Comparison and statistical validation of a model of a photovoltaic module

Moufdi Hadjab, Bendida Medjahed

Abstract—The study presented in this paper includes a comparison, and a statistical validation. The results that are obtained by a numerical simulation in MATLAB are compared with the experimental results that are taken from the Unit of Applied Research in Renewable Energy "Ghardaïa" (URAERG) (Experience in the field of solar energy). The work is to exploit the experimental data obtained by exposing the solar cells (panel BP3160W) to light (sunlight), wherever the place of use and the operating conditions. The purpose of this study was to evaluate the model of single diode proposed by Walker of University of Queensland, Australia, uses the electric model with moderate complexity. The numerical results are presented relating to the current-voltage characteristics and power-voltage; during a change of weather conditions such as light, and temperature. To compare, objectively, the performance of the model with the diode modeled using experimental data, statistical indicators proposed by Chang and Hanna (2004) were calculated for different measurement points of light and temperature; the analysis shows that the results for the current and the power reflect the physical reality. Note; however, that the model results are in a very good agreement with experimental measurements.

***Keywords*—**Model of single diode, solar panels, Matlab, statistical validation.

I. Introduction

RENEWABLE energy resources are an increasingly important part of power generation in the recent years. Aside from assisting in the reduction of the emission of greenhouse gases, they add the much needed flexibility to the energyresource mix by decreasing the dependence on fossil fuels. Due to their modular characteristics and ease of installation and because they can be located closer to the user, photovoltaic (PV) systems have great potential as distributed power source to the utilities [1], solar energy has been one of the most active research areas in the past decades. The installed PV power has been increasing in the past, and a more significant increase is expected in the near future, owing to the potential advances in the PV conversion technology and the reduction in cost-per-watt that a large-scale [2].

The solar panel is the basic module converting the irradiated solar energy into electricity. The power generated by the solar panel depends on the solar power incident on the panel, the panel temperature, and the operating panel voltage. The power capacity of standard solar panels is usually a few hundred watts peak (W_p), at operating dc voltages ranging from 15 to 35 V [2].

The benefits of power generation from these sources are widely accepted. They are:

- A reliable way, which requires little maintenance.
- Supplies electricity through renewable and free energy from the sun.
- Requires no fuel.
- Silent, non-polluting and environmentally.
- Versatile and can be adjusted as required.

From these observations, we distinguish that the photovoltaic solar energy is a topic more relevant; its control requires having effective means of forecasting can provide estimates as close as possible to reality.

II. CHOICE OF PHOTOVOLTAIC MODULE

During this work, the BP 3160 photovoltaic module is chosen for a MATLAB simulation model, shown in Figure 1, the module is made of 72 multi-crystalline silicon solar cells in series and provides 160 watts of nominal maximum power [3]. Table 1 shows its electrical specification [3].

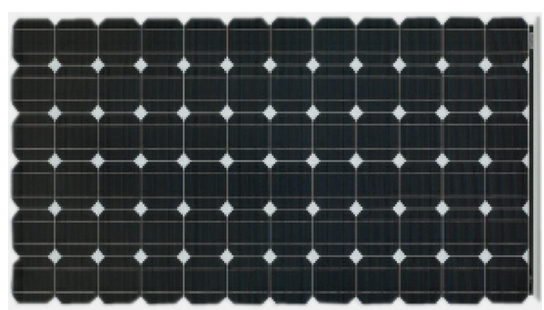


Fig. 1 image of the photovoltaic module BP3160

This work was supported in part by the applied materials laboratory, Research center, university Djillali Liabes of Sidi Bel Abbes, 22000 Algeria.

M. Hadjab is with the applied materials laboratory, Research center, university Djillali Liabes of Sidi Bel Abbes, 22000 Algeria. (moufdi84@yahoo.fr).

B. Medjahed is with Applied Mechanics Laboratory, University of Science and Technology (USTO), Oran 31000, Algeria. And Experimental and numerical modeling of mechanical phenomena Laboratory, University Abdelhamid Ibn Badis, Mostaganem 27000, Algeria.

TABLE I: ELECTRICAL CHARACTERISTICS DATA OF PV MODULE TAKEN FROM THE DATASHEET

Maximum Power (P_{max})	160W
Voltage at P_{max} (V_{mp})	34.5V
Current at P_{max} (I_{mp})	4.55A
Open-circuit voltage (V_{oc})	4.8A
Short-circuit current (I_{sc})	44.2V
Temperature coefficient of I_{sc}	(0.065±0.015)%/°C
Temperature coefficient of V_{oc}	-(160±20)mV/°C
Temperature coefficient of power	-(0.5±0.05)%/°C

In Figure 2, we presented two curves representing the solar illumination and the temperature versus time of BP3160 photovoltaic panel.

These measurements were made it during a day with high radiation changes, and extracted at the Unit of Applied Research in Renewable Energy "Ghardaïa" (URAERG), in Algeria [4].

The Measurements (current, voltage, solar illumination and temperature) are collected in an Excel file on one hundred points in the I-V curve that can be processed by the program that has developed in the MATLAB environment.

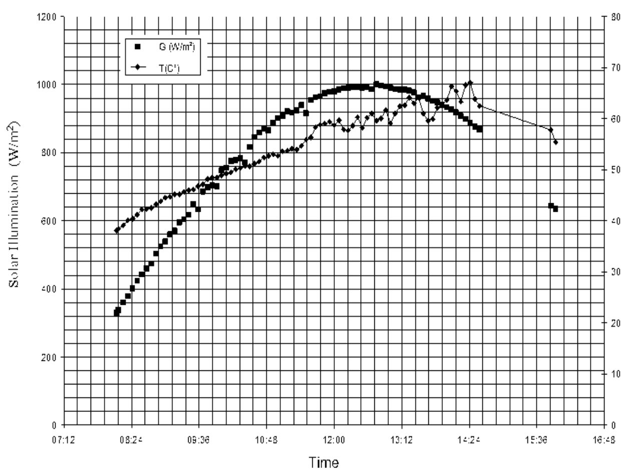


Fig. 2 the curves of temperature and irradiance versus time

III. MODELING A PV MODULE BP 3160W BY MATLAB

The strategy of modeling a PV module is no different from modeling a PV cell. It uses the same PV cell model. The parameters are the all same, but only a voltage parameter (such as the open-circuit voltage) is different and must be divided by the number of cells.

Several electrical models are used to simulate and modeling the cells (panel) PV. We will exploit the study done by Walker [5] of University of Queensland, Australia, uses the electric model with moderate complexity, shown in Figure 3.

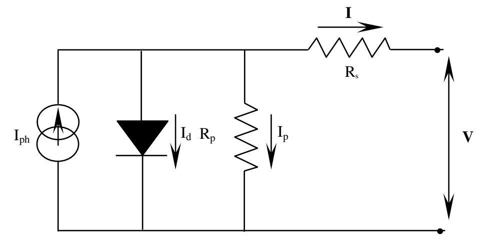


Fig. 3 the circuit diagram of the PV model.

The model consists of a current source (I_{ph}), a diode (D), and a series resistance (R_s). The effect of parallel resistance (R_p) is very small in a single module, thus the model does not include it. To make a better model, it also includes temperature effects on the short-circuit current (I_{sc}) and the reverse saturation current of diode (I_s). It uses a single diode with the diode ideality factor (n) set to achieve the best I-V curve match.

The output current supplied by the solar cell is obtained by applying Kirchhoff's law, in the equivalent circuit above:

$$I = I_{ph} - I_d - I_p \tag{1}$$

Where: I is the cell current.

I_{ph}: the photocurrent generated by the current source.

$I_d = I_s(e^{q(V+IR_s)/nkT} - 1)$: is the current shunted through the intrinsic diode.

$I_p = \dfrac{V + IR_s}{R_p}$: The current delivered by the parallel resistance.

From these equations we can deduce the expression of the current delivered by the photovoltaic cell:

$$I = I_{ph} - I_s(e^{q(V+IR_s)/nkT} - 1) - \frac{V + IR_s}{R_p} \tag{2}$$

Where:

I: is the cell current (the same as the module current),

V: is the cell voltage = {module voltage} ÷ {# of cells in series},

I_s: the saturation current of the diode.

T: is the cell temperature in Kelvin (K).

q :is the electron charge (1.602×10^{-19} C),

K: is the Boltzmann's constant (1.381×10^{-23} J/K),

T: is the junction temperature in Kelvin (K).

The simplest model of a PV cell is shown as an equivalent circuit below that consists of an ideal current source in parallel with an ideal diode. The current source represents the current generated by photons (I_{ph}), and its output is constant under constant temperature and constant incident radiation of light.

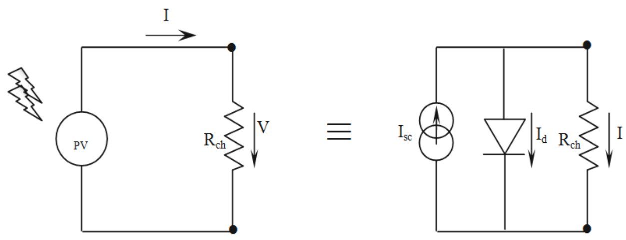
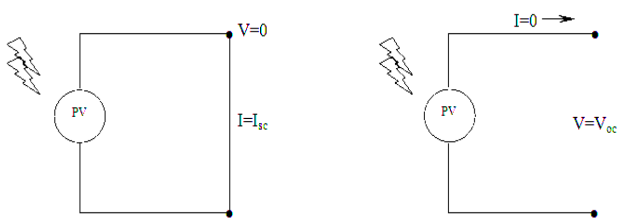


Fig. 4 PV cell with a load and its simple equivalent circuit

As shown in Figure 5 (b) there are two key parameters frequently used to characterize a PV cell. Shorting together the terminals of the cell, the photon generated current will follow out of the cell as a short-circuit current (I_{sc}). Thus,

$$I_{ph} = I_{sc} \tag{3}$$

When there is no connection to the PV cell (open-circuit), the photon generated current is shunted internally by the intrinsic p-n junction diode. This gives the open circuit voltage (V_{oc}). The PV module or cell manufacturers usually provide the values of these parameters in their datasheets.



(a) Short-circuit current (b) Open-circuit voltage

Fig. 5 Diagrams showing a short-circuit and an open-circuit condition.

Using the equality (3), the equation (2) becomes:

$$I = I_{sc} - I_s(e^{q(V+IR_s)/nkT} - 1) - \frac{V + IR_s}{R_p} \tag{4}$$

The effect of parallel resistance (R_p) is very small in a single module, thus the model does not include it, Then ($R_p = \infty$), equation (4) becomes:

$$I = I_{sc} - I_s(e^{q(V+IR_s)/nkT} - 1) \tag{5}$$

The reverse saturation current of diode (I_s) is constant under the constant temperature and found by setting the open circuit condition as shown in Figure 5 (b). Using the equation (5), let I = 0 (no output current) and solve for I_s;

$$0 = I_{sc} - I_s(e^{qV_{oc}/kT)} - 1) \tag{6}$$

$$I_{sc} = I_s(e^{qV_{oc}/kT)} - 1)$$

$$I_s = \frac{I}{(e^{qV_{oc}/kT)} - 1)} \tag{7}$$

First, calculate the short-circuit current (I_{sc}) at a given cell temperature (T):

$$I_{sc}\big|_T = I_{sc}\big|_{T_{ref}} .\left[1 + \alpha\left(T - T_{ref}\right)\right] \tag{8}$$

Where: I_{sc} at T_{ref} is given in the datasheet (measured under irradiance of 1000W/m^2), T_{ref} is the reference temperature of PV cell in Kelvin (K), usually 298K (25°C), *a* is the temperature coefficient of I_{sc} in percent change per degree temperature also given in the datasheet.

To a very good approximation, the photon generated current, which is equal to I_{sc}, is directly proportional to the irradiance, the intensity of illumination, to PV cell [6]. Thus, if the value, I_{sc}, is known from the datasheet, under the standard test condition, G_o=1000W/m^2 at the air mass (AM) = 1.5, then the photon generated current at any other irradiance, G (W/m^2), is given by:

$$I_{sc}\big|_G = \left(\frac{G}{G_o}\right) I_{sc}\big|_{G_o} \tag{9}$$

Where: G_o is the nominal value of irradiance, which is normally 1KW/m^2.

The reverse saturation current of diode (Io) at the reference temperature (T_{ref}) is given by the equation (2.6) with the diode ideality factor added:

$$I_s = \frac{I_{sc}}{(e^{qV_{oc}/kT)} - 1)} \tag{10}$$

The reverse saturation current (I_s) is temperature dependant and the I_s at a given temperature (T) is calculated by the following equation [5].

$$I_s\big|_T = I_s\big|_{T_{ref}} \cdot \left(\frac{T}{T_{ref}}\right)^{\frac{3}{n}} .e^{\frac{-qE_g}{nK}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)} \tag{11}$$

The diode ideality factor (n) is unknown and must be estimated. It takes a value between one and two; the value of n=1 (for the ideal diode) is, however, used until the more accurate value is estimated later by curve fitting [5].

The series resistance (R_s) of the PV module has a large impact on the slope of the I-V curve near the open-circuit voltage (V_{oc}), hence the value of R_s is calculated by evaluating the slope $\frac{dV}{dI}$ of the I-V curve at the V_{oc} [5]. The equation for R_s is derived by differentiating the equation (5) and then rearranging it in terms of R_s.

$$I = I_{sc} - I_s\left[e^{q\left(\frac{V + I.R_s}{nKT}\right)} - 1\right] \tag{12}$$

$$dI = 0 - I_s.q\left(\frac{dV + R_s.dI}{nKT}\right).e^{q\left(\frac{V+I.R_s}{nKT}\right)} \quad (13)$$

$$R_s = -\frac{dI}{dV} - \frac{nKT/q}{I_s.e^{q\left(\frac{V+I.R_s}{nKT}\right)}} \quad (14)$$

Then, evaluate the equation (14) at the open circuit voltage that is $V=V_{oc}$ (also let I=0).

$$R_s = -\frac{dV}{dI}\Big|_{V_{oc}} - \frac{nKT/q}{I_s.e^{\frac{qV_{oc}}{nKT}}} \quad (15)$$

Where : $\frac{dV}{dI}\Big|_{V_{oc}}$ is the slope of the I-V curve at the V_{oc} (use the I-V curve in the datasheet then divide it by the number of cells in series),
V_{oc} is the open-circuit voltage of cell (found by dividing Voc in the datasheet by the number of cells in series).

The calculation using the slope measurement of the I-V curve published on the BP 3160 datasheet gives a value of the series resistance per cell, $R_s \approx 5\ m\Omega$.

Finally, it is possible to solve the equation of I-V characteristics. It is, however, complex because the solution of current is recursive by inclusion of a series resistance in the model. Although it may be possible to find the answer by simple iterations, the Newton's method is chosen for rapid convergence of the answer [5]. The Newton's method is described as:

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)} \quad (16)$$

Where: $f'(x)$ is the derivative of the function, $f(x) = 0$, x_n is a present value, and x_{n+1} is a next value.

Rewriting the equation 5 gives the following function:

$$f(I) = I_{sc} - I - I_s\left[e^{q\left(\frac{V+I.R_s}{nKT}\right)} - 1\right] = 0 \quad (17)$$

Plugging this into the equation 16 gives a following recursive equation, and the output current (I) is computed iteratively.

$$I_{n+1} = I_n - \frac{I_{sc} - I_n - I_s\left[e^{q\left(\frac{V+I_n.R_s}{nKT}\right)} - 1\right]}{-1 - I_s\left(\frac{q.R_s}{nKT}\right)e^{q\left(\frac{V+I_n.R_s}{nKT}\right)}} \quad (18)$$

The operating principle of the photovoltaic cell uses the properties of solar radiation and semiconductors. The power supplied by the solar panel can be modified by the action of temperature and solar irradiations. We studied the importance of these two parameters on the control panel located in the Unit of Applied Research in Renewable Energy "Ghardaïa" (URAERG) and having the characteristics listed in Table 1. The figures 6 and 7 illustrates the variation I-V and P-V under the effect of temperature for a constant illumination G=1000 W/m^2. Similarly, Figures 8 and 9 shows that the variation I-V and P-V under the effect of the illumination for a constant temperature T=25°C.

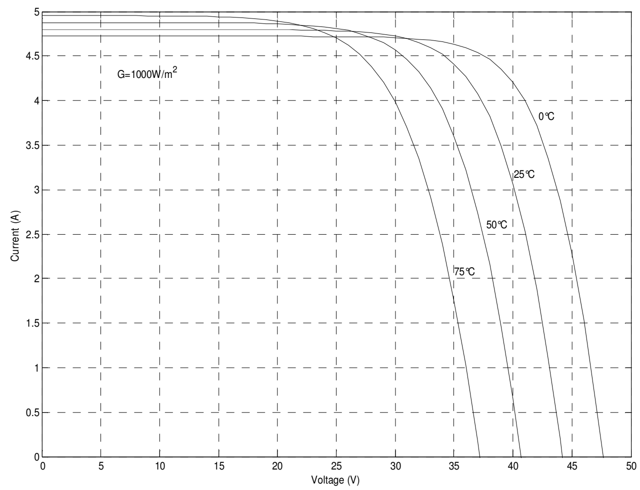


Fig. 6 Simulated I-V curves of PV module influenced by temperature at G= constant

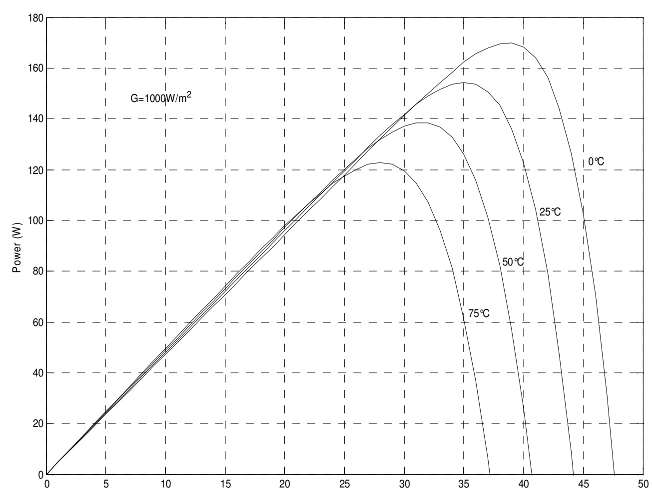


Fig. 7 Effect of temperature on the characteristic P-V of PV module at G = constant

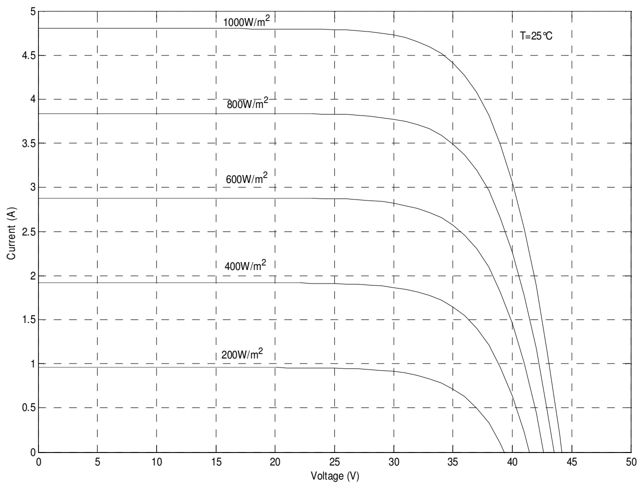


Fig. 8 Simulated I-V curves of PV module influenced by solar illumination

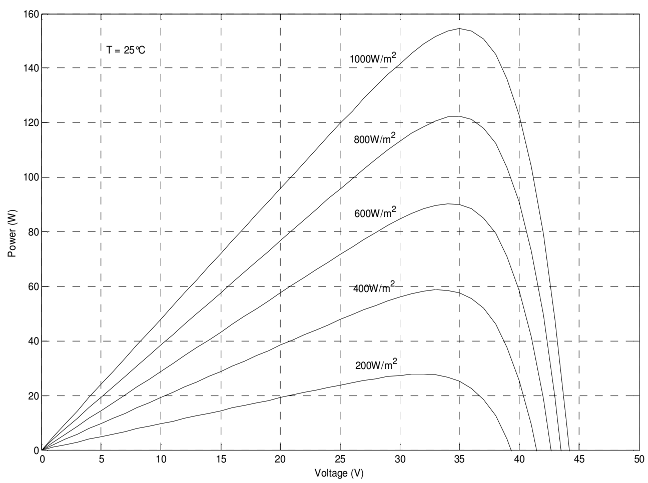


Fig. 9 Effect of illumination on the characteristic P-V of PV module at T = constant.

IV. Statistical Method of Validation

In order to evaluate the predictions of a model with observations, Hanna et al (2004) [7] recommend the use of the following statistical performance measures, which include the fractional bias (FB), the geometric mean bias (MG), the normalized mean square error (NMSE), the geometric variance (VG), and the fraction of predictions within a factor of two of observations (FAC2):

A. *The Fractional Bias (FB)*

The Fractional Bias is written in the symbolic form:

$$FB = 2 \times \left(\frac{\overline{C_0} - \overline{C_p}}{\overline{C_0} + \overline{C_p}} \right) \tag{19}$$

B. *The geometric mean bias (MG)*

The geometric mean bias is given by:

$$MG = \exp(\overline{\ln C_0} - \overline{\ln C_p}) \tag{20}$$

C. *The Normalized Mean Square Error (NMSE)*

The mean square error, also called quadratic risk for a 1-dimensional parameter C is defined by:

$$NMSE = \frac{\overline{(C_0 - C_p)^2}}{\overline{C_0} \times \overline{C_p}} \tag{21}$$

D. *The geometric variance (VG)*

The geometric variance is given by:

$$VG = \exp\left[\overline{(\ln C_0 - \ln C_p)^2}\right] \tag{22}$$

E. *Le facteur 2 (FAC2)*

The factor of two (FAC2) is defined as the percentage of predicted within a factor of two of the observed values. The ideal value of the factor of two. Must be 1, (100%).

$$FAC2 = \frac{C_p}{C_0} \tag{23}$$

Where:
C_p: model predictions;
C_o: observations;
Overbar $(\overline{C})$: average over the dataset.

A perfect model would have MG, VG, and FAC2 = 1.0; and FB and NMSE = 0.0

Multiple performance measures should be applied and considered in any model evaluation exercise, as each measure has advantages and disadvantages and there is not a single measure that is universally applicable to all conditions. The relative advantages of each performance measure are partly determined by the characteristics and distributions of the model predictions and observations [7].

FB and MG are measures of mean relative bias and indicate only systematic errors, whereas NMSE and VG are measures of mean relative scatter and reflect both systematic and unsystematic (random) errors. For FB, which is based on a linear scale, the systematic bias refers to the arithmetic difference between C_p and C_o; and for MG, which is based on a logarithmic scale; the systematic bias refers to the ratio of C_p to C_o. Because FB is based on the mean bias, it is possible for a model whose predictions are completely out of phase with observations to still have a FB=0 because of compensating errors. An alternative is to consider a slightly modified version of FB where the two error components (i.e., overprediction and underprediction) are separately treated.

V. RESULTS AND DISCUSSION

The three figures (10, 11 and 12) represent the statistical validation and comparison between the results obtained by numerical simulation using MATLAB code by comparing them with experimental results for voltage, current and power (V, I, P) according to the three measuring points selected for the temperature (T1, T2 and T3) and the solar radiation (G1, G2, G3), the figures represent the statistical analysis for the components (I, P) according to the three cases respectively;

- **Case 01**: a temperature of 38.1°C and a solar radiation of 330 W/m², the results of the current (I) and power (P) are generally acceptable for statistical factors (FB, NMSE, VG and FAC2) except factor (MF) is not acceptable.
- **Case 02**: a temperature of 43.8°C and a solar radiation 525 W/m², the results of the current (I) and power (P) are acceptable for statistical factors (FB, NMSE, and FAC2) and factors (MG, VG) are not acceptable.
- **Case 03**: a temperature of 48.2°C and a solar radiation 692 W/m², the results of the current (I) and power (P) are acceptable for statistical factors (FB, NMSE, and FAC2) and factors (MG, VG) are not acceptable.

A. Case 01: for G=330 w/m² and T= 38.1 C°

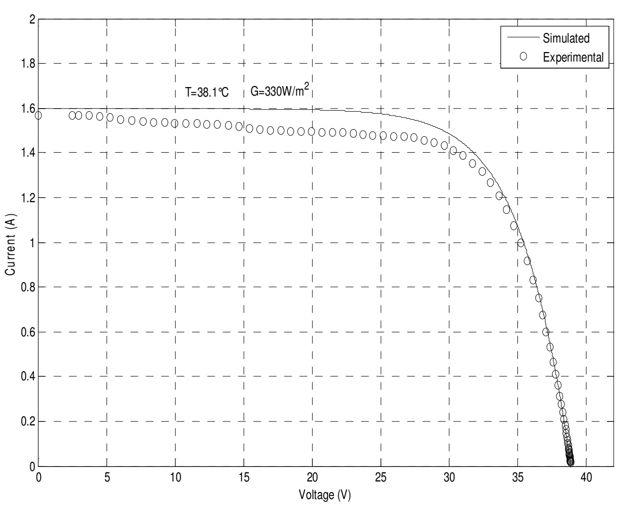


Fig. 10.a I-V characteristics of PV module (numerical simulation results with experimental data)

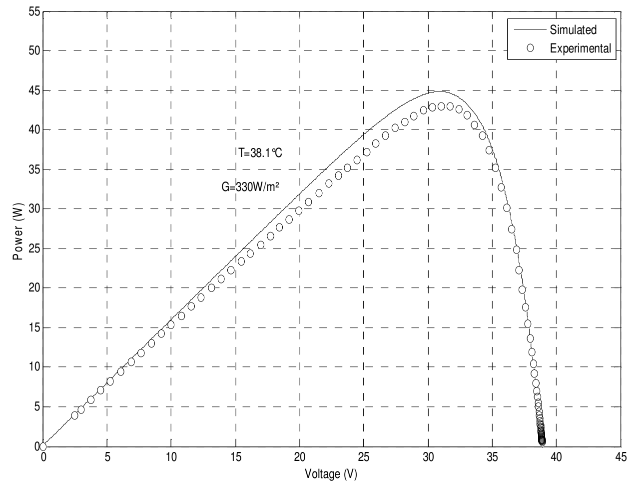


Fig. 10.b P-V characteristics of PV module (numerical simulation results with experimental data), for T=38.1°C, G=330W/m^2

Table 2 shows the values of statistical parameters of this case;

	FB	MG	NMSE	VG	FAC2
I (Current)	**4,02E-02**	**1,27E-01**	**4,09E-03**	**1,0753111**	**0,98**
P (Power)	**3,78E-02**	**8,26E-07**	**4,72E-03**	**1,0760345**	**0,9798**

B. Case 02: for G=525 w/m² and T= 43.8 C°

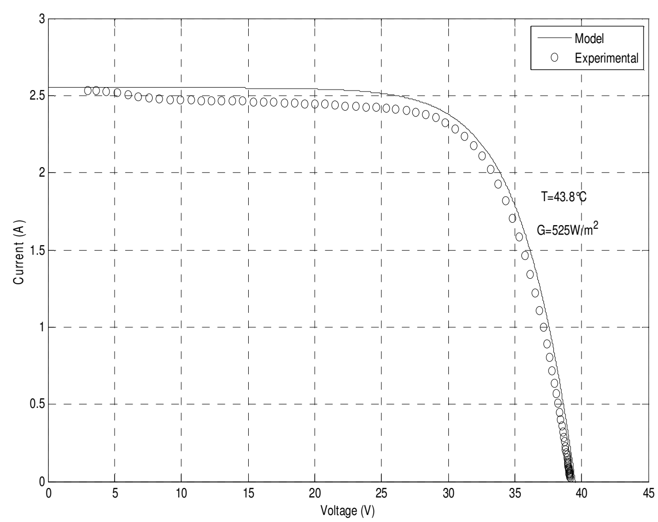


Fig. 11.a I-V characteristics of PV module (numerical simulation results with experimental data)

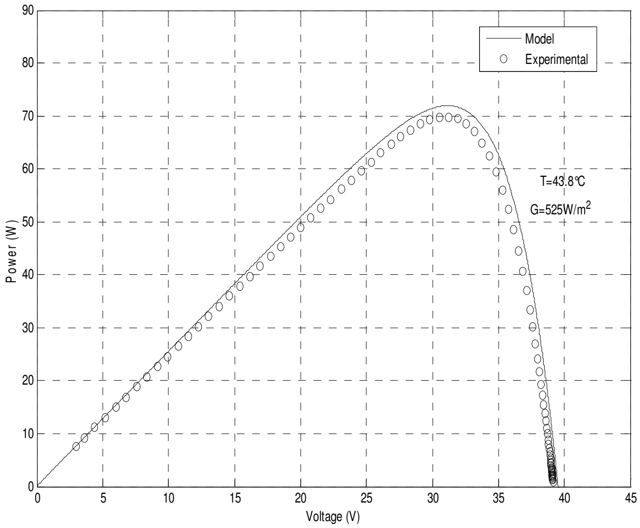


Fig. 11.b P-V characteristics of PV module (numerical simulation results with experimental data)

Table 3 shows the values of statistical parameters of this case;

	FB	MG	NMSE	VG	FAC2
I (Current)	**1,79E-01**	**0,29484447**	**4,45E-02**	**4,28104779**	**0,590**
P (Power)	**2,87E-01**	**2,8986E-14**	**1,27E-01**	**4,34439477**	**0,586**

C. Case 03: for G=698 w/m² and T= 48.2 C°

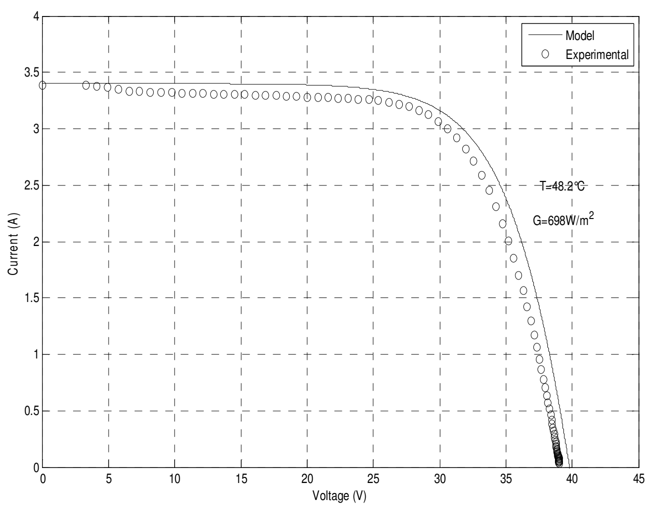


Fig. 12.a I-V characteristics of PV module (numerical simulation results with experimental data)

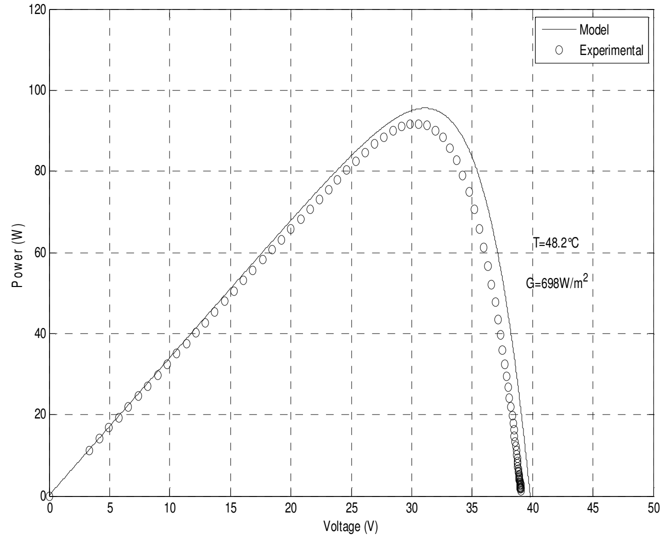


Fig. 12.b P-V characteristics of PV module (numerical simulation results with experimental data)

Table 4 shows the values of statistical parameters of this case;

	FB	MG	NMSE	VG	FAC2
I (Current)	**1,09E-01**	**0.26320176**	**1,41E-02**	**2.33581381**	**0,650**
P (Power)	**1,72E-01**	**9,1018E-11**	**4,11E-02**	**2,35591522**	**0,646**

It may be noted that the experimental characteristics do not differ much from the simulated characteristics; the small difference is due to small variations in the temperature at the time of testing.

VI. CONCLUSION

According to the results exposed on this paper, the agreement deduced - between the experimental profile and that obtained numerically in MATLAB environment is acceptable. The mathematical model simulation shows a good agreement with experimental characteristics.

The characteristics of the Current and the power show the nonlinear nature of the photovoltaic panel BP3160.

The analysis of the different results, allowed to state that the current of a solar cell is proportional to the illumination, increasing slightly with temperature. The open circuit voltage of a solar cell varies weakly with illuminance and decreases with increasing temperature. Also optimum power increases mainly with increasing illumination and decreases rapidly with increasing temperature. The simulation of these results is confirmed by experimental measurements (Statistical Validation).

Using the method of statistical calculation to better appreciate the results, it has been proven good quality of the latter.

BIBLIOGRAPHIE

[1] Byung-Duk Min and al., “A New Topology With High Efficiency Throughout All Load Range for Photovoltaic PCS”, *IEEE Transactions On Industrial Electronics*, Vol. 56, No. 11, pp. 4427-4435, 2009

[2] Sergio Busquets-Monge and al., “Multilevel Diode-Clamped Converter for Photovoltaic Generators With Independent Voltage Control of Each Solar Array”, *IEEE Transactions On Industrial Electronics*, Vol. 55, No. 7, pp. 2713-2723, 2008

[3] M. Hadjab et al., “Neural network for modeling solar panel”, *International Journal of Energy*, North Atlantic University Union, Issue 1, Vol. 6, pp. 9-16, 2012

[4] BP Solar BP3160-160W Multi-crystalline photovoltaic Module Datasheet.

[5] G. Walker, “Evaluating MPPT converter topologies using a MATLAB PV model”, *Journal of Electrical & Electronics Engineering*, Australia, IEAust, Vol. 21, No. 1, pp.49-56, 2001

[6] Messenger, Roger & Jerry Ventre, “ Photovoltaic Systems Engineering” 2nd Edition *CRC Press*, 2003

[7] Chang, J. C. et Hanna, S.R, “Air quality model performance evaluation”, *Meteorol. Atmos*. Phys., 87, pp. 167-196, 2004

M. Hadjab, was born in M'sila (Algeria) in 1984. He received the Eng. degree in Electronic Engineering from Msila’s University, Algeria, in 2007; the M.S. degree in Optoelectronic materials and components from Djillali Liabes’s University of Sidi Bel Abbes, Algeria, in 2011. Now he is a Ph.D. student at the Department of Electronic in the same university (Djillali Liabes’s University of Sidi Bel Abbes, Algeria). He is a member of the applied materials laboratory, Research center, Algeria. His research interests include the optimization and development of photovoltaic cells performances. He is an author of 01 scientific articles.