Identification of Internal Parameters of a Mono-Crystalline Photovoltaic Cell Models and Experimental Ascertainment

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Abstract- This paper presents two mathematical models of mono-crystalline solar photovoltaic (PV) cells: (i) the ideal model, and (ii) the single resistance model. An identification algorithm of internal parameters of photovoltaic cell using electrical characteristics provided by the manufacturer datasheet has been suggested. Several of these parameters are not always provided by the manufacturer. Moreover, influences and variation effects of the temperature and the effective irradiance level has been studied for the proposed models. Obtained simulations have been compared to those provided by JAC M5SF-2 cell's datasheet. These models have been implemented on Matlab-Simulink and Simpower softwares. Then, the effectiveness of the proposed models has been validated against an experimentally tests under real operating conditions. The setup is based on some sensors: current, voltage, temperature and light sensors. Two Arduino Boards are used to acquire data from sensors and send them to the computer. These results show an acceptable correspondence with the data issued by the manufacturer. Identification algorithms, based on the rated data given by the manufacturer, can thus, be very useful for researchers or engineers to quickly and easily determine the internal parameters of any photovoltaic cell.

Keywords PV cells, mathematical model, simulation, datasheet, internal parameters, temperature, solar irradiation.

1. Introduction

Nowadays, the world's energy needs are growing steadily. However, conventional sources of energy are limited. The sun, seen as a promising source of clean energy, is considered as an inexhaustible source of energy with the largest growth potential. The conversion of sunlight into electricity using solar cells system is a worthwhile way of producing this alternative energy. It produces electrical energy with clean and efficient manner, by subjecting cells on solar radiation [1], [2], [3].

Considering solar technology, the main challenge of researchers is to improve solar cells efficiency. Due to this challenge, several investigations have been developed to characterize the solar cells by determining their parameters [4], [5], [6], [7]. Indeed, it is important to know these parameters for estimating the degree of perfection and the quality of solar cells. However, the manufacturers give just the electrical features of photovoltaic panel under the standard test conditions (STC). Thus, several works focused on the identification of the unknown parameters of the PV model [8], [9], [10], [11], [12], [13].

According to NPD Solarbuzz, standard p-type multi and c-Si modules will remains the leading solar PV technology, accounting for 35% of PV modules produced in 2014, followed in the second position by the high-efficiency p-type mono modules, while production of the second type will grow by 2.8GW in 2014 due to the overall growth of the industry [14]. Thus, the mono-crystalline cell is the focus of this paper.

This paper carried out a Matlab-SIMULINK model of mono-crystalline PV cell that made possible the prediction of the PV cell behavior under different varying parameters such as solar radiation and ambient temperature.

In this work, two algorithms of determination of these parameters are described, which use a gradient approach to compute internal parameters of two single diode models of illuminated solar cells. Considered identification algorithms are mainly based on analytical or numerical solutions and use either the rated data given by the manufacturer. Calculations using these algorithms can be extended to generate the (I-V) and (P-V) curves for different temperatures and irradiances other than the standard test condition (STC) and for any photovoltaic cell.

The studied models are tested and validated for the mono-crystalline silicon. For other types of solar cells as polycrystalline silicon cells, some adjustments must take place inside the models to be faithful to the real behavior. In fact, the internal phenomenon and mechanisms inside the polycrystalline cells are more complicated due to the non normalized bandgap state, and that affect the forward current and the recombination paths, some studied are occurred to describe this problem [15]. The comparison between different types of PV cells could be the object of another interesting research work.

2. Mathematical Models of Photovoltaic Cell

When not exposed to light, the solar cell looks exactly like a diode junction, which, in the case where the junction is forward biased, it allows the passage of the current from P-area to the N-area. When the diode is subjected to light, a photocurrent I_{ph} proportionate to the incident radiation G is generated, and then distributed from the N-area to the P-area [1]. This arrangement can be easily represented by an equivalent electrical circuit consisting of an ideal source of current I_{ph} and a diode and some resistors if necessary characterizing the leakage currents.

Developing an accurate equivalent circuit for a PV cell, it is needful to understand the physical configuration of the elements of the cell as well as the electrical characteristics of each element.

2.1. The Ideal Photovoltaic Model

The ideal equivalent circuit of a PV cell is a current source in parallel with a single diode. The configuration of the ideal equivalent circuit of ideal solar cell with single-diode is shown in figure 1. The equivalent model is composed from a current source which generates the photocurrent I_{ph} and a diode traversed by a current I_d.

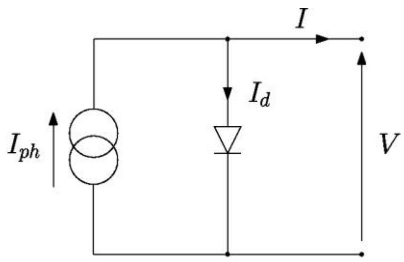

Fig. 1. Equivalent circuit of an ideal photovoltaic cell with single-diode.

The current I delivered by the cell can be expressed in terms of the photocurrent I_{ph}, the current I_d through the diode according to the following relationship:

$$I = I_{ph} - I_d \quad (1)$$

The relationship between the current I delivered by the cell and the voltage V at its terminals is described by:

$$I = I_{ph} - I_s(e^{\left(\frac{V}{V_t}\right)} - 1) \quad (2)$$

With: $$V_t = \frac{T_c\ K\ n}{q} \quad (3)$$

Where:

- Is: saturation current of the junction in the cell,
- Tc: temperature of the operating cell (°C)
- k: Boltzmann constant ($k = 1.38 \times 10^{-23}$ J / K)
- n: quality factor of the diode which is between 1 and 2,
- q: charge of an electron ($q = 1.6 \times 10^{-19}$C).

2.2. The Photovoltaic Model with Single-Diode and Single Resistance

More accuracy and complexity can be introduced to the previous model by adding one series resistance. Figure 2 shows the single diode equivalent circuit model with a single resistance of the PV cell which is commonly used in many studies and provides sufficient accuracy for most applications [10],[12]. This model comprises one resistance, namely R_s which is connected in series and represents various resistances connections.

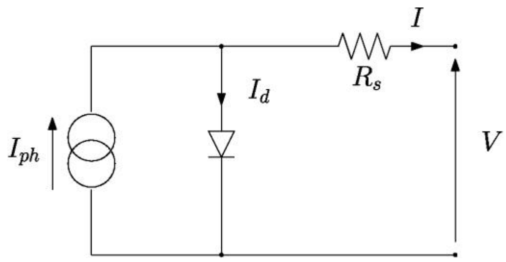

Fig. 2. Equivalent circuit of PV cell with single-diode and single resistance

The relationship between the currents I_d, and the voltage V across, is described by the following equations:

$$I_d = I_s\left(e^{\left[\frac{(V+R_s\,I)}{V_t}\right]} - 1\right) \quad (4)$$

Substituting the current I_d by his expression, Eq. (1) becomes:

$$I = I_{ph} - I_s\left(e^{\left[\frac{(V+R_s\,I)}{V_t}\right]} - 1\right) \quad (5)$$

3. Determination of Unknown Parameters

In order to define an electrical equivalent model of the PV cell, a system of equations should be established and then solved to determine unknown parameters which mark the cell properties [14], [16], [17], [18], [19]. In the second part of this section, an identification methodology will be proposed. Then, in the third part, a logical deduction sequence of mathematical relations will be developed to assess accurately the internal parameters of the photovoltaic cell.

3.1. The Manufacturer's Rate Data

Photovoltaic Solar Cell Proposed to be studied in this paper is the mono-crystalline Photovoltaic cell marketed under the reference JA Solar JAC M5SF-2 [20]. Electrical performances of the Photovoltaic Cell provided by the manufacturers consist of measuring the electrical current versus voltage (I-V) characteristic, while illuminated by suitable stable light source and maintained in a fixed temperature value. This performance test is the object of multiple Standards specifications and it provides a recognized method for testing and reporting the electrical behavior of photovoltaic cells [21].

The Standard Test Conditions (STC) includes the Cell temperature (Junction temperature), the total irradiation, and the reference spectral irradiance distribution. The following Table 1 summarizes the STC conditions:

Table 1. Standard test conditions

Test Condition	*Symbol*	*Value*
Irradiation	G_{ref}	1000 W/m2
Cell temperature	T_{ref}	25 °C

Electrical specifications provided by the manufacturer at the STC conditions in the cell's datasheet are summarized in Table 2.

Table 2. Electrical specifications of JAC M5SF-2 at STC

Electrical quantities	*Symbol*	*Value*
Maximum Power Point	Pm_{ref}	2.97 W
Voltage at Maximum Point	Vm_{ref}	0.537 V
Current at Maximum Point	Im_{ref}	5.531 A
Open Circuit Voltage	Voc_{ref}	0.637 V
Short Circuit Current	Isc_{ref}	5.888 A
Power Temperature Coefficient	Kp	-0.370 % /K
Voltage Temperature Coefficient	Kv	-0.241 % /K
Current Temperature Coefficient	Ki	0.033 %/K

The manufacturer of Photovoltaic cells includes in the product's datasheet the evolution of the (I-V) Characteristic supplied by the PV Cell at STC like the following Figure 3:

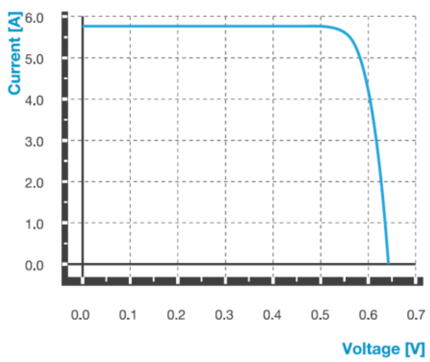

Fig. 3. (I-V) characteristic of the PV Cell "JA Solar JAC M5SF-2" at STC

3.2. Identification Algorithms for Unknown Parameters

The basic idea adopted in identifying internal parameters of the PV Cell is to exploit values of the electrical characteristics (V_{oc}, I_{sc}, P_m, V_m, I_m, K_i, K_v) provided by the manufacturer's data-sheet or directly measured from the PV cell. Considering models mentioned above, four electrical parameters are unknown and must be defined to identify these models. These parameters are: (i) the photocurrent I_{ph}, (ii) the diode reverse current I_d, (iii) the series resistance R_s, and (iv) the quality factor of the diode n. The determination of these quantities is based on solving a four equations system using only manufacturer's information of Table 2.

The (I-V) and (P-V) Characteristics Curves of the PV Cell are defined in Figure 4 which illustrates three key points, namely:

- The Short-Circuit point, coordinated (V, I) = (0, I_{sc}).
- The Open-Circuit point, coordinated (V, I) = (V_{oc}, 0).
- The maximum power point (MPP), coordinated (V, I) = (V_m, I_m).

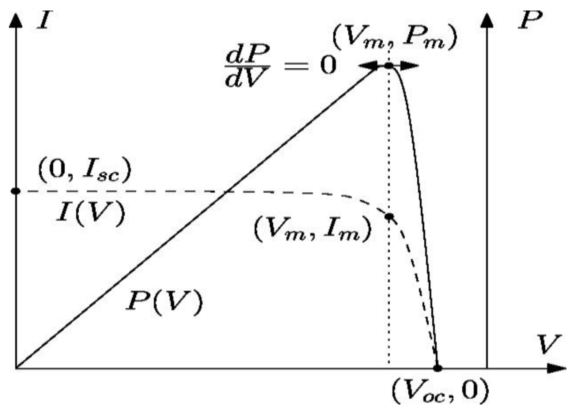

Fig. 4. Key points of (I-V) and (P-V) characteristics of the PV cell

The application of the current expression of the PV cell, on theses three key points, gives rise to three equations could be used to identify three unknowns' parameters. The fourth equation basically needed to solve the forth parameter of the one resistance model, correspond to the zero derivative of the power P relatively to the voltage V at the maximum power point (V, I) = (V_{mref}, I_{mref}) corresponding to P_{mref}.

A. Identification algorithm of unknown parameters of the ideal model :

Unknown parameters of the ideal model are: I_{ph}, I_s and n.

Applying Eq. (2) at the short-circuit point gives the following relationship:

$$I_{sc} = I_{ph} - I_s\left(e^{\left[\frac{0}{V_t}\right]} - 1\right) \tag{6}$$

At the open circuit Point, the Eq. (2) is written as follows:

$$0 = I_{ph} - I_s\left(e^{\left[\frac{(V_{oc})}{V_t}\right]} - 1\right) \tag{7}$$

Rewriting Eq. (2) at the maximum power point, gives rise to the following relationship:

$$I_m = I_{ph} - I_s\left(e^{\left[\frac{(V_m)}{V_t}\right]} - 1\right) \tag{8}$$

Taking into account the Eq. (7), the expression of the photocurrent I_{ph} is:

$$I_{ph} = I_{sc} \tag{10}$$

Thus, the saturation current I_s could be expressed from equation (8), as follows:

$$I_s = \frac{I_{sc}}{\left[\left(e^{\left[\frac{(V_{oc})}{V_t}\right]}\right)-1\right]} \tag{11}$$

Rewriting the Eq. (9), with replacing currents I_{ph} and I_s by their expressions, gives rise to the relationship of the current I_m at the maximum power point as follows:

$$I_m = I_{sc}\left(1 - \frac{\left[e^{\left[\frac{(V_m)}{V_t}\right]}-1\right]}{\left[e^{\left[\frac{(V_{oc})}{V_t}\right]}-1\right]}\right) \tag{12}$$

Using Eq. (10) and Eq. (11), the current I_{ph} and I_s could be easily calculated and determined only by using the information of the manufacturer's datasheet.

Otherwise the determination of the parameter n is based on the numerical resolution of Eq. (12). While the relation is not linear and difficult to resolve, we have to elaborate a numerical algorithm for the research of n. Figure 5 gives the adopted algorithm for the identification of the loss parameter n. The entries of such algorithm are previously summarized in Table2.

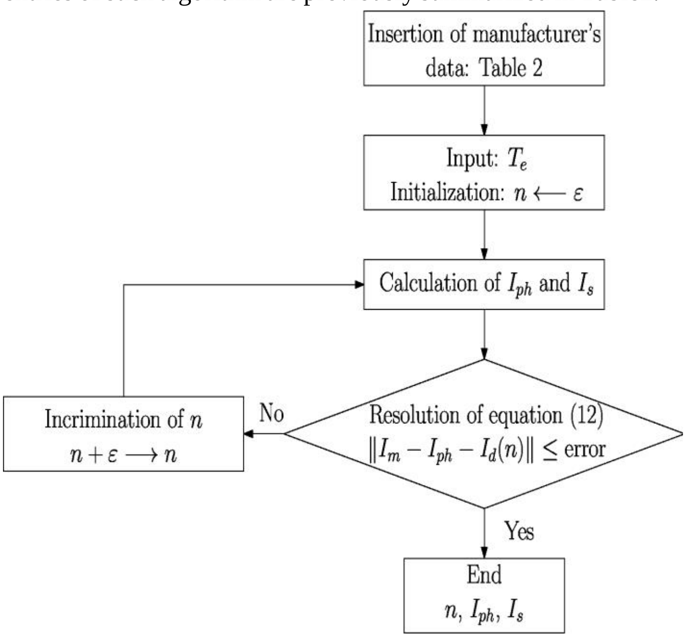

Fig.5. Research Algorithm for the ideal model

B. Identification algorithm of unknown parameters of the single resistance model :

The determination of the four unknown parameters of the single resistance model which are: I_{ph}, I_s, R_s and n need the use of the four equation system as follows.

Applying Eq. (6) at the short-circuit point gives the following relationship:

$$I_{sc} = I_{ph} - I_s\left(e^{\left[\frac{(I_{sc}\,R_S)}{V_t}\right]} - 1\right) \tag{12}$$

At the open circuit Point, Eq. (6) is written as follows:

$$0 = I_{ph} - I_s\left(e^{\left[\frac{(V_{oc})}{V_t}\right]} - 1\right) \tag{13}$$

Rewriting Eq. (6) at the maximum power point, gives rise to the following relationship:

$$I_m = I_{ph} - I_s\left(e^{\left[\frac{(V_m+I_m\,R_S)}{V_t}\right]} - 1\right) \tag{14}$$

Moreover, considering the Power derivative relatively to the voltage at the maximum power point, we can write:

$$\frac{dP}{dV} = \frac{d(I\,V)}{dV} = I + V\,\frac{dI}{dV} = 0 \tag{15}$$

The identification of the unknown parameters (I_{ph}, I_s, R_s, n) of the equivalent electrical model is based on solving the system formed by the relations (12), (13), (14) and (15).

Considering the following relations:

$$e_1 = \left(e^{\left[\frac{(V_{oc})}{V_t}\right]}\right) \tag{16}$$

$$e_2 = \left(e^{\left[\frac{(I_{sc}\,R_S)}{V_t}\right]}\right) \tag{17}$$

$$e_3 = \left(e^{\left[\frac{(V_m+I_m\,R_S)}{V_t}\right]}\right) \tag{18}$$

The subtraction of the relation (13) from relation (12) gives the following result:

$$I_{sc} = I_s\left[\left(e^{\left[\frac{(V_{oc})}{V_t}\right]}\right) - \left(e^{\left[\frac{(I_{sc}\,R_S)}{V_t}\right]}\right)\right] \tag{19}$$

Thus, the saturation current I_s could be expressed from Eq. (19) as follows:

$$I_s = \frac{I_{sc}}{e_1 - e_2} \tag{20}$$

Taking into account the Eq. (13), the expression of the photocurrent I_{ph} is:

$$I_{ph} = I_s\left(e^{\left[\frac{(V_{oc})}{V_t}\right]} - 1\right) \tag{21}$$

The substitution of the saturation current I_s, obtained from Eq. (20) in the expression of photocurrent Iph Eq. (21), leads to:

$$I_{ph} = I_{sc}\left(\frac{e_1-1}{e_1-e_2}\right) \quad (22)$$

Relations (20) and (22) are expressed in terms of the two other unknowns parameters: R_s and n. To solve this problem, we can use Eq. (14) and Eq. (15).

Rewriting the Eq. (14), with replacing the currents I_{ph} and I_s by their expressions, gives rise to the relationship of the current I_m at the maximum power point as follows:

$$I_m = I_{sc}\left(\frac{e_1-e_3}{e_1-e_2}\right) \quad (23)$$

Eq. (15) of the power derivative relatively to the voltage at the maximum power point is needed to find the forth losses parameter.

For the development of the derivatives in Eq. (15) we could use the expression of the (I-V) characteristics given by the Eq. (5)

$$I = f(I,V) = I_{ph} - I_s\left(e^{\left[\frac{(V+R_S\,I)}{V_t}\right]} - 1\right) \quad (24)$$

Letting:

$$dI = \frac{\partial f(I,V)}{\partial V}dV + \frac{\partial f(I,V)}{\partial I}dI \quad (25)$$

The derivative of the current I relatively to the voltage V, is written as:

$$\frac{dI}{dV} = \frac{\frac{\partial f(I,V)}{\partial V}}{1-\frac{\partial f(I,V)}{\partial I}} \quad (26)$$

And the derivative of the power P relatively to the voltage V is written as:

$$\frac{dP}{dV} = I + V\frac{\frac{\partial f(I,V)}{\partial V}}{1-\frac{\partial f(I,V)}{\partial I}} \quad (27)$$

Considering the Eq. (24), we have:

$$\frac{\partial f}{\partial V} = -\frac{I_s}{V_t}e^{\frac{(V+I\,R_S)}{V_t}} \quad (28)$$

$$\frac{\partial f}{\partial I} = -\frac{I_S R_S}{V_t}e^{\frac{(V+IR_S)}{V_t}} \quad (29)$$

Substituting Eq. (28) and Eq. (29) in Eq. (27) leads to:

$$\frac{dP}{dV} = I + V\frac{-\frac{I_S}{V_t}e^{\frac{(V+I\,R_S)}{V_t}}}{1+\frac{I_S\,R_S}{V_t}e^{\frac{(V+I\,R_S)}{V_t}}} \quad (30)$$

At the maximum power point, the Eq. (30) is written as:

$$\frac{dP}{dV} = I_m - \frac{V_m\,I_{SC}\,e_3}{V_t\,(e_1-e_2)+I_{SC}\,R_S\,e_3} = 0 \quad (32)$$

As previously done for the ideal model, the determination of the losses parameters of the single resistance model requires the elaboration of a research numerical algorithm. This time, the equation system is more complex and the convergence of the values needs the use of the gradient method. Figure 6 gives the adopted algorithm for the identification of R_s and n.

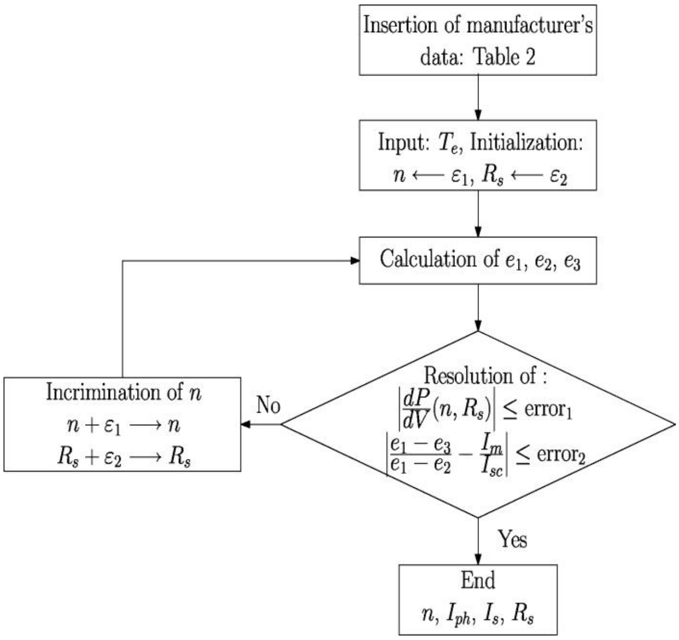

Fig. 6. Research Algorithm of single resistance model

4. Simulation Results: Models Validation

The simulation works, made in the MATLAB-Simulink environment, focus on the analysis of the electric characteristics of the developed equivalent electric models [22], [23], [24], [25], [26].

At the first part, we are interested in finding model parameters using two algorithms. In the second part, the study of the behavior of the solar cell by analyzing the effect of the irradiation and the temperature, in order to study the electric performances of the cell has been realized.

4.1. Results of The Identification Algorithms

Developed models and algorithms are tested on the solar cell JAC M5SF-2-, results are summarized in Table 3.

Table 3. Electrical parameters of JAC M5SF-2 on "STC"

JAC M5SF	***Ideal model***	***Single resistance model***
Cells number	(1)	(1)
I_{ph}	5.888 A	5.889 A
Is	1.04225 e-07 A	5.42634e-08 A
Rs		0.64 mΩ
n	1.389	1.34

Figure 7 show the comparison between (I-V) characteristic of datasheet, ideal model PV cell and one resistance model PV cell, respectively, at STC. One can notice a good agreement between the datasheet characteristic and the models.

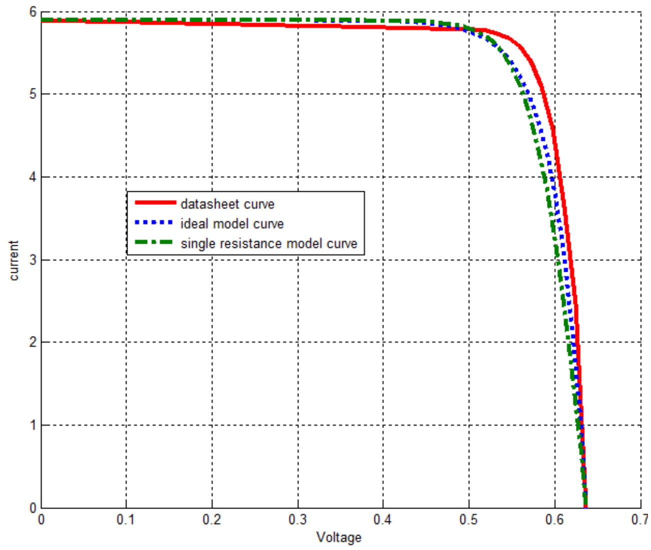

Fig.7. (I-V) cell characteristics of datasheet, ideal model PV cell and one resistance model PV cell under STC

4.2. PV cell Characteristics at Various Temperature and Irradiation

Equations and parameters of solar cell pre-described in the previous sections are all based on the following quantities: V_{oc}, I_{sc}, P_m, V_m, I_m, K_i, K_v.

When the cell is put under the standard conditions "STC", these quantities take the values described in the datasheet. Otherwise, under other climatic conditions in which the temperature is different from 25 ° C and the irradiance change from 1000Wm^{-2}, these quantities take other values. Hence, the correction should take place according to the values of the irradiance and the temperature [22].

The current delivered by the PV cell depends linearly to the variation of the junction temperature T_c while it depends proportionally to the light irradiation G, and we can write:

$$I(G,T) = \frac{G}{G_{ref}}\left(I_{ref} + K_i(T_c - T_{ref})\right) \quad (33)$$

With:

- T_{ref}, G_{ref}, I_{ref}: are the junction temperature, irradiation, and the measured current of the reference state.
- T_c, G, I: are the junction temperature, irradiation, and the measured current of the actual state.
- K_i: is the current coefficient

In a similar way, voltages delivered by the PV cell depend linearly to the temperature variation, and we can write:

$$V(T) = V_{ref} + K_v(T_c - T_{ref}) \quad (34)$$

Contrary to what has been written for currents, the irradiation doesn't affect directly the cell voltages, the relation between them is not proportional or linear, and the determination of the variation law V (G) could not be expressed independently from the current I (G).

Figures 8 and 9 show the effect of the irradiation variation G from 100W/m^2 to 1000W/m^2 with a step of 200 W/m^2 for a constant temperature T_c of the photovoltaic cell equals to 25°C.

Figures 10 and 11, show the variation effects of the temperature T_c of the photovoltaic cells from 0°C to 60°C with a step of 20°C, for a constant irradiation G equal to 1000W/m^2

The analysis of these results leads to the following remarks:

- The PV cell current is strongly dependent on the solar radiation. However, the voltage has small variations when the solar radiation increased from 150W/m^2 to 1000 W/m^2.
- For given solar radiation, when the cell temperature increases, the open circuit voltage V_{oc} drops slightly, while the short circuit current I_{sc} increases.
- For every level of irradiation G the solar cell delivers a single maximal power P_m which corresponds to a single point given by a couple (V_m, I_m). The maximal power P_m varies according to the voltage V_m with a nonlinear law especially for lowest values of G.

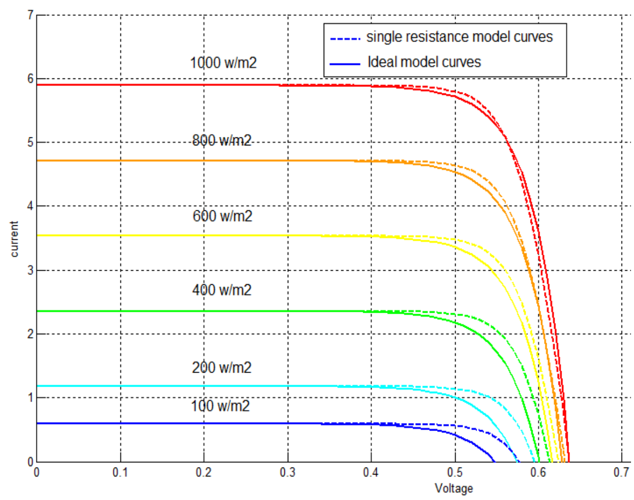

Fig.8. (I-V) cell characteristics for ideal and single resistance models under various level of Irradiation G

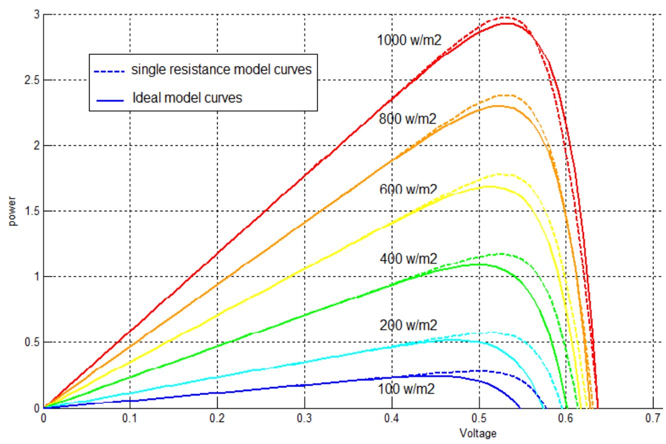

Fig.9. (P-V) cell characteristics for ideal and single resistance models under various level of Irradiation G

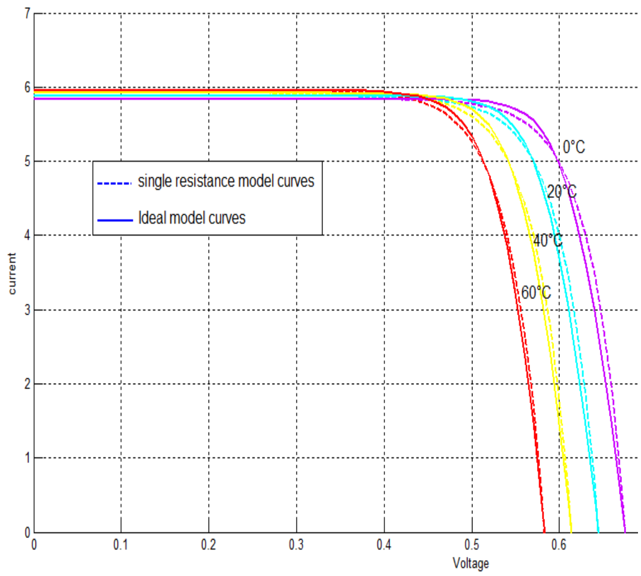

Fig.10. (I-V) cell characteristics for ideal and single resistance models under various level of Temperature T_c

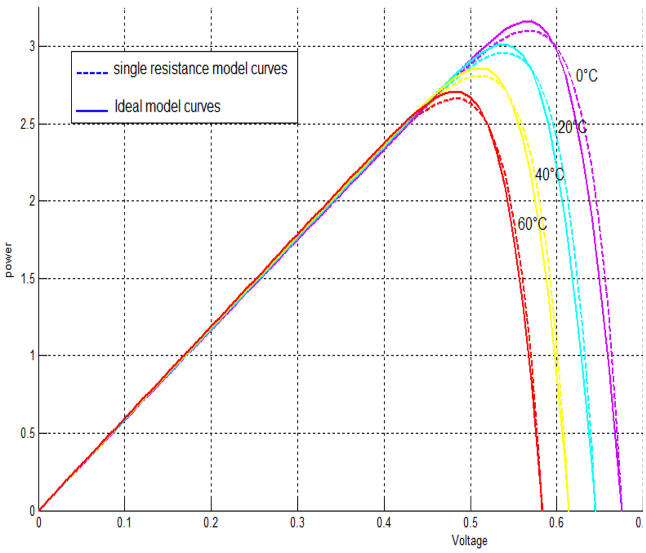

Fig.11. (P-V) cell characteristics for ideal and single resistance models under various level of Temperature T_c

5. Experimental Results and Validation

In order to validate the Matlab/SIMULINK models, the PV test bench of Figure 12 has been investigated. It consists of the following components:

- Mono-crystalline solar cell: JA Solar JAC M5SF,
- Current sensor: for the measurement of the PV cell current,
- Voltage sensor: for the measurement of the voltage on PV terminals,
- Potentiometer: to change the connected resistance value,
- Digital light sensor: to measure the incident light value,
- Infrared temperature sensor: to measure the cell junction temperature,
- ARDUINO Boards: acquisition of sensors data and registration on computer file.

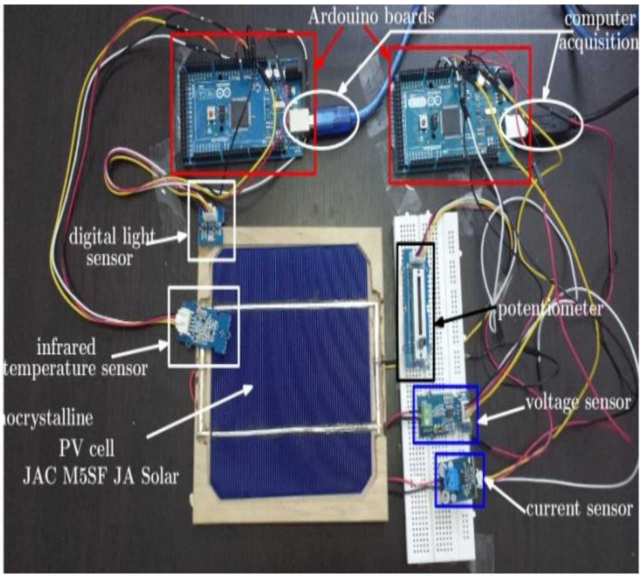

Fig.12. Test bench of internal parameters identification of mono-crystalline photovoltaic cell "JAC M5SF"

- Figure13 and Figure 14 show the comparison between the measured I-V and P-V characteristics and the values predicted by the ideal model where the Iph, Is and n are estimated using the proposed algorithm above-described. The I-V and P-V simulation and experimental results show a good agreement in terms of the short circuit current, the open circuit voltage and the maximum power.

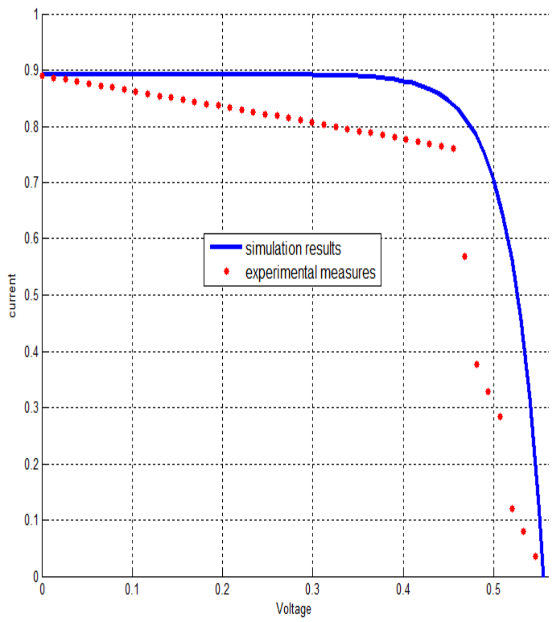

Fig.13. Mono-crystalline photovoltaic cell "JAC M5SF" (I-V) characteristic: simulation and experimental results

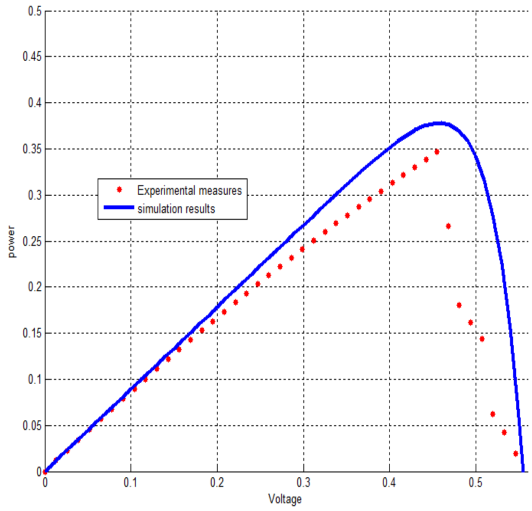

Fig.14. Mono-crystalline photovoltaic cell "JAC M5SF" (P-V) characteristic: simulation and experimental results

6. Conclusion

This paper has been devoted to the development and performance analysis of a two models of a mono-crystalline PV cell, using new methodologies of identification algorithms. These algorithms have been implemented in MATLAB-Simulink in order to search the loss internal parameters of every model using the manufacturer's datasheet. The studied models of the PV cell have been built on Matlab-Simulink and they could imitate the behavior of the real solar cell. The experimental validation of this work has been applied on a mono-crystalline photovoltaic cell ``JAC M5SF". The setup has been based on some sensors: current, voltage, temperature and light sensors. Two Arduino Boards have been used to acquire data from sensors and send them to the computer. The solar cell exposed to the sunlight generates current and voltage which are measured by the current and voltage sensors. The sliding potentiometer connected in the PV cell terminals aim to change the voltage value so that we could trace the cell characteristics. The effectiveness of the proposed models has been carried out considering simulation works whose results have been validated by experiments.

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