.

Solar irradiation (W/m^2)	1000	800
Temperature (°C)	25	45
I_{sc} (A)	3.0159	2.4627
V_{oc}(V)	35.8734	32.2764
V_m(V)	29.1546	26.2862
P_m(W)	82.4687	59.7715

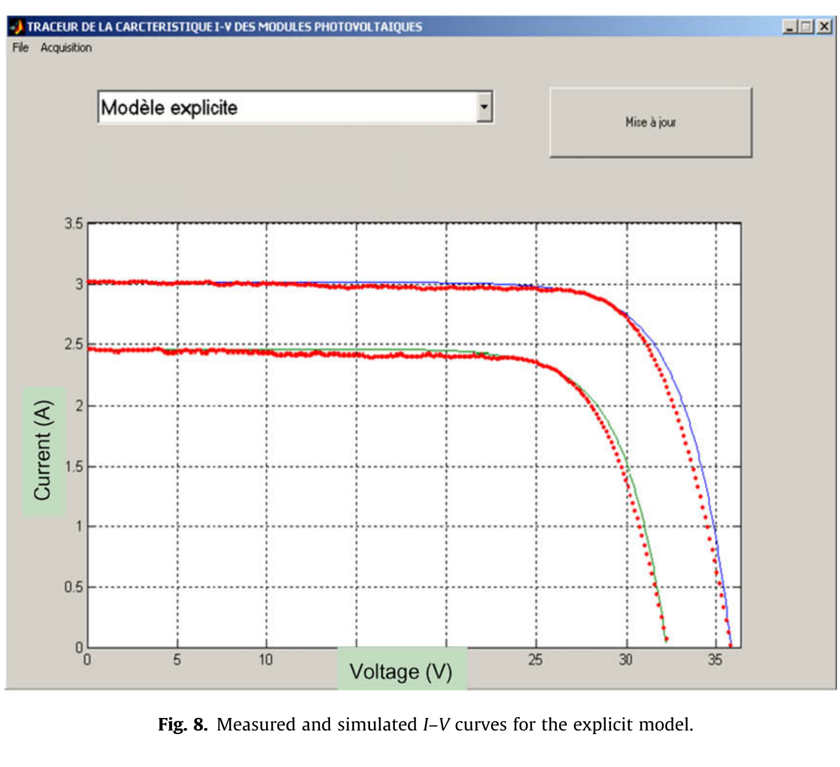

Fig. 8. Measured and simulated *I–V* curves for the explicit model.

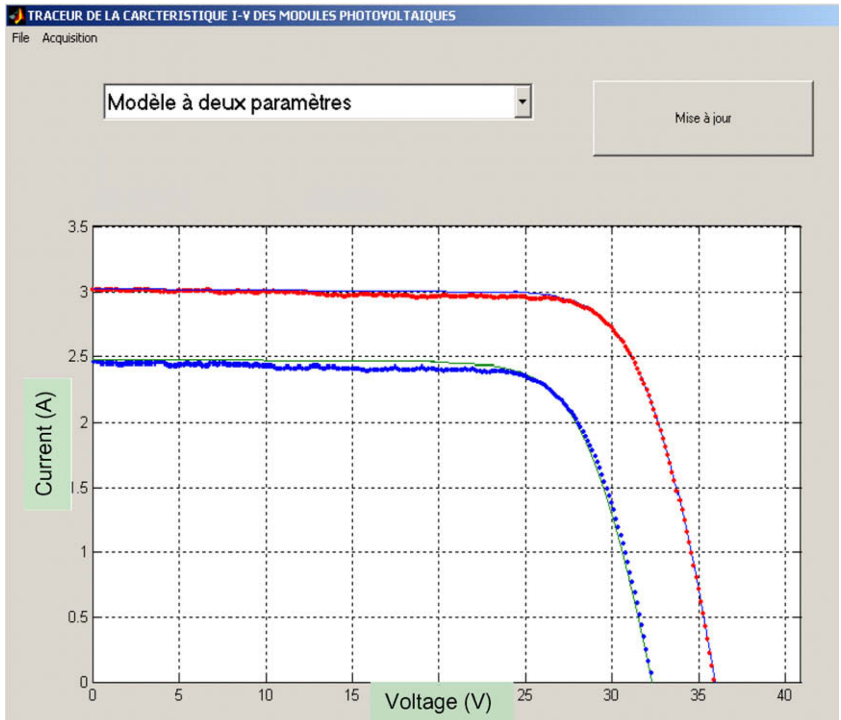

Fig. 9. Measured and simulated *I–V* curves for the two parameters model.

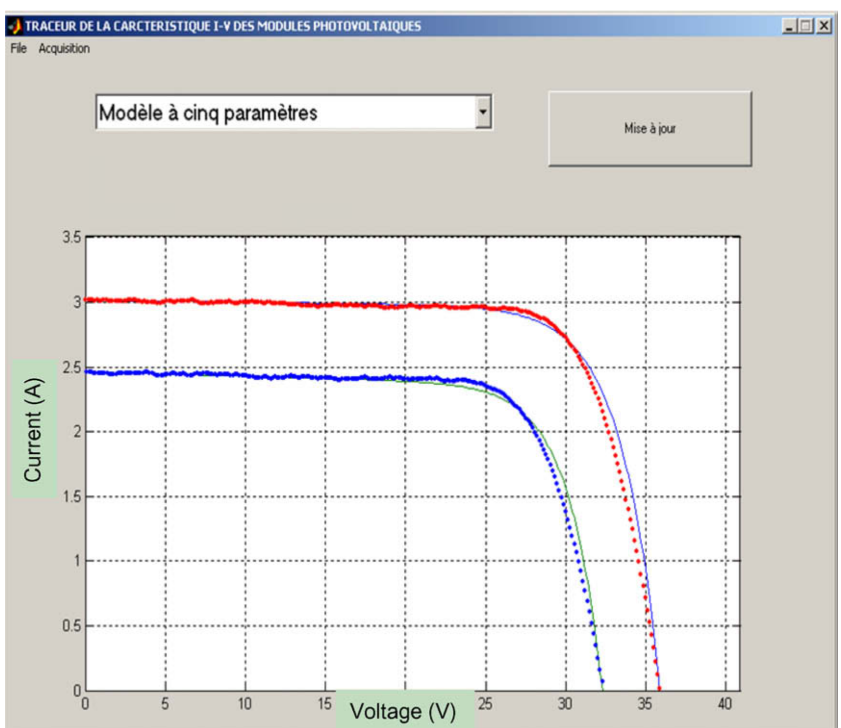

Fig. 10. Measured and simulated *I–V* curve for the five parameters model.

– The explicit model does not require an iterative method but it presents a bad adjustment to the right of the elbow of the *I–V* characteristic.
– The two parameters model adjusts exactly the experimental curve but it requires a calculation of the parameters with iterative numerical methods.
– The five parameters model presents a good adjustment of the experimental characteristic; it requires the measures with good precision of slopes near I_{sc} and V_{oc}.
– The model of Akbaba uses the easy explicit equations to simulate the *I–V* curve but it presents a very bad adjustment especially to the left of the elbow of the IV characteristic.

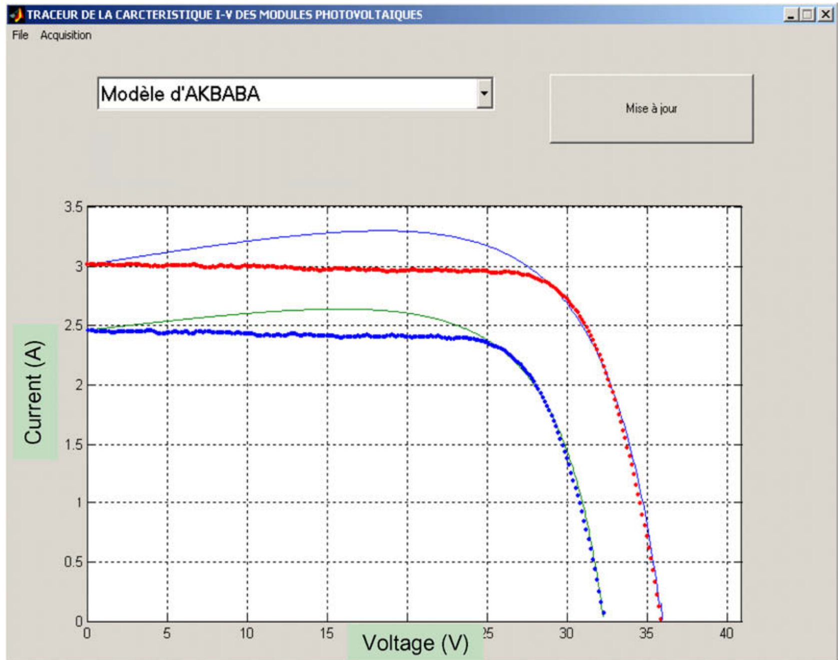

Fig. 11. Measured and simulated *I–V* curve for the Akbaba's model.

Table 2
Results and RMSE errors.

Models	Parameters	
	RMSE (A) 25 °C, 1000 W/m^2	RMSE (A) 45 °C, 800 W/m^2
Explicit model	0.1255	0.0807
Two parameters model	0.07794	0.09464
Five parameters model	0.0731	0.0552
Akbaba's model	0.2177	0.1518
Explicit model Proposed	0.0304	0.0121

This is due to the choice based on the arbitrary points of the *I–V* curve. The model of Akbaba do not take account of photovoltaic resistance of the PV module.

– The new proposed model presents an excellent adjustment of the experimental *I–V* curve.

So, we can recommend the explicit model proposed in order to characterize the behavior of PV module of type ISOFOTON. Also, we recommend the two parameters model and the five parameters model with precaution.

6. Conclusion

In remote areas, it is necessary to master the behavior of the photovoltaic generator and all the components constituting the PV system. The modeling of the PV systems gave good results. The system of follow-up and control realized allows verifying the performances of the theoretical models and the management of the PV systems in isolated sites. The contribution of this work is to control the functioning of PV system and also to give the *I–V* curve of PV modules in real conditions and to study the performances of the PV system in real time. By using an HF connection, we reduce considerably the cost of all management system.

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