A Comparative Study to Select a Mathematical Model for I-V Characteristics Accuracy under Outdoor Conditions

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Abstract—**The purpose of the present work is to select an adequate mathematical model for the PV module electrical production estimation. The I-V characteristic performances have been investigated at outdoor conditions of local site in Ghardaia located at 600 km south of Algiers. Recurrent tests of characterization have been carried out on eight modules of four different technologies. Then, four different mathematical models have been applied to process the recorded experimental data. Through a comparative study based on the RMSE (Root Mean Square Error), it has been averred that the five parameter model showed a better accuracy. The selected model is used to determine PV module performance parameters for all operating conditions. The obtained results have been used to establish correlation for each parameter upon solar irradiance intensity and PV module temperature.**

***Index Terms*— modeling, simulation, model, Photovoltaic modules.**

I. INTRODUCTION:

The performances of a PV module strongly depend on the availability of solar irradiance and the PV module temperature at the required location. Thus, The PV module performances behavior under different operating conditions still of great concern of Photovoltaic field researchers.

For the purpose to implement a photovoltaic PV system simulation program, it will be necessary to adopt a mathematical model that reproduces the I-V characteristic curve with high accuracy. The most methods are usually validated in standard test conditions STC (T=25 °C; E=1000 W/m2). However, the indoor characteristics don't reflect the real performances under outdoor testing condition. In fact, PV module characteristics are directly influenced by solar irradiance, the module temperature and by other parameters such as tilt and azimuth angles.

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An extensive works on PV module characterization have been carried out based upon the four fundamental chracteristics of the PV module, namely: short circuit (Isc), open circuit (Voc), maximum current (Im) and maximum voltage (Vm). Many mathematical methods were developed for an operating conditions performance prediction. These developed methods help photovoltaic users to control the PV modules production based on measured data, which can be performed far away from photovoltaic reference laboratories even when standard conditions are not availables.

A number of eight PV modules of four different Photovoltaic technologies, namely: Mono-crystalline silicon, polycrystalline silicon, triples –junction Amorphous and Thin-film (CIS) have been put into test. Then, four mathematical models have been suggested to process the recorded data. These are: Explicit model, Simplified model, double exponential model and five parameters model. The results were compared to those recorded from the experimental data under the local outdoor conditions. The five parameters model fits better the generated characteristic curves. The selected method is introduced to provide PV module performance parameters for all operating conditions. The obtained results have been used to macke a correlation for each parameter upon solar irradiance intensity and PV module temperature.

II. CHARACTERISTICS OF THE SITE:

Characterization tests were performed at outdoor conditions of the testing site (Applied Research Unit for Renewable Energies). The site is located in Ghardaia about 600 km south of Algiers. Having the following coordinates Latitude. 32°36' N, Longitude: 3°81' E and elevation of 450 m above sea level, this area is classified as an arid region. Based upon meteorological data the solar resources and temperatures are as follows: rate of sunny days varies between 77% and 80 % per year; the average daylight hours is approximately 5 hours in winter and up to 10 hours over the remaining seasons. The daily average irradiation on an horizontal surface varies between 6 kW/m2 per day and 7 kW/m2 /day.

III. DESCRIPTION OF THE LAB.

The instrument for recording IV-curves was a PV Photovoltaic Field Array Tester. It is a portable array tester and it uses a discharged capacitor that functions as 'load resistor'. Current and voltage are measured during the process of charging the capacitor.

A calibrated reference solar cell was used for measuring irradiance and cell temperature (Figure 2). It consists of m-Si cell. A Pt1000 temperature sensor is glued at centre of cell backside. The Pt1000 sensor returns automatically the temperature value.

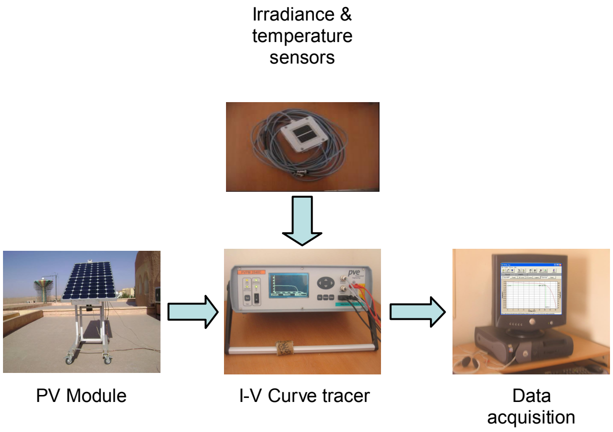

Fig. 1 Test Bench Synoptic

TABLE1 STATEMENT UNDER THE STC OF THE DIFFERENT TESTED PV MODULES

Module	Techno -logy	Electric characteristics				
		I_{SC} (A)	V_{OC} (V)	Im (A)	Vm (V)	P (W)
ASE100 GTFT95	mc-Si	3.2	42.3	2.80	34.1	95
BP3160	pc-Si	4.8	44.2	4.55	35.1	160
US64	TJ a-Si	5.1	21.3	4.10	15.6	64
ST40	TF (CIS)	2.6 8	23.3	2.41	16.6	40
NTR5E3 E	mc-Si	5	4.4	4.95	35.4	175
S75	pc-Si	4.7	21.6	4.26	17.6	75
SLK60P 6	pc-Si	7.3 8	36.9	6.70	30	200
SLK72M 6	mc-Si	5.4 8	44.4	4.85	36.8	180

IV. MATHEMATICAL MODELS:

Mathematical model is usually used to make an accurate approach of the I-V characteristics curve produced from the experimental data at outdoor conditions. The best model which shows a better similitude with the real I-V curve is selected.

Below, four mathematical models have been put into test to produce the same I-V characteristics and then the four approaches were compared:

A. *Explicit model*

This model requires the four parameters data known as the short-circuit current (Isc), open circuit voltage (VOC), maximum point current (Im) maximum point voltage (Vm) [1]. The relation between current I and voltage V is given by the following equations:

$$I = I_{SC}\left[1 - C_1\left(\exp\left(\frac{V}{C_2 V_{OC}}\right) - 1\right)\right] \qquad (1)$$

With:

$$C_1 = \left(1 - \frac{I_m}{I_{SC}}\right)\exp\left(\frac{-V_m}{C_2 V_{OC}}\right) \qquad (2)$$

$$C_2 = \frac{\dfrac{V_m}{V_{OC}} - 1}{Ln\left(1 - \dfrac{I_m}{I_{SC}}\right)} \qquad (3)$$

The constants C1 and C2 are evaluated in the beginning of the iteration; however, the equation (1) is evaluated at each iteration step.

B. *Simple exponential model*

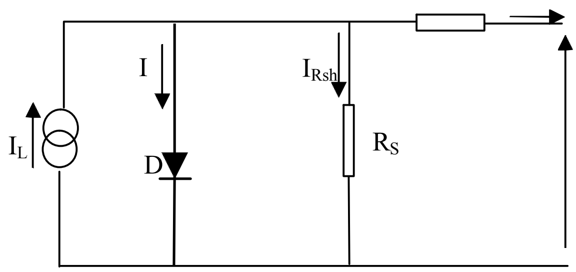

Fig.2 Equivalent circuit of one diode model

In this model the following hypothesis are made to use the simplified model [2] :

- The resistance RSh is very high: VOC / RSh << ISC
- The photo- generated current, IL, and the short circuit current, ISC, are equal
- $\exp\dfrac{V + IR_S}{mV_t} >> 1$
- m = 1
- Open circuit condition:

$$I_0 = I_{SC}\exp\left(-\frac{V_{OC}}{mV_t}\right) \qquad (4)$$

The equivalent scheme is the same as the one shown in the figure (2.1??). The following equations are obtained:

$$I = I_{SC}\left[1-\exp\left(\frac{V-V_{OC}+IR_S}{mV_t}\right)\right] \quad (5)$$

With:

$$FF_0 = \frac{v_{OC}-\ln\left(v_{OC}+0{,}72\right)}{v_{OC}+1} \quad (6)$$

$$FF = \frac{\mathrm{Im}\,Vm}{I_{SC}V_{OC}} = FF_0\left(1-r_S\right) \quad (7)$$

Considering:

$$rs = Rs\left(\frac{I_{SC}}{V_{OC}}\right) \quad \text{et} \quad v_{OC} = \frac{V_{OC}}{mV_t} \quad (8)$$

The empiric value 0,72 of the equation (6) is only valid for the Silicium crystalline modules.

C The double exponential model

The analytical expression of this model is deduced from the electrical circuit shown in the figure 2, [3].

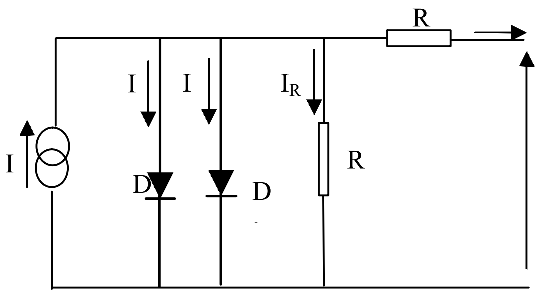

Fig. 3 Equivalent circuit of two exponentials

$$I = I_L - I_{01}\left[\exp\left(\frac{V+IR_S}{m_1V_t}\right)-1\right] - I_{02}\left[\exp\left(\frac{V+IR_S}{m_2V_t}\right)-1\right] - \frac{V+IR_S}{R_{Sh}} \quad (9)$$

The model different parameters determination (IL, m1,m2, I01, I02, RS, RSh) is done on the basis of the following approximations.

- Ideal factor m is considered constant:
$m = m_1 = m_2 = 2$

- IL is approximated to ISC as follows:
$I_L = I_{SC}$

- The two saturation currents are determinate by the following equations:

$$I_{01} = \frac{1}{2}\frac{I_L}{\left(\exp\left(\frac{eV_{OC}}{kT}\right)-1\right)} \quad (10)$$

$$I_{02} = \frac{1}{2}\frac{I_L}{\left(\exp\left(\frac{eV_{OC}}{2kT}\right)-1\right)} \quad (11)$$

- R_S is calculated by derivation of the equation (2.40) for V=VOC:

$$R_S = -\left[\left.\frac{dV}{dI}\right|_{V_{OC}} + \frac{1}{\left(X_{1V}+X_{2V}+\frac{1}{R_{Sh}}\right)}\right] \quad (12)$$

Explicated as:

$$X_{1V} = \frac{eI_{01}}{kT}\exp\left(\frac{eV_{OC}}{kT}\right) \quad (13)$$

$$X_{2V} = \frac{eI_{02}}{mkT}\exp\left(\frac{eV_{OC}}{mkT}\right) \quad (14)$$

The ratio $\frac{1}{R_{Sh}}$ is negligible in front of ($X_{1V}+X_{2V}$) from where the final expression is drawn:

$$R_S = -\left[\left.\frac{dV}{dI}\right|_{V_{OC}} + \frac{1}{\left(X_{1V}+X_{2V}\right)}\right] \quad (15)$$

The resistance RSh is provided from equation 2.43 for I=ISC ; which gives :

$$R_{Sh} = -\frac{1}{\left(\frac{1}{\left(\left.\frac{dV}{dI}\right|_{I_{SC}}+R_S\right)}+X_{1i}+X_{2i}\right)} \quad (16)$$

Explicitly as:

$$X_{1i} = \frac{I_{01}}{V_t} \exp\left(\frac{I_{SC} R_S}{V_t} \right) \quad (17)$$

$$X_{2i} = \frac{I_{02}}{mV_t} \exp\left(\frac{I_{SC} R_S}{mV_t} \right) \quad (18)$$

Other approach to calculate RSh consists to evaluate the equation (9) at maximum operating point by using the value RS (15); yielding the following equation:

$$R_{Sh} = \frac{V_{mpp} + I_{mpp} R_S}{I_{mpp} - I_{I0} + I_{01}\left[\exp\left(\frac{e(V_{mpp} + I_{mpp} R_S)}{kT} \right) - 1 \right] + I_{02}\left[\exp\left(\frac{e(V_{mpp} + I_{mpp} R_S)}{mkT} \right) - 1 \right]} \quad (19)$$

D The five parameters model

In this model [4] the recombination current effect is neglected. for a given solar irradiance and temperature , the five parameters IL, I0, RS, Rsh and m can be determined from VOC, ISC, Im and the maximum power point (Vm) and the slopes nearest of Voc et Isc.

The behavior of a photovoltaic generator may be closely represented by the five parameter model based on one diode equivalent circuit of a solar cell, it consists of a diode, a current source, a series resistance, and a parallel resistance

The current source generates photocurrent (Iph) which is a function of incident solar irradiation and cell temperature. The diode represents p–n junction of the solar cell. At real solar cells, the voltage loss on the way to the external contacts is observed. This voltage loss is expressed by a series resistance (Rs). Furthermore, leakage currents are described by a parallel resistance (Rp). Using Kirchhoff's first law, the equation for the extended I–V curve is derived as shown by equation 20:

$$I = I_L - I_0\left[\exp\left(\frac{V + IR_s}{mV_t} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \quad (20)$$

Where I is the output current of PV module, V is the terminal voltage of the cell or module, q is the electric charge (1.6×10^{-19} C), k is the Boltzman constant (1.38×10^{-23} J/K), and T is the cell temperature (K). m is the ideality factor, IL the photogenerated current under insolation, Rsh: shunt resistor; RS: series resistor and I0 is the diode saturation current.

The five equivalent circuit parameters can be determined by using the available operating points on the I–V curve by the equations 21-26:

$$\left(\frac{dV}{dI} \right)_{V=Voc} = -R_{so} \quad (21)$$

$$\left(\frac{dV}{dI} \right)_{I=Isc} = -R_{sho} \quad (22)$$

$$m = \frac{V_m + I_m R_{so} - V_{oc}}{V_t\left[\ln\left(I_{sc} - \frac{V_m}{R_{sh}} - I_m \right) - \ln\left(I_{sc} - \frac{V_{oc}}{R_{sh}} \right) + \left(\frac{I_m}{I_{sc} - \frac{V_{oc}}{R_{sho}}} \right) \right]} \quad (23)$$

$$I_0 = \left(I_{sc} - \frac{V_{oc}}{R_{sh}} \right) . \exp\left(\frac{V_{oc}}{mV_t} \right) \quad (24)$$

$$R_s = R_{so} - \frac{mV_t}{I_0} \exp\left(- \frac{V_{oc}}{mV_t} \right) \quad (25)$$

$$I_L = I_{sc}\left(1 + \frac{R_s}{R_{sh}} \right) + I_0\left(\exp\frac{I_{sc} R_s}{mV_t} - 1 \right) \quad (26)$$

After the parameter calculation their value were substituted at Equation 20 and the I-V characteristic curve (current versus voltage) for the photovoltaic module was simulated. The values of Voc, ISC, Vmp, Imp, are given by the manufactures (or measured) were used in the simulation.

One file with all data measured was created and one can simulate different photovoltaic modules to any given solar radiation and cell temperature.

V. RESULTS AND DISCUSSION

Under the local outdoor test condition, four models have been applied on the eight different mentioned solar modules. The standard characteristics of the subjected modules are shown in the table below, namely: Mono-crystalline silicon, Poly-crystalline silicon, triple-junction Amorphous and Thin-film (CIS). Characterization was performed at outdoor conditions of the Ghardaïa site. The standard characteristics of tested module are done in table 1.

A Comparison between the four used models

The statistic indicators used to test the quality of the fit to the experimental data are the Root Mean Square Error (RMSE) equation 27.

$$RMSE = \left[\frac{\sum \left(I_{cal} - I_{\exp}\right)^2}{N} \right]^{0,5} \quad (27)$$

The analysis of the recorded results by mean of RMSE (Root Mean Square Error)

TABLE.2
MAXIMUM RMSE BETWEEN THE SIMULATED AND MEASURED VALUES

	RMSE5P	RMSEE	RMSES	RMSE 2EXP
ASE95M	0.03800	0.03154	0.15522	0.20141
SLK72M	0.06240	0.05520	1.87090	0.25610
SHARP 175M	0.06842	0.06178	0.33682	0.27069
SLK60P	0.08370	0.21023	0.84654	0.56789
US64A	0.06777	0.06094	0.36352	0.61267
BP3160P	0.04861	0.06367	0.54574	0.25804
ST40CIS	0.03359	0.18207	0.29436	0.19598
S75P	0.06064	0.07933	?	0.27671

With all the necessary data and parameters for plotting the curves (IL, I RS, Vm, Voc, ISC and Im), it was possible to simulate, the desired photovoltaic module. Figures 4-7 shows an example of the simulation output that are the graphs of voltage versus current and measured curve for the photovoltaic different modules, for different radiation levels (400 W/m2 - 1000 W/m2) and different temperatures (25ºC - 50ºC).

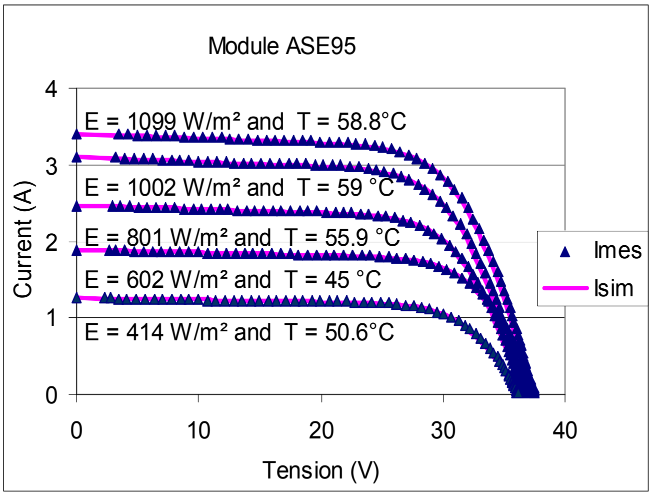

Fig. 4 Characteristics measured and simulated under different test conditions for ASE95.

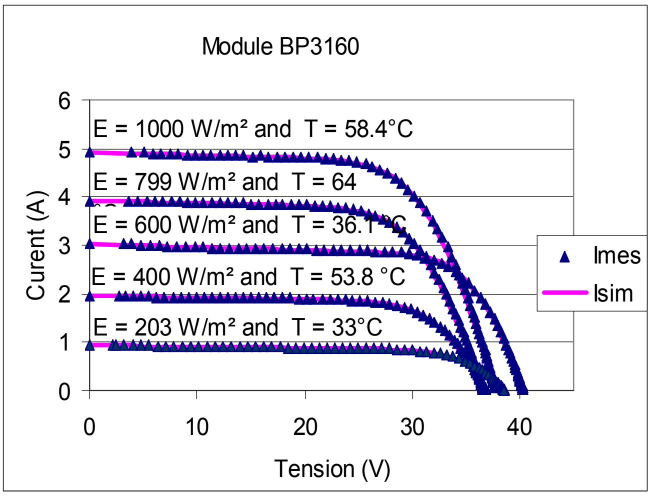

Fig. 5 Characteristics measured and simulated under different test conditions for BP3160

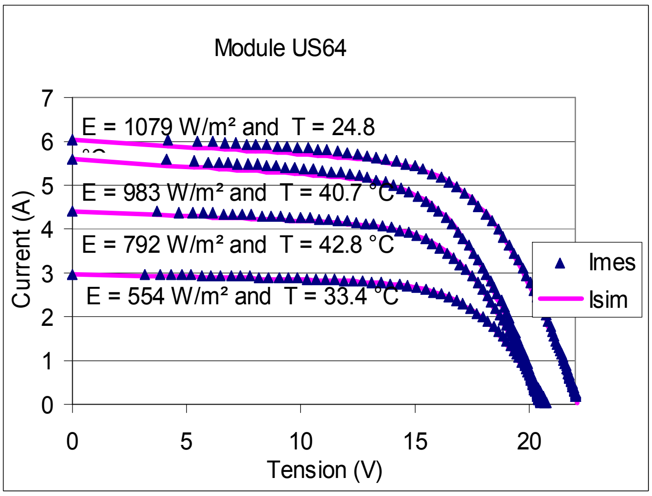

Fig. 6 Characteristics measured and simulated under different test conditions for US64

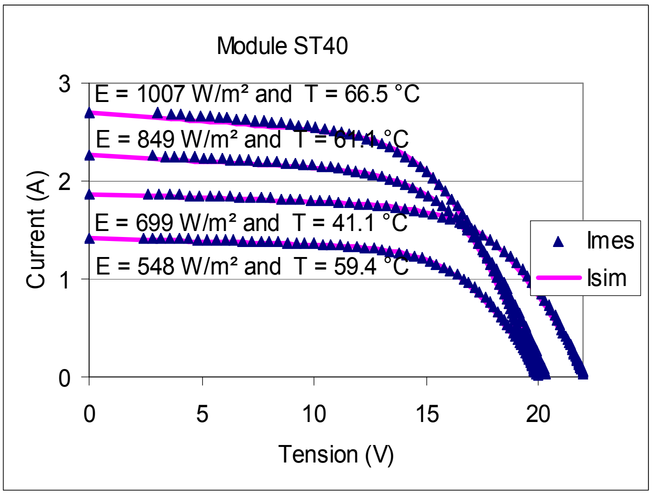

Figure 7 Characteristics measured and simulated under different test conditions for ST40

Through a comparative study of the obtained results for the different models, it has been showed that the five parameters is more accurate model. However, it is necessary to calculate the slopes vicinity of ISC and de VOC.

The explicit model is the most simplified, there is no need for iterative methods.

5.2 Correlation of module parameters

To characterize a PV module as a power source in performance analysis, it is very important to take into consideration the dependence of all equivalent circuit parameters of PV module on irradiation and cell temperature [5, 6, 7, 8, 9] to be able to obtain the variations of the parameters over the whole range of operating condition. For the determination of the veracity of the simulated I-V characteristic curves, the curves supplied by measured data (what it means this sentence in red color). Simple correlations, as: a*E + b*T + c, were used to compare, and quantify errors between the Simulated curves with the ones provided by measured ones by the coefficient of determination are given by:

$$R^2 = \left(\frac{\sum \left(I_{\exp} - \overline{I_{\exp}}\right)\left(I_{cal} - \overline{I_{cal}}\right)}{\sqrt{\sum \left(I_{\exp} - \overline{I_{\exp}}\right)^2 \sum \left(I_{cal} - \overline{I_{cal}}\right)^2}} \right)^2 \qquad (28)$$

Where Ical and Iexp are respectively, the calculated and measured currents, and N numbers of points of measure.

Comparing the simulated values with the measured values, it is noted that the results are practically identical.

The maximum RMSE the simulated and observed values, supplied by the measured, was presented at below. This indicates that the model used for simulation of the eight type photovoltaic modules is valid.

TABLE3 DETERMINATION COEFFICIENTS OF THE EIGHT PV MODULE CHARACTERISTICS

	Module			
Param	BP3160	SLK60	US64	ST40
P	0.9963	0.9900	0.9935	0.9907
Isc	0.9964	0.9989	0.9998	0.9986
Voc	0.9445	0.8800	0.9343	0.9652
Im	0.9973	0.9960	0.9968	0.9951
Vm	0.9293	0.8771	0.9123	0.9613
M	0.3019	0.0212	0.7837	0.9583
I0	0.0009	0.0500	0.0144	0.3798
IL	0.9982	0.9989	0.9985	0.9991
Rsh	0.6165	0.7427	0.9372	0.9286
Rs	0.6959	0.7817	0.4412	0.7881

From table 3, it is obviously showed the better correlation of the IV characteristics of the ST40 module. A bad correlation for I0 is remarked for non-existed linear correlation and a polynomial correlation for RS parameter should be better. .

The results of parameter correlation are presented in graphic form as shown in figure 8 to figure 13.

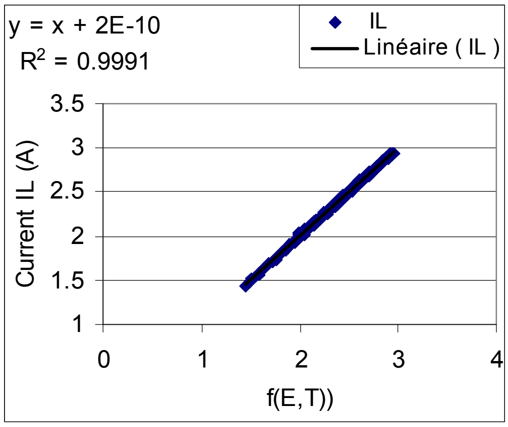

Fig. 8 Correlation of light current as function of insolation and temperature for ST40.

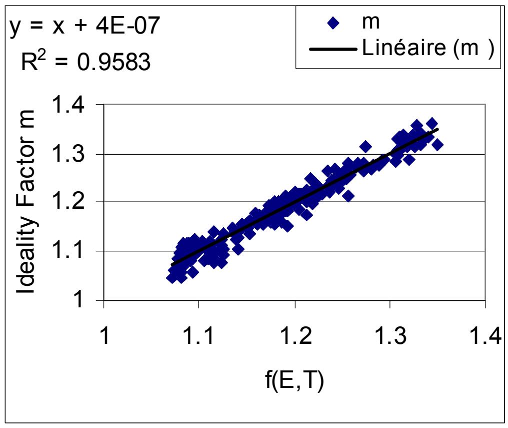

Fig.9 Correlation of ideality factor as function of insolation and temperature for ST40.

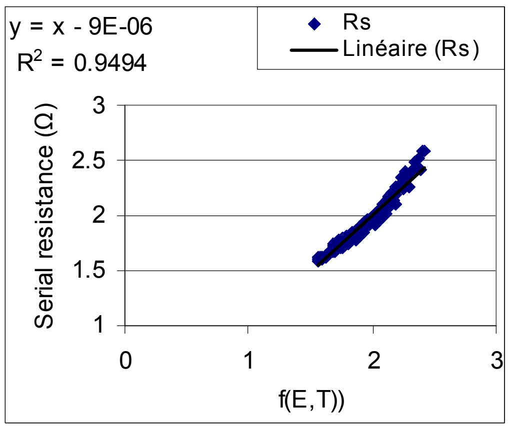

Fig. 10 Correlation of series resistor as function of insolation and temperature for ST40.

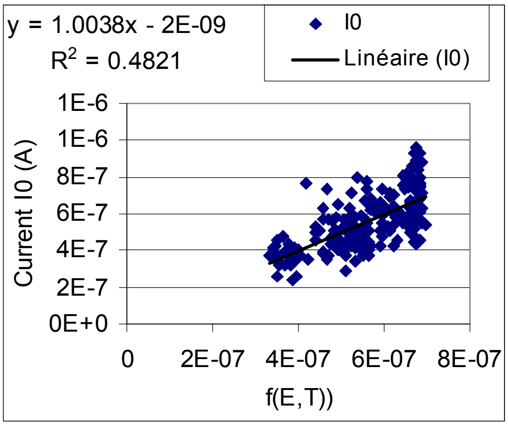

Fig. 11Correlation of saturation current as function of insolation and temperature for ST40.

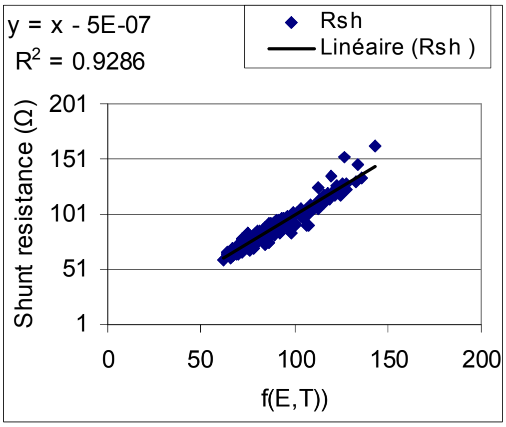

Fig.12 Correlation of shunt resistor as function of Insolation and temperature for ST40.

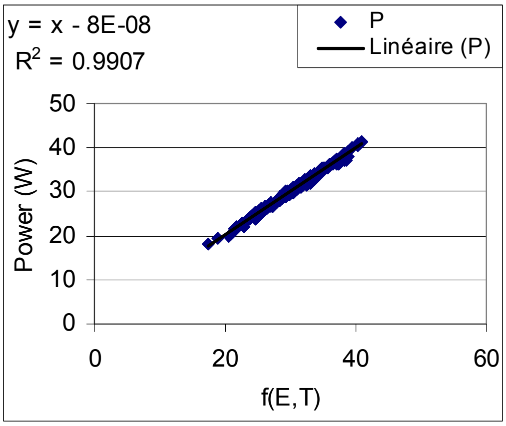

Fig. 13 Correlation of maximum power in function of insolation and temperature for ST40.

VI. Conclusion

In the current contribution, we have investigated the IV characteristics performances of eight PV modules made through different technology using four mathematical models. It was found that five parameters model fit better; therefore it is selected to determine PV module parameters performances under outdoors operation conditions.

A simple correlation has been used in order to illustrate the relationship between the five parameters in function of solar radiation and PV module temperature. The obtained results revealed that the eight modules present a tolerable correlation, thus, this correlation approach can be used for further IV characteristics translation under different operating conditions.

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