Determination of Mono-crystalline Silicon Photovoltaic Module Parameters Using Three Different Methods

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ABSTRACT

For modeling a photovoltaic module, it is necessary to calculate the basic parameters which control the current-voltage characteristic curves, that is not provided by the manufacturer. Generally, for mono crystalline silicon module, the shunt resistance is generally high, and it is neglected in this model. In this study, three methods are presented for four parameters model. Explicit simplified method based on an analytical solution, slope method based on manufacturer data, and iterative method based on a numerical resolution. The results obtained for these methods were compared with experimental measured data. The iterative method was more accurate than the other two methods but more complexity. The average deviation of the iterative method not more than 5% of current- voltage values with the corresponding experimental data. The average deviation for the other two method 9.3% for slope method and 7.9% for simplifies method.

Key words: photovoltaic; module parameters; modeling; temperature effect;

حساب عوامل لوح السلكون الفوتوفولتائي احادي التبلور باستخدام ثلاث طرق مختلفة

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الخلاصة

من الضروري لنمذجة اللوح الفوتوفولتائي حساب العوامل الاساسية التي تحكم بمنحنيات التيار- الفولتية والتي لا تعطى من قبل الجهة المصنعة. تم انجاز عمل جاد لحساب تلك العوامل. بشكل عام ، مقاومة التوالي تكون عالية بالنسبة للوح الشمسي نوع السيليكون احادي التبلور وفي هذا النموذج يمكن اهمالها. وبهذه الدراسة تم استخدام ثلاث طرق .الطريقة الضمنية المبسطة وتعتمد على الحل التحليلي، طريقة الميل وتعتمد على بيانات المصنع وطريقة التكرار وتعتمد على حل عددي.تمت مقارنة النتائج المستخلصة من الطرق المذكورة مع نتائج القياسات المختبرية وكانت طريقة التكرار الاكثر دقة ولكن الاكثر تعقيدا من بين الطرق الثلاث. معدل الانحراف لطريقة التكرار لم تكن اكثر من 5% لقيم التيار – الفولتية مقارنة مع القيم العملية. معدل الانحراف للطرقتين الاخرى كانت 9.3% لطريقة الميل و 7.9% لطريقة للطريقة الضمنية المبسطة.

1. INTRODUCTION

The world faces a big problem of depletion of conventional sources of energy which have to be replaced by new ones. The solar energy is one of the fast developing renewable energy sources. Solar energy may be used to produce thermal energy for residential requirements and can be used to produce electricity indirectly by converting the heat generated to electrical energy through heat engine or directly using photovoltaic (PV) solar system.

Solar is envisaged to be an important source of energy in the future. In particular, the photovoltaic (PV) power system, which converts solar energy to electrical power, is becoming a popular renewable energy source due to its long term economic prospect and ease of maintenance. However, due to high initial cost of such a system, optimal capturing of the available solar energy has to be ensured. Enormous amount of work has been carried out to physically improve the performance of solar cells/modules **Wang Y. et al, 2009,**. However, it appears that a proper system design also plays a vital role in increasing the overall efficiency. One area that could complement this effort is the development of a reliable and efficient PV simulator which can be used to optimize the system design prior to installation **Ishaque K et al, 2011,**. The accuracy of commercially available software for PV module or system simulation mainly depends on the accuracy of the solar cell/module models and the extraction method being used to determine the model's parameters. The choice of a model that closely emulates the characteristics of solar modules is very crucial; a model is known to be accurate if it fits the measured I–V data at all operating conditions. Over the years, several models are introduced – among the more popular ones are the circuit based single diode and the two diode model. The latter, despite it is more computationally extensive, is preferable because its I–V characteristics closely resemble the behavior of a physical module **Walker, 2001.**

Generally, there are two possible approaches to extract the solar module parameters: (1) the analytical **Chan DSH, 1987,** and (2) numerical extraction techniques **Liu C-C, 2008.** The former requires information on several key points of the I–V characteristic curve, i.e. the current and voltage at the maximum power point (M_{PP}), short-circuit current (I_{SC}), open-circuit voltage (V_{OC}), and slopes of the I–V characteristic at the axis intersections. Accuracy-depends on the correctness of the selected points (short current, open current voltage, and maximum power point) on the I–V curve. It has to be noted that the I–V curve is highly non-linear and any wrongly selected points may result in significant errors in the computed parameters. Furthermore, a typical module datasheet provides only information at Standard Test Condition (STC).

However, it is known that the parameters vary with environmental conditions such as irradiance and temperature. On the other hand, the numerical extraction technique is based on certain mathematical algorithm to fit all the points on the I–V curve. More accurate results can be obtained because all the points on the I–V curve are utilized. Deviation of several data points may not severely affect the accuracy of the parameters as in the case of the analytical approach. However, the curve-fitting algorithm requires extensive computation. Its accuracy depends on the type of fitting algorithm, the cost function and the initial values of the parameters to be extracted **Gottschalg R., 1999.** As the number of parameters in the model increases, the conventional extraction methods lose their ability to provide accurate values.

The growing of PV technologies led many researchers to focus on the various sides of PV system components from the basic fundamental cell manufacturing to the large PV power station modeling, sizing and performance of PV modules with the environmental conditions changes **Hernanz et al., 2010, Andrews et al., 2012, Chouder et al., 2012,** and **Chakrasali et al., 2013**. Modeling of PV module provides ways to understand the voltage, current, and power relationships. The estimation of mathematical models is affected by various factors, which ultimately alter the behavior of voltage and current.

Solar cells are the basic components of the PV systems to convert solar radiation into electrical power. They are connected in series or in parallel to form a PV module. The electric behavior of a photovoltaic device under given operating conditions is characterized by its electrical parameters and the current-voltage (I-V) curves describing its operation. Equivalent electrical circuit of PV cell, module and array is configured with either single or double diode with taking in consideration the connection of the cells or the modules in either series or parallel. The single diode models usually have seven, five, four, or even three unknown parameters. The four unknown parameters of a single diode model the photocurrent (I_{ph}), the saturation current (I_o), diode ideality factor (A) and the series resistance (R_s). These parameters are determined from measurements of the I-V characteristic at reference values of irradiance and temperature (G_{ref} =1000 W/m², T_{ref} =25 °C, spectrum AM1.5), many researchers have presented methods to extract these parameters from data mainly provided by manufacturers **De Soto et al., 2006, Carrero et al., 2011** and **Sera et al., 2007.** The four parameter model assumes that the shunt resistance is infinite and it is ignored **Kuo et al., 2001**. In three parameters model the series resistance assumed to be zero in addition to the infinite shunt resistance.

In this work, three different methods are used to determine the unknown parameters: the photocurrent (I_{ph}), the saturation current (I_o), diode ideality factor (A) and the series resistance (R_s) of a mono-crystalline silicon solar module. The models provide the calculation of the equation of the I-V characteristic curves and compare the results with the I-V curves extracted from experimental measurements.

2. FOUR PARAMETERS MODEL

For simplicity, the single-diode model shown in **Fig.** 1 offers a good compromise between simplicity and accuracy and has been used by numerous authors **Arab et al., 2004, Carrero et al. 2007** and **Celik and Acikgoz, 2007**. The four-parameter model assuming the shunt resistance as infinite, the four-parameter model is obtained from the basic equation of output current I of the PV module **Townsend,1989**:

$$I = I_{ph} - I_o \left[exp\left(\frac{q\,(V + I\,R_s)}{N_s\,A\,k_B\,T} \right) - 1 \right] \quad (1)$$

where, I: output current of photovoltaic module, *A*, I_{ph}: photo-generated current, *A*, I_o :reverse saturation current, *A*, q: the charge of electron =1.6e^{-19} *C*, V: output voltage of photovoltaic module, *V*, R_s :series resistance, *Ω*, N_s : the number of solar cells connected in series, A: diode ideality factor, k_B: Boltzmann's constant=1.38e^{-23}, T: solar module temperature, ^{o}C .

Three important points on the I-V curve are given by manufacturer at STC (short circuit current, open circuit voltage and maximum power point) so, Eq. (1) can be written as **Townsend, 1989:**

Short circuit current point (0, I_{sc}),:

$$I_{sc} = I_{ph} - I_o \left[exp\left(\frac{q\ I_{sc}\ R_s}{N_s\ A\ k_B\ T}\right) - 1 \right] \tag{2}$$

Open circuit voltage point (V_{oc}, 0):

$$0 = I_{ph} - I_o \left[exp\left(\frac{q\ V_{oc}}{N_s\ A\ k_B\ T}\right) - 1 \right] \tag{3}$$

Maximum power point (V_m, I_m):

$$I_m = I_{ph} - I_o \left[exp\left(\frac{q\ (V_m + I_m\ R_s)}{N_s\ A\ k_B\ T}\right) - 1 \right] \tag{4}$$

3. PARAMETERS IDENTIFICATION METHODS

Three different methods will be used to evaluate the four parameters. The first one is the explicit simplified method which is based on a purely mathematical solution with some simplifications. The second one is the method of slope which is based in part of its algorithm on a geometry calculation, and the third one is the iterative method which is based in part of its algorithm on a numerical resolution.

3.1 Simplified explicit method

This method considers the following assumptions **Eckstein,1990**:

$$I_{ph} = I_{sc} \tag{5}$$

From Eq. (3) the value of exponential is much greater than one, so:

$$0 = I_{ph} - I_o \left[exp\left(\frac{q \ \ V_{oc}}{N_s \ A \ k_B \ T}\right)\right] \qquad (6)$$

From Eq. (5) and Eq. (6) one can deduce the saturation current:

$$I_o = I_{sc} \ exp\left(-\frac{q \ V_{oc}}{N_s \ A \ k_B \ T}\right) \qquad (7)$$

From that Eq. (1) becomes:

$$I = I_{sc} \ \left[1 - exp\left(\frac{q(V - V_{oc} + I \ R_s)}{N_s \ A \ k_B \ T}\right)\right] \qquad (8)$$

From Eq. (4) the value of exponential is much greater than one, so:

$$I_m = I_{sc} - I_o \left[exp\left(\frac{q \ (V_m + I_m \ R_s)}{N_s \ A \ k_B \ T}\right)\right] \qquad (9)$$

Substituting Eq. (7) in Eq. (9):

$$I_m = I_{sc} \left[1 - exp\left(\frac{q \ (V_m + I_m \ R_s)}{N_s \ A \ k_B \ T}\right)\right] \qquad (10)$$

Then the series resistance can easily found from:

$$R_s = \frac{\frac{N_s \ A \ k_B \ T}{q} \ ln\left(1 - \frac{I_m}{I_{sc}}\right) + V_{oc} - V_m}{I_m} \qquad (11)$$

The ideality factor A, is determined from the fact that the derivative of the maximum power equals zero:

$$\frac{\partial P}{\partial V} = \frac{\partial (IV)}{\partial V} = V\frac{\partial I}{\partial V} + I = 0 \tag{12}$$

Substituting the derivative of Eq. (1), Substituting I_o from Eq. (7) and R_s from Eq. (11). Then A can be found:

$$A = \frac{q}{N_s\ k_B\ T_c} \cdot \frac{2V_m - V_{oc}}{\left[\frac{I_m}{I_{sc} - I_m} + \ ln\left(1 - \frac{I_m}{I_{sc}}\right)\right]} \tag{13}$$

3.2 Slope Method

The difference given by this method in comparison of the previous method is in the manner of calculating the series resistance **Walker, 2001, Gow and Manning, 1999.** It is based on the fact that the series resistance influences remarkably the slope of the characteristic curve I-V in the vicinity of the point (V_{oc} ,0). So, in order to calculate Rs one uses the derivative of current described in Eq. (1) as:

$$\frac{dI}{dV} = -I_o\left[exp\left(\frac{q\ (V + I\ R_s)}{N_s\ A\ k_B\ T}\right) - 1\right]\frac{q}{N_s\ \ k_B\ \ T_c}\left(1 + R_s\frac{dI}{dV}\right) \tag{14}$$

$$R_s = -\frac{dV}{dI}_{\ at\ V_{oc}} - \frac{1}{\frac{I_o\ \ q}{N_s\ \ k_B\ \ T_c}exp\left(\frac{q\ V_{oc}}{N_s\ A\ k_B\ T}\right)} \tag{15}$$

The slope $\frac{dV}{dI}$ at the point (V_{co}, 0) is deduced geometrically from manufacturer data (**Fig. 2**).

3.3 Iterative Method

This method differs from the two previous methods in the way of calculating of the series resistance, where the temperature coefficient of the open circuit voltage given by experimental data may be used to provide an additional equation for calculating the series resistance. The temperature coefficient of the open circuit voltage can be evaluated theoretically from the derivative of the open circuit voltage with respect to temperature as follows:

$$\mu_{V_{oc}} = \frac{\partial V_{oc}}{\partial T} = \frac{A\ N_s\ k_B}{q}\ \left[\ ln\left(\frac{I_{sc}}{I_o}\right) + \frac{T\ \mu_{I_{sc}}}{I_{sc}} - 3 - \frac{q\ \ E_g}{A\ \ \ k_B\ \ T}\right] \tag{16}$$

In this method, the value of R_s is calculated, Using an iterative method in the interval [0, $R_{s,max}$], where R_s max is the maximum possible value of series resistance **Celik and Acikgoz, 2007, Townsend, 1989**. The value of A is close to 1 for $R_{s,max}$, so set A = 1 in Eq. (11), that yields to:

$$R_{s,max} = \frac{\frac{N_s\ \ k_B\, T}{q}\ ln\left(1 - \frac{I_m}{I_{sc}}\right) + V_{oc} - V_m}{I_m} \tag{17}$$

The other three parameters are calculated using the same equations Eq. (5), Eq. (7) and Eq. (11) as the first method.

The behavior of the PV module output with change in solar radiation and temperature is presented by many authors. The short circuit current has a linear relationship with the solar irradiance while the open circuit voltage has a logarithmic with solar irradiance. The temperature coefficients provided by the manufacturer or evaluated experimentally used to predict the variations of different PV output parameters with temperature. That can be presented in the following formulas:

$$I_{sc} = I_{sc,ref}\,\frac{G}{G_{ref}} + \mu_{sc}(T - T_{ref}) \tag{18}$$

$$V_{oc} = V_{oc,ref} + V_T\,\ln\left(\frac{G}{G_{ref}}\right) + \mu_{oc}(T - T_{ref}) \tag{19}$$

where, V_T is the thermal voltage which is given by:

$$V_T = \frac{N_s\, A\, k_B\, T}{q} \tag{20}$$

The ideality factor varies with temperature as given by **Villalva, 2009**:

$$\frac{A}{A_{ref}} = \frac{T}{T_{ref}} \tag{21}$$

The change of the reverse saturation current with temperature as given by **Villalva, 2009**:

$$I_o = I_{o,ref} \left(\frac{T}{T_{ref}}\right)^3 \exp\left[\frac{q\,E_g}{A\,k_B}\left(\frac{1}{T}\Big|_{ref} - \frac{1}{T}\Big|_{T}\right)\right] \tag{22}$$

4. EXPERIMENTAL WORK

A mono-crystalline silicon solar PV module is used with electrical specification listed in **Table 1**. The performance of the module is tested at different conditions in the Energy Engineering Department/College of Engineering / University of Baghdad. The exponential work have made during the five months from April to June 2015. This work is done at an average ambient temperature of 38 ^oC and average wind speed 2.3 km/hr.

The output parameters of the module are measured by Prova200 solar panel analyzer which is a device used for testing of PV modules. When it is used in the installation of solar panels, the Prova 200 solar panel analyzer assists in determining the proper inverter size as well as optimum power output position of panels and helps identify defective cells or panels that have worn out over time.

The solar panel analyzer also provides the user with current and voltage (IV) test curves, maximum solar power as well as current and voltage. Solar cell properties are easily determined using the following units: I-V Curve Test for Solar Cell, Single Point I-V Test, Maximum Solar Power (P_m) search by auto-scan, Maximum Voltage (V_m) at P_m, Maximum Current (I_m) at P_m, Voltage at open circuit (V_{oc}), Current at short circuit (I_{sc}), I-V curve with cursor, Efficiency (%) calculation of solar panel, Scan delay setting (0 ~ 9999ms) *(i. e. solar module analyzer will be operate with load resistance (0- ∞ Ω) connected with the solar module range with a time not more than 9999 ms (approximately 10 sec))* , Solar panel area setting range (0.001 m^2 ~ 9999 m^2), Standard light source setting. (10 W/m^2 ~ 1000 W/m^2), Min. power setting for alarm function, Built-in Calendar Clock, Rechargeable batteries with built-in charging circuit, Optical USB cable for PC and The terminals of solar cell.

TES-1333R solar power meter has been used to measure the incident solar radiation on the PV module. The measuring range of the solar power meter is 0-2000 W/m^2 with resolution of 0.1 W/m^2 and induced error of ±0.38 W/m2/°C. The temperature of the back side of the module is measured by a simple thermometer TPM-10 thermocouple.

5. RESULTS AND DISCUSSION

Firstly, the unknown parameters are evaluated by the different methods using Matlab based on the data provided by the manufacturer in STC. Secondly, from the results it is possible to estimate the performance of solar module for different radiations and temperatures. To validate the four parameter model, an experimental data extracted from outdoor measured data. The outdoor exposure tests were done on May 21, 2015 in the Energy Engineering Department/College of Engineering / University of Baghdad.

Matlab code used for the calculation process of the four parameter at STC and the results of the program are tabulated in **Table 2**. Two cases of different solar radiation and temperature were considered and introduced in **Table 3** and **Table 4**. Based on these values of the four parameters, it is possible to plot the I-V and P-V curves at specific conditions.

Fig. 4 and **Fig. 5** give the results of I-V and P-V curves of the three methods and from the experimental results at different operating module temperature 25ºC and 50ºC. When the operating module temperature increases, the output current increases marginally while the output voltage decreases dramatically, which results in a net reduction in the output power. There was a deviation at the open circuit region because of the difference in the approaches to determine the series resistance. The slope method showed the largest deviation from the experimental curves followed by the simplified explicit method. The iterative method has been shown a good agreement with the experimental results.

To show the effect of irradiance on the performance of a module, the temperature was kept fixed at 25°C and measurements was taken for two incident solar radiations 750 and 1000W/m^2. From **Fig. 6** and **Fig. 7** the short circuit current increased from 1.27A to 1.7A while the open circuit voltage showed a small raise.

The average deviation of the iterative method not more than 5% of current- voltage values with the corresponding experimental data. The average deviation for the other two method 9.3% for slope method and 7.9 for simplifies method.

6. CONCLUSION

In order to evaluate the PV module parameters defining and measuring its characteristic curves (I-V and P-V curves) are achieved. Three different methods of PV module parameters extracting have been examined. The values of the parameters were used to simulate the current-voltage and power-voltage characteristics of the module. The three methods were, explicit simplified method based on an analytical solution, slope method based in part of on an experimental data, and iterative method based on a numerical resolution. The iterative method was more accurate than the other two methods but more complexity. The average percentage error of the iterative method not more than 5% of current- voltage values with the corresponding measured data. The average percentage error for the slope method is 9.3% while for simplified method is 7.9%.

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NOMENCLATURE

A =diode ideality factor

I_{sc} =short circuit Current, A

I_{ph} =photo-generated current, A

G =solar radiation, W/m^2

I_m =current at maximum power point, A

I_o =reverse Saturation current, A

N_s =number of cells

q =charge of electron, C

k_B =Boltzmann constant.

V_{oc} =open circuit Voltage, V

R_s =series resistance, Ω

V_m =voltage at maximum power point, V

P_m =maximum Power output, W

Table 1. Solar module specifications.

Area	0.26 m^2
Short circuit current $I_{sc\ ref}$	1.9
Open circuit voltage $V_{oc\ ref}$	22
P_{maxref}	30
Current at maximal power point	1.76
Voltage at maximal power point $V_{m\ ref}$	17
Temperature coefficient of open circuit voltage μV	-0.073
Temperature coefficient of short circuit current μ_{Isc}	0.00086
Number of cell in series	36
Slope at open circuit region	-1.142

Table 2. Four parameters values at reference STC.

	Simplified method	Slope method	Iterative method
I_{ph}	1.9000	1.9000	1.9000
I_o	2.2171e-08	2.2171e-08	1.26619e-10
A	1.3021	1.3021	1.015099
R_s	1.0562	0.506	1.458200

Table 3. Four parameters values at 750W/m^2 and 25ºC.

	Simplified method	Slope method	Iterative method
I_{ph}	1.425	1.425	1.425
I_o	2.16E-08	2.22E-08	1.18E-10
A	1.612892	0.861567	1.33696
R_s	0.540277	0.506	-1.02309

Table 4. Four parameters values at 1000W/m^2 and 50ºC.

	Simplified method	Slope method	Iterative method
I_{ph}	1.911801	1.911801	1.911801
I_o	2.32E-08	2.16E-08	1.21E-10
A	0.322334	1.196524	1.218119
R_s	1.997061	0.849815	2.323333

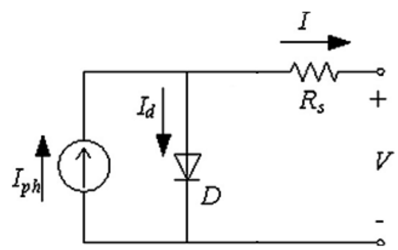

Figure 1. Equivalent circuit for four parameters model of a solar cell

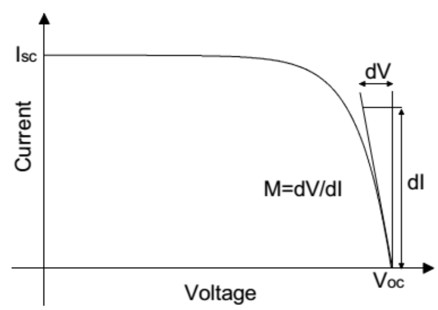

Figure 2. The slope at the open circuit voltage region at the I-V curve

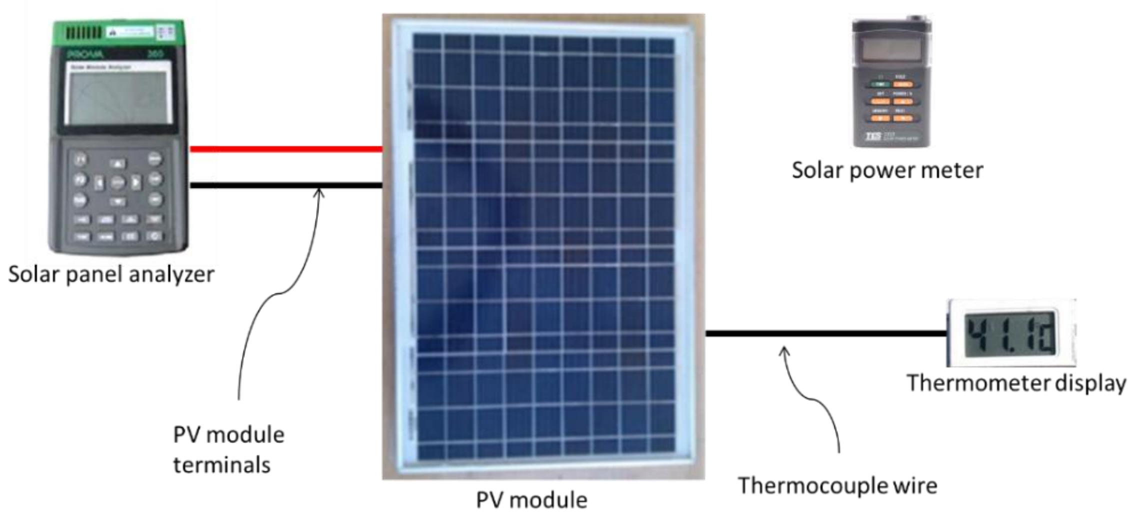

Figure 3. Measurement apparatus (left) PROVA200A solar module analyzer, (right) TES133R solar power meter

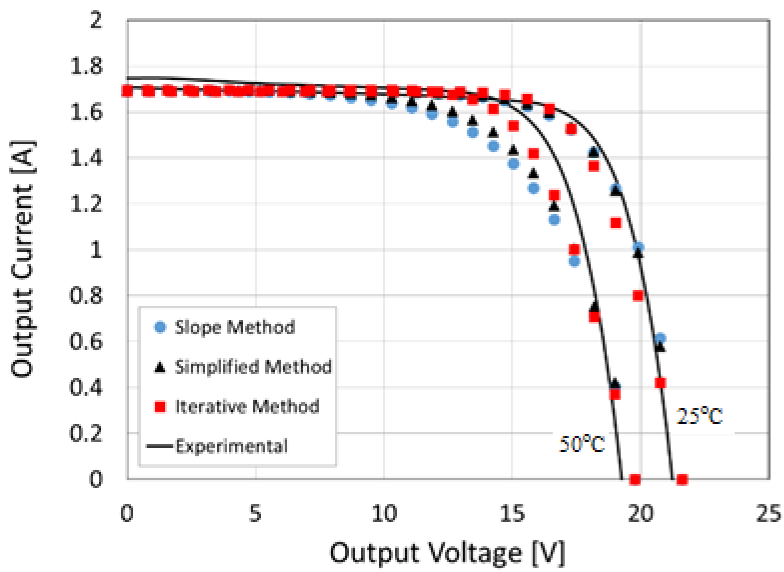

Figure 4. Current-voltage curve at 1000W/m^2 solar radiation and two different temperatures 25^{o}C and 50^{o}C.

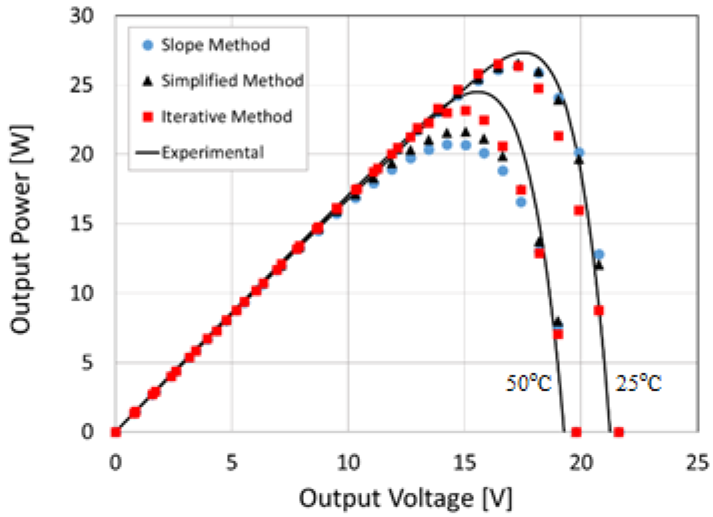

Figure 5. Power-voltage curve at 1000 W/m^2 solar radiation and two different temperatures 25^{o}C and 50^{o}C.

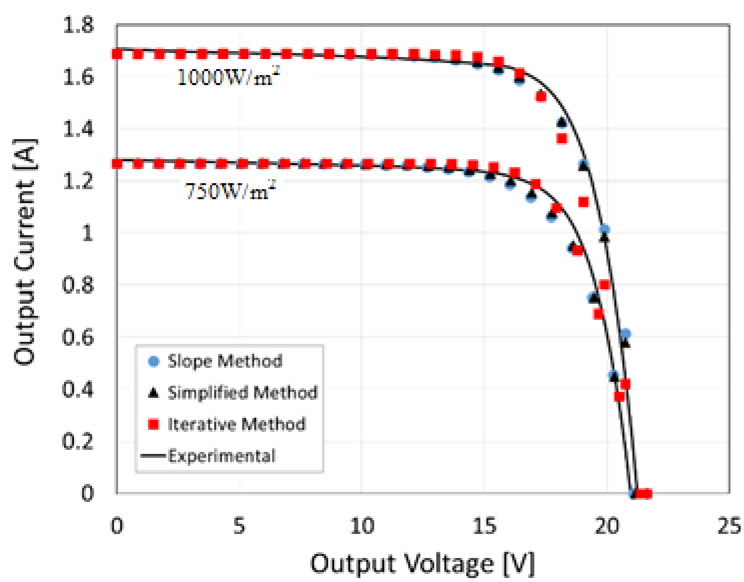

Figure 6. current-voltage curve at 25^{o}C and two different solar radiation: 750W/m^2 and 1000W/m^2

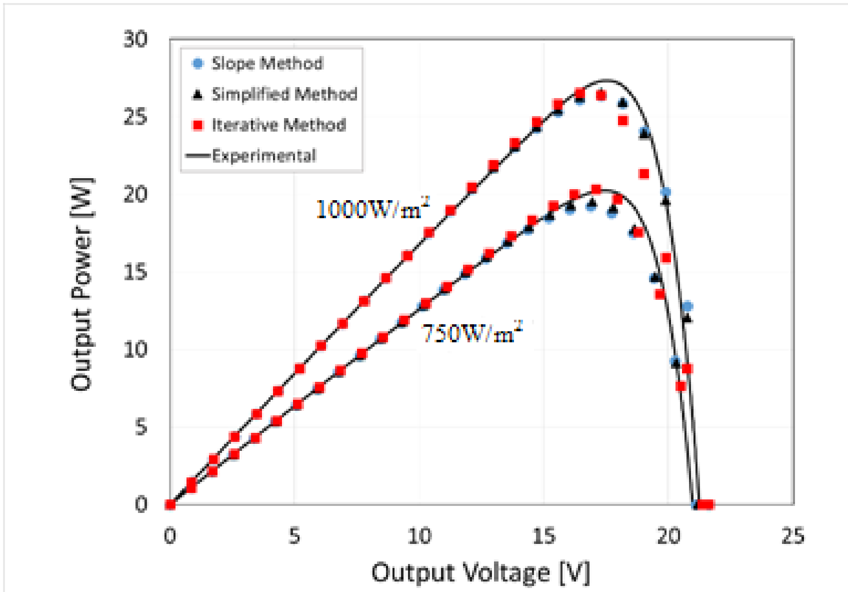

Figure 7. Power-voltage curve at 25^{o}C and two different solar radiation: 750W/m^2 and 1000W/m^2