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# Evaluation the Accuracy of One-Diode and Two-Diode Models for a Solar Panel Based Open-Air Climate Measurements

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## 1. Introduction

Increasingly, using lower energy cost system to overcome the need of human beings is of interest in today's energy conservation environment. To address the solution, several approaches have been undertaken in past. Where, renewable energy sources such as photovoltaic systems are one of the suitable options that will study in this paper. Furthermore, significant work has been carried out in the area of photovoltaic system as one of the main types of renewable energy sources whose utilization becomes more common due to its nature. On the other hand, modeling and simulation of a photovoltaic system could be used to predict system electrical behaviour in various environmental and load conditions. In this modeling, solar panels are one of the essential parts of a photovoltaic system which convert solar energy to electrical energy and have nonlinear I-V characteristic curves. Accurate prediction of the system electrical behaviour needs to have comprehensive and precise models for all parts of the system especially their solar panels. Consequently, it provides a valuable tool in order to investigate the electrical behaviour of the solar cell/panel. In the literature, models that used to express electrical behaviour of a solar cell/panel are mostly one-diode or two-diode models with a specific and close accuracy with respect to each other. One-diode model has five variable parameters and two-diode model has seven variable parameters in different environmental conditions respectively.

During the last decades, different approaches have been developed in order to identify electrical characteristics of both models. (Castaner & Silvestre, 2002) have introduced and evaluated two separate models (one-diode and two-diode models) for a solar cell but dependency of the models parameters on environmental conditions has not been fully considered. Hence, the proposed models are not completely accurate. (Sera et al., 2007) have introduced a photovoltaic panel model based on datasheet values; however with some restrict assumptions. Series and shunt resistances of the proposed model have been stated constant and their dependencies on environmental conditions have been ignored. Furthermore, dark-saturation current has been considered as a variable which depend on the temperature but its variations with irradiance has been also neglected. Model equations have been merely stated for a solar panel which composed by several series cells.

(De Soto et al., 2006) have also described a detailed model for a solar panel based on data provided by manufacturers. Several equations for the model have been expressed and one of them is derivative of open-circuit voltage respect to the temperature but with some assumptions. Shunt and series resistances have been considered constant through the paper, also their dependency over environmental conditions has been ignored. Meanwhile, only dependency of dark-saturation current to temperature has been considered. (Celik & Acikgoz, 2007) have also presented an analytical one-diode model for a solar panel. In this model, an approximation has been considered to describe the series and shunt resistances; they have been stated by the slopes at the open-circuit voltage and short-circuit current, respectively. Dependencies of the model parameters over environmental conditions have been briefly expressed. Therefore, the model is not suitable for high accuracy applications. (Chenni et al., 2007) have used a model based on four parameters to evaluate three popular types of photovoltaic panels; thin film, multi and mono crystalline silicon. In the proposed model, value of shunt resistance has been considered infinite. The dark-saturation current has been dependent only on the temperature. (Gow & Manning, 1999) have demonstrated a circuit-based simulation model for a photovoltaic cell. The interaction between a proposed power converter and a photovoltaic array has been also studied. In order to extract the initial values of the model parameters at standard conditions, it has been assumed that the slope of current-voltage curve in open-circuit voltage available from the manufacturers. Clearly, this parameter is not supported by a solar panel datasheet and it is obtained only through experiment.

There are also several researches regarding evaluation of solar panel's models parameters from different conditions point of view by (Merbah et al., 2005; Xiao et al., 2004; Walker, 2001). In all of them, solar panel's models have been proposed with some restrictions.

The main goal of this study is investigation the accuracy of two mentioned models in the open-air climate measurements. At first step of the research, a new approach to model a solar panel is fully introduced that it has high accuracy. The approach could be used to define the both models (on-diode and two diode models) with a little bit modifications. Meanwhile, the corresponding models parameters will also evaluate and compare. To assess the accuracy of the models, several extracted I-V characteristic curves are utilized using comprehensive designed measurement system. In order to coverage of a wide range of environmental conditions, almost one hundred solar panel I-V curves have been extracted from the measurement system during several days of the year in different seasons. Hence, the rest of chapter is organized as follows.

In section 2 of the report, derivation of an approach to evaluate the models accuracy will be described. Nonlinear mathematical expressions for both models are fully derived. The Newton's method is selected to solve the nonlinear models equations. A measurement system in order to extract I-V curves of solar panel is described in section 3. In section 4, the extracted unknown parameters of the models for according to former approach are presented. Results and their interpretation are presented in section 5. Detailed discussion on the results of the research and conclusions will provide in the final section.

## 2. Study method

The characteristics of a solar cell "current versus voltage" under environmental conditions (irradiance and temperature) is usually translated either to an equivalent circuits of one-

diode model (Fig. 1a) or to an equivalent circuit of two-diode model (Fig. 1b) containing photocurrent source, a diode or two diodes, a shunt resistor and a series resistor in the load branch.

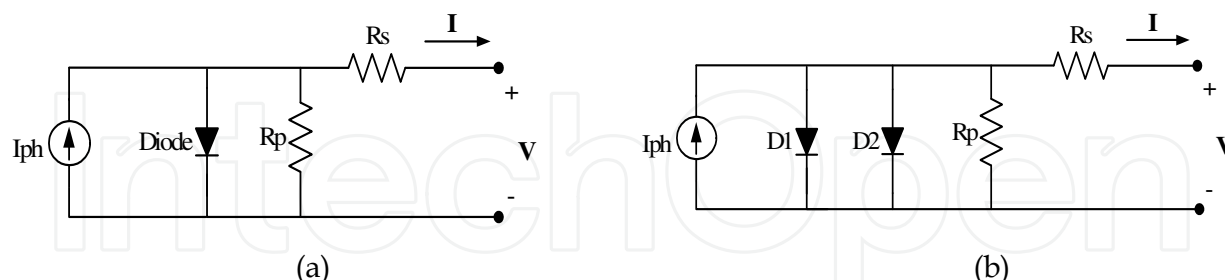


Fig. 1. The equivalent circuits of one-diode and two-diode models of a solar cell.

One-diode model and two-diode model can be represented by Eqs. (1) and (2) accordingly:

$$i = I_{ph} - I_0 \left( e^{\frac{v+iR_s}{V_T}} - 1 \right) - \frac{v+iR_s}{R_p}, \quad V_T = \frac{nkT}{q} \quad (1)$$

$$i = I_{ph} - I_{01} \left( e^{\frac{v+iR_s}{V_{T1}}} - 1 \right) - I_{02} \left( e^{\frac{v+iR_s}{V_{T2}}} - 1 \right) - \frac{v+iR_s}{R_p}, \quad V_{Tj} = \frac{n_j kT}{q} \quad j=1,2 \quad (2)$$

Where, one-diode model has five unknown parameters;  $I_{ph}, I_0, n, R_s$  and  $R_p$  and the two-diode model has seven unknown parameters;  $I_{ph}, I_{01}, n_1, I_{02}, n_2, R_s$  and  $R_p$ . On the other hand, a solar panel is composed of parallel combination of several cell strings and a string contains several cells in series. Therefore, the both models can be also stated for a solar panel. In this research, the idea is to compare the accuracy of the two mentioned models for a solar panel. As it is known, the unknown parameters of the models are functions of the incident solar irradiation and panel temperature; hence dependency between them should be taken into account.

In this section, evaluation of the unknown one-diode model parameters based on five equations are presented. The specific five points (are shown in Fig. 2) on the I-V curve are used to define the equations, where  $I_{sc}$  is the short circuit current,  $I_x$  is the current at  $V_x = 0.5V_{oc}$ ,  $I_{xx}$  is current at  $V_{xx} = 0.5(V_{oc} + V_{mp})$ ,  $V_{oc}$  is the open circuit voltage and  $V_{mp}$  is the voltage at the maximum power point. In this study, the mentioned points are generated for 113 operating conditions between 15-65°C and 100-1000W/m<sup>2</sup> to solve the five coupled implicit nonlinear equations for a solar panel that consists of 36 series connected poly-crystalline silicon solar cells at different operating conditions. By solving the nonlinear equations in a specific environmental condition, we will find five unknown parameters of the model in one operating condition. Equation (3) shows the system nonlinear equations for one-diode model.

$$F_j = -i_j + I_{ph} - I_0 \left( e^{\frac{v+iR_s}{a}} - 1 \right) - \frac{v+iR_s}{R_p}, \quad a = \frac{nkT}{q} \quad j=1,2,...,5 \quad (3)$$

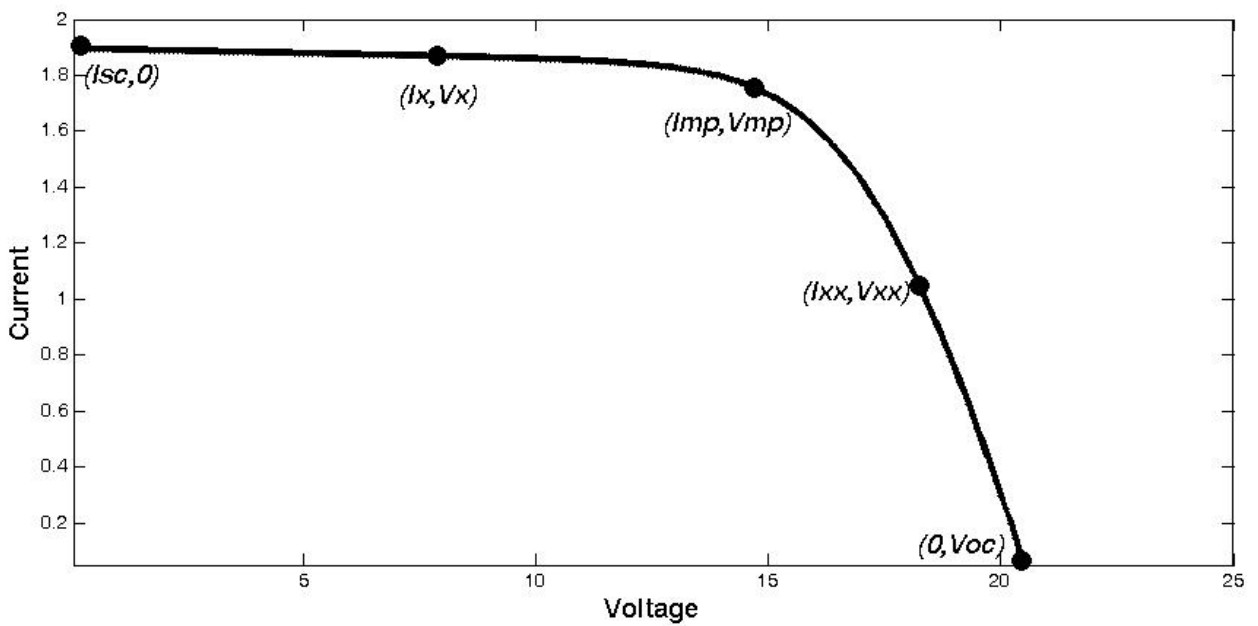


Fig. 2. Five points on the I-V curve of a solar panel are used to solve the nonlinear equations.

Former approach is used to solve seven coupled implicit nonlinear equations of the two-diode model for a solar panel. The specific seven points (are shown in Fig. 3) on the I-V curve are used to define the equations, where  $I_b$  is the current at  $V_b = \frac{V_{mp}}{3}$ ,  $I_c$  is the current at  $V_c = \frac{2V_{mp}}{3}$ ,  $I_e$  is the current at  $V_e = \frac{2V_{mp} + V_{oc}}{3}$  and  $I_f$  is the current at  $V_f = \frac{V_{mp} + 2V_{oc}}{3}$ .

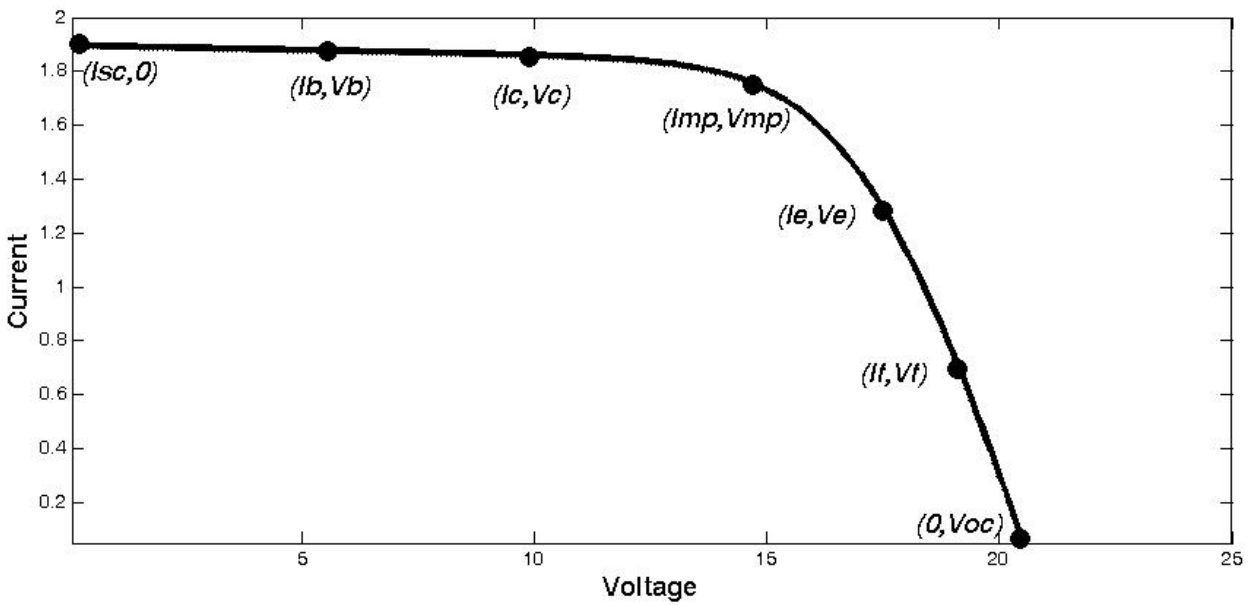


Fig. 3. Seven points on the I-V curve of a solar panel to solve the nonlinear equations.

The points are also generated for the 113 operating conditions to solve the seven coupled implicit nonlinear equations for the solar panel. Solving the nonlinear equations in a specific environmental condition leads to define seven unknown model parameters in one operating condition. Equation (4) shows the system nonlinear equations for the two-diode model.

$$G_j = -i_j + I_{ph} - I_{01} \left( e^{\frac{v+iR_s}{a_1}} - 1 \right) - I_{02} \left( e^{\frac{v+iR_s}{a_2}} - 1 \right) - \frac{v+iR_s}{R_p},$$
$$a_k = \frac{n_k k T}{q}, \quad k = 1, 2, \quad j = 1, 2, \dots, 7$$

(4)

Figs. 4 and 5 show the implemented algorithms in order to solve the nonlinear equations for the both models.

3. Measurement system

A block diagram of a measurement system is shown in Fig. 6. The main function of this system is extracting the solar panel’s I-V curves. In this system, an AVR microcontroller (ATMEGA64) is used as the central processing unit. This unit measures, processes and controls input data. Then the processed data transmit to a PC through a serial link. In the proposed system, the PC has two main tasks; monitoring (acquiring the results) and programming the microcontroller. Extracting the solar panel’s I-V curves shall be carried out in different environmental conditions. Different levels of received solar irradiance are achieved by changing in solar panel’s orientation which is performed by controlling two DC motors in horizontal and vertical directions. Although the ambient temperature changing is not controllable, the measurements are carried out in different days and different conditions in order to cover this problem. A portable pyranometer and thermometer are used for measuring the environmental conditions; irradiance and temperature. Hence, 113 acceptable I-V curves (*out of two hundred*) were extracted. Motor driver block diagram is also shown in Fig. 7. Driving the motors is achieved through two full bridge PWM choppers with current protection. Table 1 reports electrical specifications of the under investigation solar panel at standard conditions based on datasheets.

| Solar Panel            |                   | Poly-Crystalline Silicon Solar Panel |
|------------------------|-------------------|--------------------------------------|
| Standard conditions    | Irradiance (W/m²) | 1000                                 |
|                        | Temperature (°C)  | 25                                   |
| I <sub>sc</sub> (A)    |                   | 2.98                                 |
| V <sub>oc</sub> (V)    |                   | 20.5                                 |
| I <sub>mpp</sub> (A)   |                   | 2.73                                 |
| V <sub>mpp</sub> (V)   |                   | 16.5                                 |
| P <sub>mpp</sub> (W)   |                   | 45                                   |
| n <sub>s</sub>         |                   | 36                                   |
| n <sub>p</sub>         |                   | 1                                    |
| k <sub>i</sub> (%/°C)  |                   | 0.07                                 |
| k <sub>v</sub> (mv/°C) |                   | -0.038                               |

Table 1. Datasheet information of the under investigation solar panel

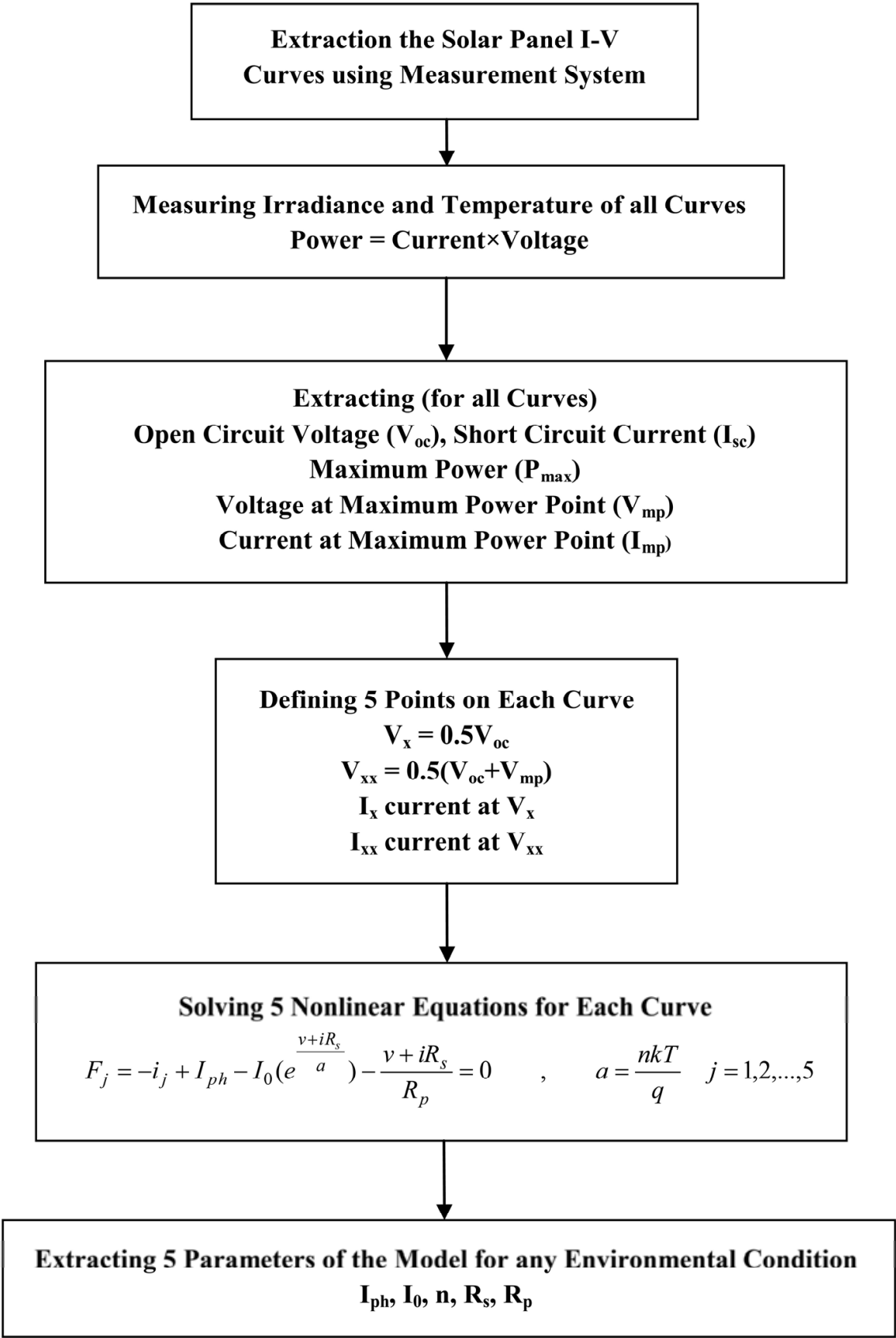


Fig. 4. Flowchart of extraction the one-diode model parameters

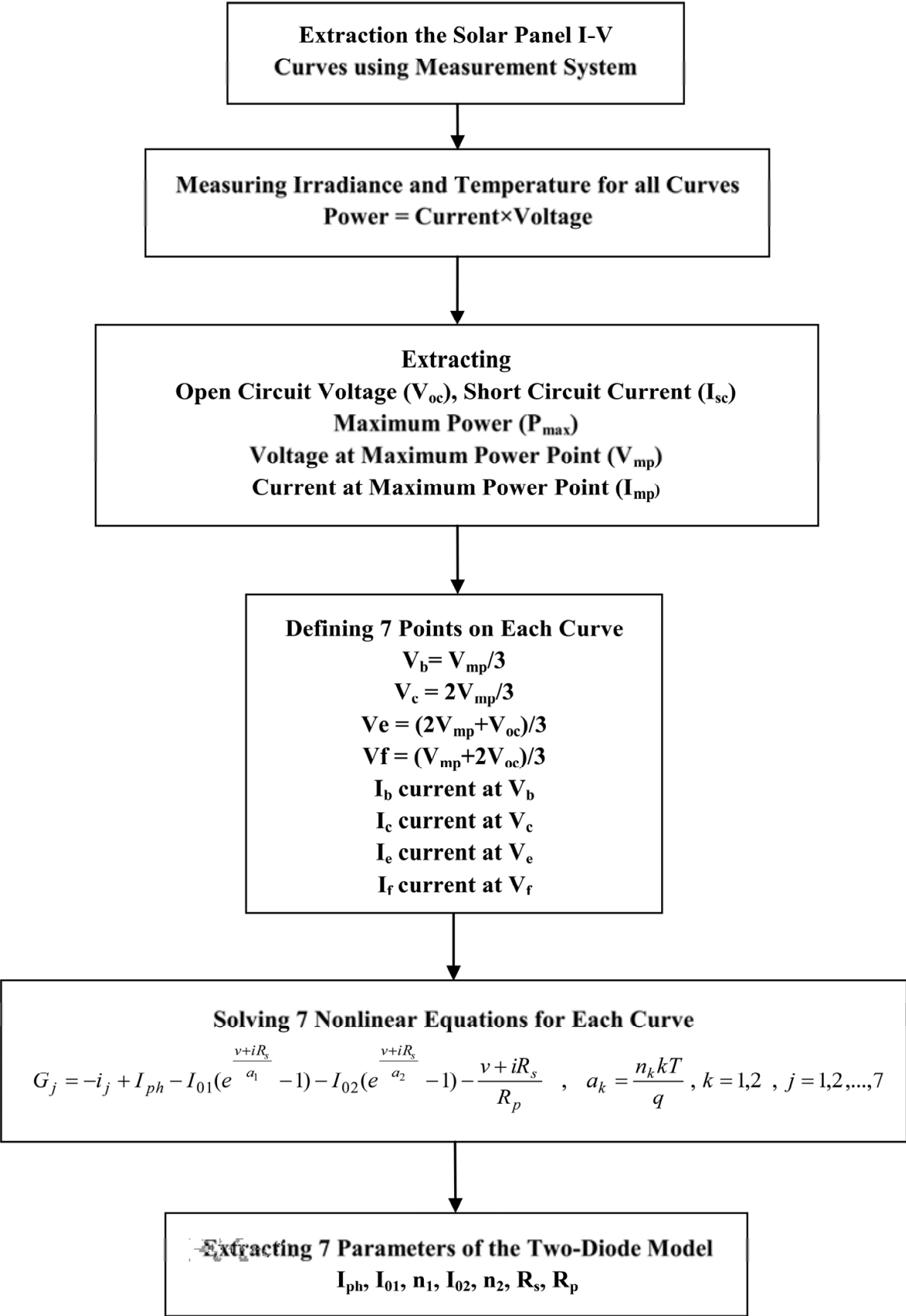


Fig. 5. Flowchart of extraction the two-diode model parameters



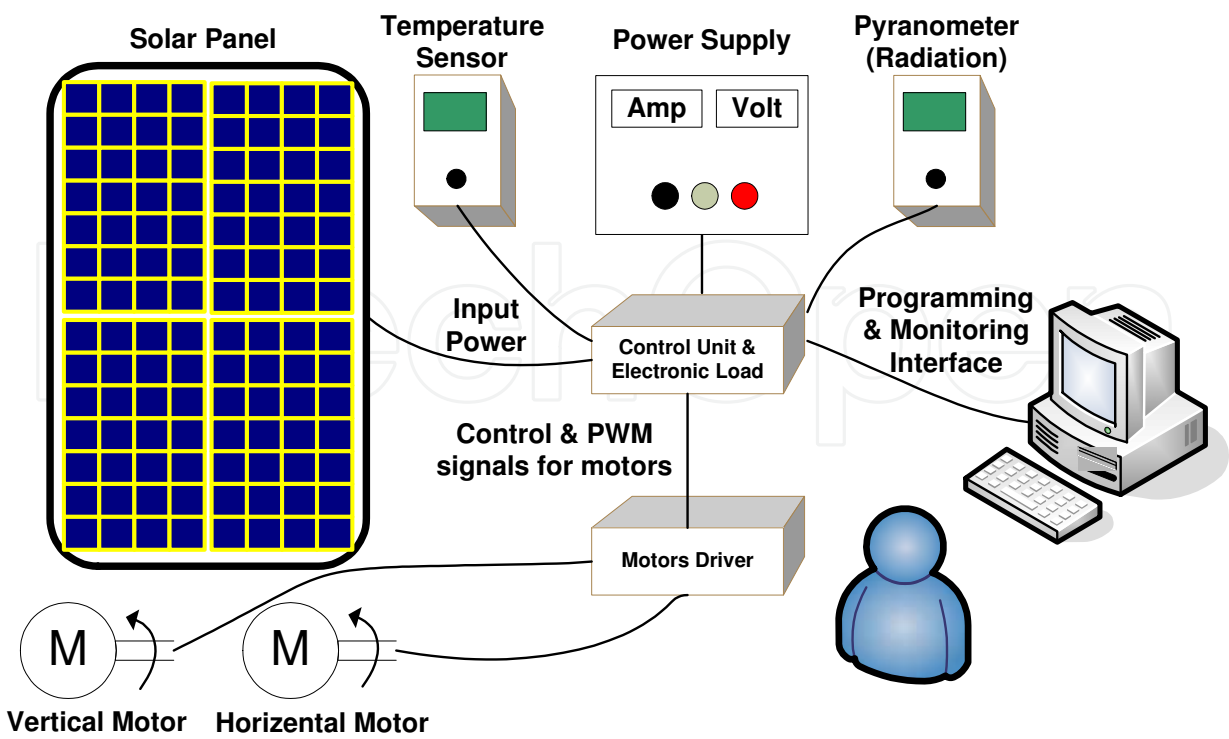


Fig. 6. Block diagram of the proposed measurement system

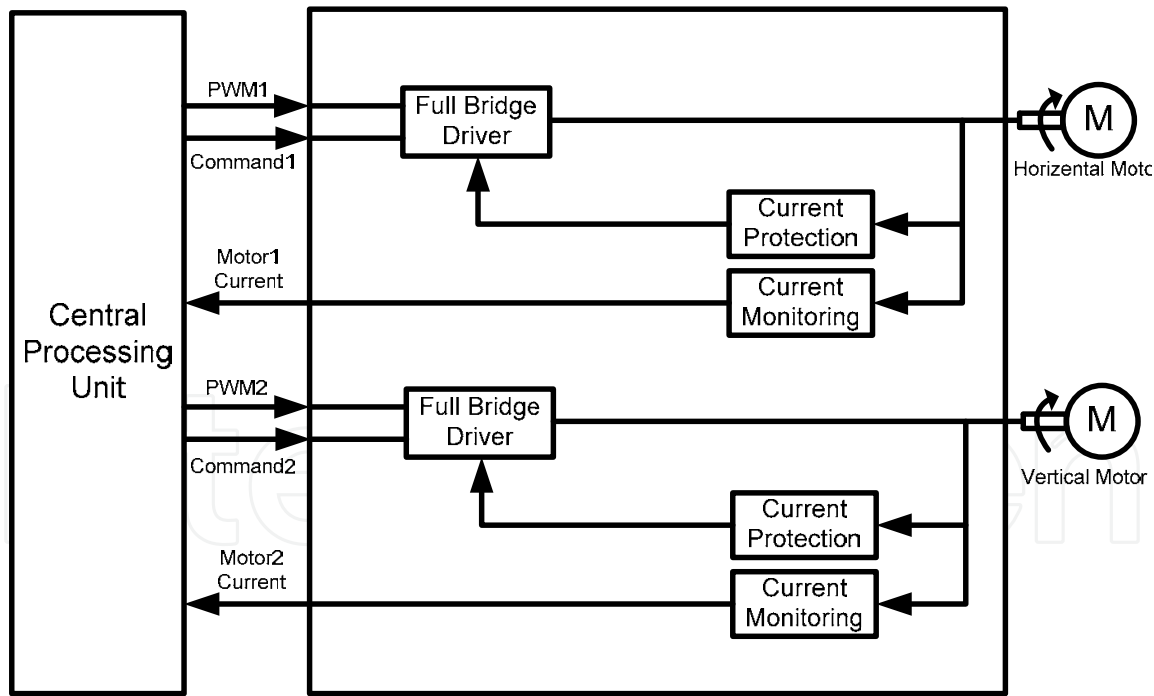


Fig. 7. Motor driver block diagram

3.1 The I-V curve extractor

There is an important rule for solar panel’s I-V curves in photovoltaic system designing. Although the manufacturers give specifications of their products (cell or panel) generally in the standard condition, behavior of solar cells and panels are more required in non-standard

environmental conditions. In order to extract a solar panels' I-V curve, it is sufficient to change the panel current between zero (open-circuit) to its maximum value (short-circuit) continuously or step by step when environmental condition was stable (the incident solar irradiance and panel temperature). Then the characteristic curve could be obtained by measuring the corresponding voltages and currents. Therefore, a variable load is required across the panel output ports.

Since the solar panel's I-V curve is nonlinear, the load variation profile has a significant impact on the precision of the extracted curve. If the load resistance (or conductance) varies linearly, the density of the measured points will be high near  $I_{sc}$  or  $V_{oc}$  and it is not desired. Hence, the nonlinear electronic load is more suitable. There are generally two methods for implementation a variable load, which will be discussed below.

### 3.1.1 Discrete method

As mentioned above, extracting the solar panel I-V curve could be carried out by its output load variation. An easy way is switching of some paralleled resistors to have different loads. If the resistors have been chosen according to Eq. (5), it is possible to have  $2^n$  different load values by switching of  $n$  resistors.

$$R_n = \frac{1}{2} R_{n-1} \quad (5)$$

The schematic for the proposed switching load is shown in Fig. 8. This method may cause some switching noise in the measurement system. Therefore, a controllable continuous electronic load is suitable.

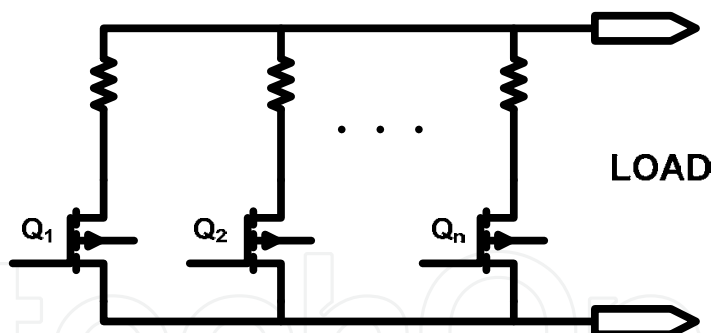


Fig. 8. The proposed switching load circuit

### 3.1.2 Continuous method

The schematic diagram for the proposed continuous electronic load is shown in Fig. 9. The drain-source resistor of a MOSFET in linear area of its electrical characteristic curves is used as a load. As we know, the value of this resistor could be controlled by gate-source voltage. Mathematical relationship between the value of this resistor and applied voltage is described in Eq. (6).

$$R_{ds} = \frac{t_{ox}L}{\mu\epsilon W} \left( \frac{1}{V_{gs} - V_T} \right) \quad (6)$$

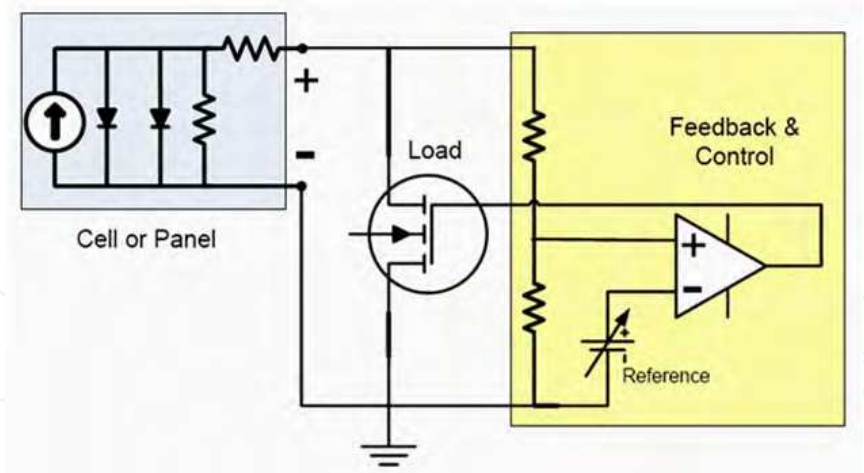


Fig. 9. The proposed continuous electronic load

In this equation,  $L$  is channel length,  $W$  is channel width,  $\varepsilon$  is electric permittivity,  $\mu$  is electron mobility and  $t_{ox}$  is oxide thickness in the MOSFET. Implementation of this method is much quicker and easier than the previous one, and doesn't induce any switching noise in the measurement system. Simulation results and the measured data for the proposed electronic load (continuous method) are performed by Orcad/Pspice 9.2. The simulation result and experimental data are shown in Fig. 10. We observed that the simulation result and experimental data have similar electrical behavior. Their difference between curves was raised because of error in measurement and inequality real components with components in the simulation program. Anyway, the proposed electronic load (continuous method) was suitable for our purpose.

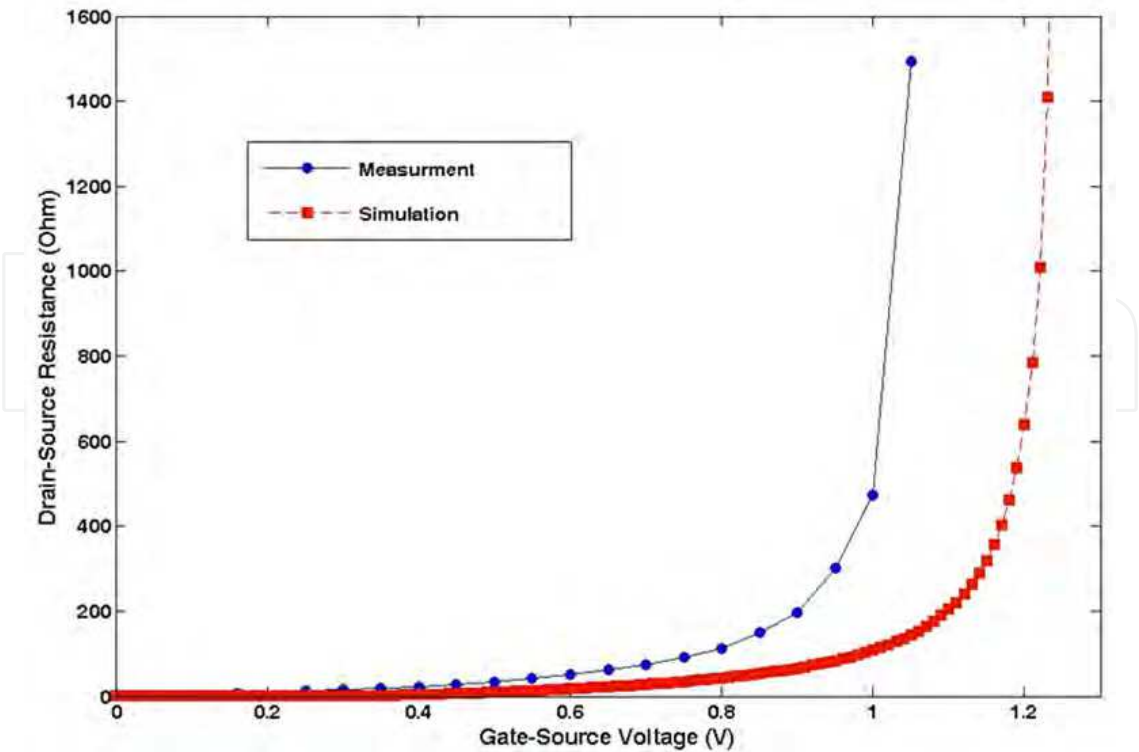


Fig. 10. Experimental data and simulation results of continuous electronic load profile

The schematic diagram of the implemented continuous electronic load is shown in Fig. 11.

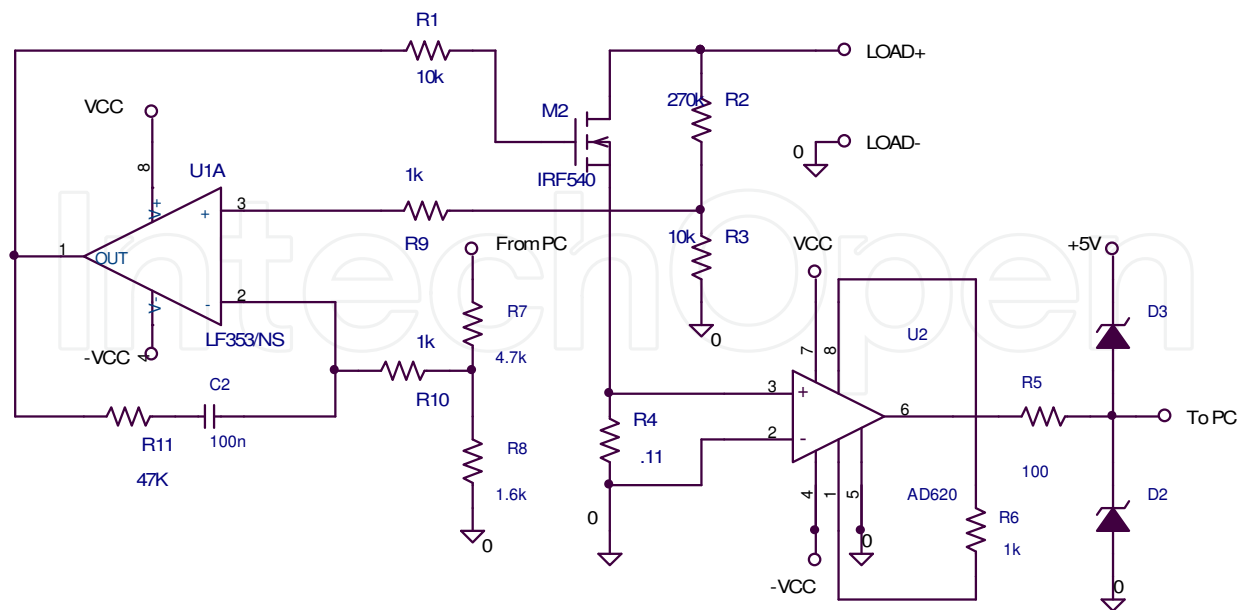


Fig. 11. The schematic diagram of continuous electronic load

Fig. 12 shows a typical extracted I-V and P-V curves by this method in the following conditions; irradiance = 500 w/m<sup>2</sup> and temperature = 34.5 °C. It is observed that the proposed electronic load could be suitable to extract the solar panel’s I-V curves.

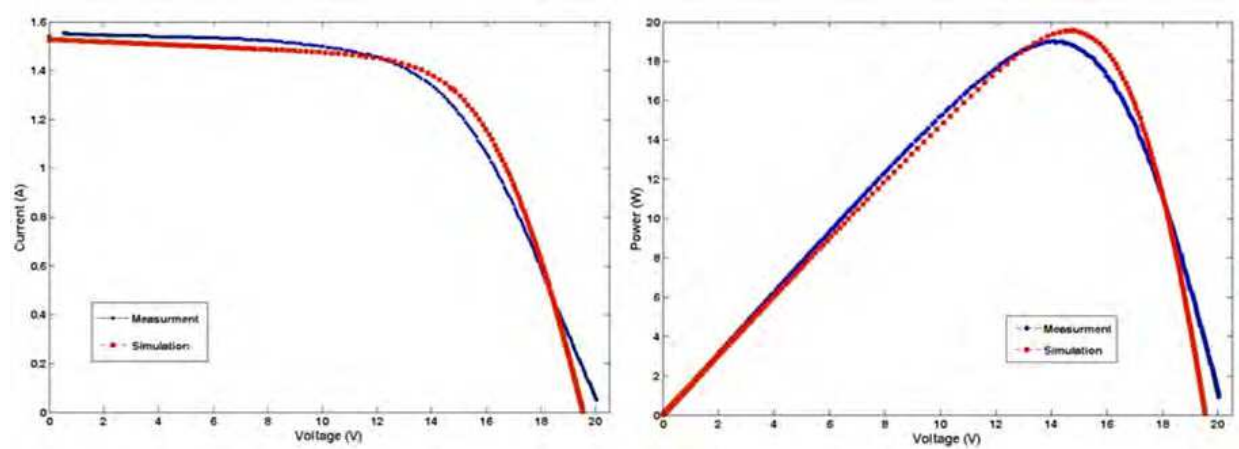


Fig. 12. A typical extracted solar panel’s I-V curve

4. The extracted models unknown parameters

The Newton method is chosen to solve the nonlinear equations. A modification is also reported in the Newton's solving approach to attain the best convergence. MATLAB software environment is used to implement the nonlinear equations and their solving method. At first, the main electrical characteristics ( $I_{sc}$ ,  $V_{oc}$ ,  $V_{mp}$  &  $I_{mp}$ ) are extracted for all I-V curves of the solar panel (extracted by the measurement system) which Table 2 shows them. The main electrical characteristics of the solar panel are used in nonlinear equations models.

| The I-V<br>Curves | Environmental Conditions          |                     | V <sub>oc</sub><br>(V) | I <sub>sc</sub><br>(A) | V <sub>mp</sub><br>(V) | I <sub>mp</sub><br>(A) |
|-------------------|-----------------------------------|---------------------|------------------------|------------------------|------------------------|------------------------|
|                   | Irradiance<br>(W/m <sup>2</sup> ) | Temperature<br>(°C) |                        |                        |                        |                        |
| 1                 | 644.30                            | 22.95               | 20.58                  | 1.90                   | 15.55                  | 1.67                   |
| 2                 | 657.70                            | 24.00               | 20.53                  | 1.94                   | 15.52                  | 1.70                   |
| 3                 | 662.18                            | 24.50               | 20.50                  | 1.95                   | 15.55                  | 1.70                   |
| 4                 | 665.16                            | 25.20               | 20.50                  | 1.97                   | 15.60                  | 1.71                   |
| 5                 | 668.85                            | 25.20               | 20.50                  | 1.98                   | 15.40                  | 1.74                   |
| 6                 | 456.36                            | 15.20               | 21.10                  | 1.35                   | 16.43                  | 1.21                   |
| 7                 | 467.55                            | 14.50               | 21.15                  | 1.39                   | 16.50                  | 1.22                   |
| 8                 | 478.00                            | 14.15               | 21.15                  | 1.43                   | 16.50                  | 1.24                   |
| 9                 | 558.50                            | 17.80               | 21.00                  | 1.63                   | 16.14                  | 1.47                   |
| 10                | 529.50                            | 17.90               | 20.90                  | 1.57                   | 16.17                  | 1.38                   |
| 11                | 575.00                            | 17.40               | 20.90                  | 1.70                   | 16.10                  | 1.49                   |
| 12                | 601.00                            | 18.10               | 20.90                  | 1.77                   | 16.00                  | 1.55                   |
| 13                | 605.50                            | 18.45               | 20.90                  | 1.78                   | 16.10                  | 1.56                   |
| 14                | 474.25                            | 13.65               | 21.00                  | 1.38                   | 16.40                  | 1.22                   |
| 15                | 495.15                            | 14.20               | 21.00                  | 1.45                   | 16.30                  | 1.27                   |
| 16                | 528.00                            | 18.30               | 20.60                  | 1.53                   | 16.00                  | 1.34                   |
| 17                | 528.00                            | 18.45               | 20.60                  | 1.54                   | 15.95                  | 1.36                   |
| 18                | 537.00                            | 18.30               | 20.58                  | 1.56                   | 15.86                  | 1.37                   |
| 19                | 557.80                            | 21.00               | 20.28                  | 1.61                   | 15.35                  | 1.44                   |
| 20                | 548.80                            | 22.00               | 20.25                  | 1.59                   | 15.47                  | 1.40                   |
| 21                | 524.25                            | 21.5                | 20.22                  | 1.51                   | 15.50                  | 1.36                   |
| 22                | 517.50                            | 20.65               | 20.19                  | 1.47                   | 15.47                  | 1.31                   |
| 23                | 533.15                            | 19.85               | 20.45                  | 1.53                   | 15.92                  | 1.39                   |
| 24                | 946.25                            | 40.85               | 18.95                  | 2.65                   | 13.00                  | 2.29                   |
| 25                | 945.50                            | 42.90               | 18.93                  | 2.64                   | 12.91                  | 2.30                   |
| 26                | 778.50                            | 33.40               | 20.30                  | 2.26                   | 14.60                  | 1.97                   |
| 27                | 762.30                            | 33.15               | 20.22                  | 2.22                   | 14.70                  | 1.94                   |
| 28                | 789.00                            | 34.15               | 20.22                  | 2.28                   | 14.48                  | 2.03                   |
| 29                | 782.25                            | 33.80               | 20.27                  | 2.27                   | 14.60                  | 2.01                   |
| 30                | 391.20                            | 41.80               | 18.34                  | 1.43                   | 13.67                  | 1.26                   |
| 31                | 914.95                            | 21.95               | 20.50                  | 2.56                   | 14.76                  | 2.21                   |
| 32                | 917.95                            | 23.85               | 20.30                  | 2.58                   | 14.42                  | 2.25                   |
| 33                | 923.20                            | 27.00               | 20.00                  | 2.60                   | 14.15                  | 2.25                   |
| 34                | 1004.50                           | 34.60               | 19.10                  | 2.82                   | 13.00                  | 2.42                   |
| 35                | 1004.50                           | 35.15               | 19.07                  | 2.83                   | 12.91                  | 2.43                   |
| 36                | 994.75                            | 34.25               | 19.04                  | 2.80                   | 13.08                  | 2.39                   |
| 37                | 900.80                            | 34.90               | 18.98                  | 2.62                   | 13.05                  | 2.26                   |
| 38                | 899.30                            | 35.55               | 18.98                  | 2.63                   | 13.33                  | 2.22                   |
| 39                | 808.30                            | 36.40               | 18.84                  | 2.45                   | 13.16                  | 2.11                   |
| 40                | 811.30                            | 36.80               | 18.84                  | 2.47                   | 13.08                  | 2.13                   |
| 41                | 630.90                            | 36.10               | 18.73                  | 2.13                   | 13.36                  | 1.85                   |

| The I-V<br>Curves | Environmental Conditions          |                     | V <sub>oc</sub><br>(V) | I <sub>sc</sub><br>(A) | V <sub>mp</sub><br>(V) | I <sub>mp</sub><br>(A) |
|-------------------|-----------------------------------|---------------------|------------------------|------------------------|------------------------|------------------------|
|                   | Irradiance<br>(W/m <sup>2</sup> ) | Temperature<br>(°C) |                        |                        |                        |                        |
| 42                | 633.85                            | 36.20               | 18.79                  | 2.13                   | 13.39                  | 1.85                   |
| 43                | 637.55                            | 35.85               | 18.84                  | 2.14                   | 13.44                  | 1.86                   |
| 44                | 406.40                            | 34.10               | 18.70                  | 1.59                   | 13.81                  | 1.40                   |
| 45                | 412.35                            | 33.00               | 18.87                  | 1.61                   | 14.10                  | 1.40                   |
| 46                | 1006.70                           | 33.05               | 19.46                  | 2.82                   | 13.30                  | 2.43                   |
| 47                | 1014.20                           | 33.20               | 19.38                  | 2.85                   | 13.22                  | 2.45                   |
| 48                | 1014.90                           | 33.95               | 19.32                  | 2.86                   | 13.19                  | 2.45                   |
| 49                | 599.50                            | 44.10               | 17.86                  | 2.00                   | 12.54                  | 1.73                   |
| 50                | 756.85                            | 50.55               | 17.92                  | 2.23                   | 12.63                  | 1.86                   |
| 51                | 776.20                            | 50.35               | 17.97                  | 2.29                   | 12.37                  | 1.94                   |
| 52                | 759.90                            | 50.10               | 18.06                  | 2.32                   | 12.54                  | 1.93                   |
| 53                | 769.55                            | 49.55               | 18.11                  | 2.33                   | 12.71                  | 1.96                   |
| 54                | 590.60                            | 48.20               | 18.00                  | 1.93                   | 12.94                  | 1.64                   |
| 55                | 392.25                            | 45.35               | 17.94                  | 1.45                   | 13.28                  | 1.27                   |
| 56                | 701.00                            | 36.40               | 19.13                  | 2.17                   | 13.75                  | 1.88                   |
| 57                | 822.55                            | 36.55               | 19.21                  | 2.41                   | 13.53                  | 2.09                   |
| 58                | 815.00                            | 36.25               | 19.21                  | 2.39                   | 13.44                  | 2.07                   |
| 59                | 937.35                            | 35.90               | 19.35                  | 2.61                   | 13.36                  | 2.27                   |
| 60                | 948.10                            | 35.40               | 19.43                  | 2.61                   | 13.73                  | 2.24                   |
| 61                | 458.65                            | 37.40               | 19.60                  | 1.72                   | 14.60                  | 1.52                   |
| 62                | 455.65                            | 37.60               | 19.58                  | 1.72                   | 14.43                  | 1.53                   |
| 63                | 602.50                            | 38.40               | 19.63                  | 1.99                   | 14.34                  | 1.75                   |
| 64                | 706.90                            | 38.45               | 19.66                  | 2.17                   | 14.20                  | 1.90                   |
| 65                | 705.40                            | 36.60               | 19.69                  | 2.16                   | 14.32                  | 1.89                   |
| 66                | 703.90                            | 38.70               | 19.66                  | 2.16                   | 14.37                  | 1.87                   |
| 67                | 780.75                            | 37.00               | 19.86                  | 2.27                   | 14.43                  | 1.96                   |
| 68                | 777.75                            | 36.40               | 19.91                  | 2.25                   | 14.32                  | 1.98                   |
| 69                | 777.00                            | 35.80               | 19.97                  | 2.24                   | 14.57                  | 1.95                   |
| 70                | 886.60                            | 44.45               | 19.38                  | 2.52                   | 13.84                  | 2.14                   |
| 71                | 879.15                            | 44.25               | 19.41                  | 2.43                   | 13.75                  | 2.12                   |
| 72                | 830.70                            | 40.05               | 19.58                  | 2.41                   | 14.03                  | 2.10                   |
| 73                | 818.80                            | 40.30               | 19.60                  | 2.40                   | 14.06                  | 2.07                   |
| 74                | 749.45                            | 38.95               | 19.66                  | 2.26                   | 14.12                  | 1.99                   |
| 75                | 746.45                            | 38.70               | 19.69                  | 2.26                   | 14.23                  | 1.98                   |
| 76                | 604.75                            | 45.95               | 17.75                  | 2.00                   | 12.49                  | 1.73                   |
| 77                | 987.30                            | 48.80               | 17.89                  | 2.71                   | 11.93                  | 2.3                    |
| 78                | 981.05                            | 50.00               | 17.83                  | 2.68                   | 12.09                  | 2.23                   |
| 79                | 519.00                            | 33.70               | 19.29                  | 1.79                   | 14.09                  | 1.59                   |
| 80                | 516.00                            | 34.90               | 19.24                  | 1.79                   | 14.29                  | 1.56                   |
| 81                | 615.95                            | 36.35               | 19.10                  | 2.00                   | 13.95                  | 1.74                   |
| 82                | 615.20                            | 36.50               | 19.07                  | 2.00                   | 13.81                  | 1.74                   |

| The I-V Curves | Environmental Conditions       |                  | V <sub>oc</sub> (V) | I <sub>sc</sub> (A) | V <sub>mp</sub> (V) | I <sub>mp</sub> (A) |
|----------------|--------------------------------|------------------|---------------------|---------------------|---------------------|---------------------|
|                | Irradiance (W/m <sup>2</sup> ) | Temperature (°C) |                     |                     |                     |                     |
| 83             | 648.75                         | 37.90            | 19.38               | 2.08                | 14.23               | 1.79                |
| 84             | 778.50                         | 35.70            | 19.80               | 2.37                | 14.46               | 2.02                |
| 85             | 836.70                         | 25.00            | 20.78               | 2.4                 | 15.16               | 2.12                |
| 86             | 850.10                         | 25.40            | 20.78               | 2.45                | 15.24               | 2.13                |
| 87             | 839.65                         | 23.15            | 20.90               | 2.43                | 15.22               | 2.14                |
| 88             | 838.16                         | 23.05            | 20.90               | 2.42                | 15.22               | 2.14                |
| 89             | 844.15                         | 23.35            | 20.90               | 2.43                | 15.22               | 2.14                |
| 90             | 781.50                         | 20.80            | 21.07               | 2.24                | 15.55               | 2.00                |
| 91             | 775.50                         | 20.45            | 21.07               | 2.23                | 15.75               | 1.96                |
| 92             | 612.25                         | 15.55            | 21.43               | 1.78                | 16.54               | 1.57                |
| 93             | 609.25                         | 15.00            | 21.46               | 1.77                | 16.48               | 1.57                |
| 94             | 601.75                         | 14.75            | 21.46               | 1.75                | 16.68               | 1.55                |
| 95             | 240.85                         | 31.40            | 18.59               | 1.08                | 14.46               | 0.93                |
| 96             | 241.60                         | 31.65            | 18.48               | 1.08                | 14.26               | 0.94                |
| 97             | 876.20                         | 35.40            | 19.13               | 2.42                | 13.53               | 2.08                |
| 98             | 873.25                         | 36.45            | 19.13               | 2.40                | 13.56               | 2.06                |
| 99             | 453.40                         | 34.10            | 18.90               | 1.64                | 14.03               | 1.44                |
| 100            | 617.40                         | 38.50            | 19.60               | 2.00                | 14.54               | 1.74                |
| 101            | 620.40                         | 37.40            | 19.60               | 2.00                | 14.43               | 1.75                |
| 102            | 453.40                         | 37.00            | 19.35               | 1.64                | 14.63               | 1.48                |
| 103            | 678.60                         | 14.75            | 21.54               | 1.91                | 16.26               | 1.70                |
| 104            | 718.10                         | 13.15            | 21.71               | 2.05                | 16.43               | 1.83                |
| 105            | 615.20                         | 33.10            | 19.77               | 2.09                | 14.48               | 1.79                |
| 106            | 589.10                         | 33.55            | 19.72               | 1.95                | 14.63               | 1.70                |
| 107            | 649.50                         | 37.85            | 19.35               | 2.09                | 13.92               | 1.83                |
| 108            | 648.05                         | 37.90            | 18.79               | 2.08                | 13.42               | 1.82                |
| 109            | 653.95                         | 38.15            | 18.76               | 2.08                | 13.33               | 1.83                |
| 110            | 665.20                         | 39.20            | 18.73               | 2.13                | 13.19               | 1.87                |
| 111            | 947.05                         | 42.55            | 18.90               | 2.65                | 13.02               | 2.28                |
| 112            | 454.90                         | 37.75            | 18.73               | 1.64                | 13.84               | 1.44                |
| 113            | 458.65                         | 36.10            | 18.68               | 1.64                | 13.92               | 1.42                |

Table 2. The main electrical characteristic of the panel

Then, the five and the seven nonlinear equations of the models are implemented and the nonlinear least square approach is used to solve them. Tables 3 and 4 show the extracted unknown parameters of the models for environmental conditions.

|   | Irradiance (W/m <sup>2</sup> ) | Temperature (°C) | I <sub>ph</sub> (A) | I <sub>0</sub> (A)      | a      | Rs(Ω)  | Rp(Ω)    |
|---|--------------------------------|------------------|---------------------|-------------------------|--------|--------|----------|
| 1 | 644.30                         | 22.95            | 1.9054              | 1.3645×10 <sup>-7</sup> | 1.2544 | 1.2078 | 279.6413 |
| 2 | 657.70                         | 24.00            | 1.9406              | 2.0381×10 <sup>-7</sup> | 1.2807 | 1.1805 | 287.2463 |
| 3 | 662.18                         | 24.50            | 1.9579              | 1.0977×10 <sup>-7</sup> | 1.2311 | 1.2276 | 252.0760 |



|    | Irradiance<br>(W/m <sup>2</sup> ) | Temperature<br>(°C) | I <sub>ph</sub> (A) | I <sub>0</sub> (A)      | a      | Rs(Ω)  | Rp(Ω)    |
|----|-----------------------------------|---------------------|---------------------|-------------------------|--------|--------|----------|
| 4  | 665.16                            | 25.20               | 1.9738              | 9.0465×10 <sup>-8</sup> | 1.2164 | 1.2520 | 255.1335 |
| 5  | 668.85                            | 25.20               | 1.9776              | 1.4502×10 <sup>-7</sup> | 1.2513 | 1.2238 | 253.4728 |
| 6  | 456.36                            | 15.20               | 1.3443              | 2.0084×10 <sup>-7</sup> | 1.3468 | 1.0289 | 475.3187 |
| 7  | 467.55                            | 14.50               | 1.3822              | 5.7962×10 <sup>-8</sup> | 1.2489 | 1.1676 | 303.7811 |
| 8  | 478.00                            | 14.15               | 1.4235              | 5.2113×10 <sup>-8</sup> | 1.2401 | 1.1492 | 228.1600 |
| 9  | 558.50                            | 17.80               | 1.6448              | 1.6758×10 <sup>-7</sup> | 1.3089 | 1.1391 | 488.4681 |
| 10 | 529.50                            | 17.90               | 1.5640              | 1.3622×10 <sup>-7</sup> | 1.2908 | 1.1252 | 305.8098 |
| 11 | 575.00                            | 17.40               | 1.6993              | 1.4140×10 <sup>-7</sup> | 1.2872 | 1.1635 | 280.1520 |
| 12 | 601.00                            | 18.10               | 1.7753              | 1.0810×10 <sup>-7</sup> | 1.2614 | 1.1667 | 252.2827 |
| 13 | 605.50                            | 18.45               | 1.7854              | 1.8325×10 <sup>-7</sup> | 1.3034 | 1.1494 | 313.9411 |
| 14 | 474.25                            | 13.65               | 1.3814              | 2.0780×10 <sup>-7</sup> | 1.3435 | 0.9994 | 307.3284 |
| 15 | 495.15                            | 14.20               | 1.4413              | 2.1472×10 <sup>-7</sup> | 1.3430 | 1.0062 | 275.3528 |
| 16 | 528.00                            | 18.30               | 1.5321              | 2.1087×10 <sup>-7</sup> | 1.3087 | 1.0844 | 307.3237 |
| 17 | 528.00                            | 18.45               | 1.54442             | 1.8252×10 <sup>-7</sup> | 1.2961 | 1.1175 | 303.6138 |
| 18 | 537.00                            | 18.30               | 1.5615              | 9.6833×10 <sup>-8</sup> | 1.2447 | 1.1485 | 245.5091 |
| 19 | 557.80                            | 21.00               | 1.6145              | 3.2875×10 <sup>-7</sup> | 1.3193 | 1.1212 | 354.5386 |
| 20 | 548.80                            | 22.00               | 1.5919              | 2.1440×10 <sup>-7</sup> | 1.2835 | 1.1649 | 305.2178 |
| 21 | 524.25                            | 21.50               | 1.5309              | 5.5771×10 <sup>-7</sup> | 1.3667 | 1.0884 | 474.5784 |
| 22 | 517.50                            | 20.65               | 1.4714              | 3.9398×10 <sup>-7</sup> | 1.3375 | 1.0842 | 405.6716 |
| 23 | 533.15                            | 19.85               | 1.5753              | 2.1603×10 <sup>-7</sup> | 1.2953 | 1.1464 | 805.5353 |
| 24 | 946.25                            | 40.85               | 2.6666              | 8.9271×10 <sup>-7</sup> | 1.2757 | 1.3558 | 146.2230 |
| 25 | 945.50                            | 42.90               | 2.6574              | 1.2424×10 <sup>-6</sup> | 1.3030 | 1.3219 | 150.3004 |
| 26 | 778.50                            | 33.40               | 2.1973              | 3.1128×10 <sup>-7</sup> | 1.2892 | 1.2567 | 515.2084 |
| 27 | 762.30                            | 33.15               | 2.2171              | 5.3812×10 <sup>-7</sup> | 1.3316 | 1.1894 | 210.1448 |
| 28 | 789.00                            | 34.15               | 2.2886              | 3.9798×10 <sup>-7</sup> | 1.3028 | 1.2315 | 214.3753 |
| 29 | 782.25                            | 33.80               | 2.2765              | 5.0119×10 <sup>-7</sup> | 1.3266 | 1.1978 | 212.4934 |
| 30 | 391.20                            | 41.80               | 1.4409              | 2.2284×10 <sup>-6</sup> | 1.3744 | 1.2030 | 357.0918 |
| 31 | 914.95                            | 21.95               | 2.5657              | 2.9407×10 <sup>-7</sup> | 1.2866 | 1.2771 | 178.6504 |
| 32 | 917.95                            | 23.85               | 2.5853              | 4.0314×10 <sup>-7</sup> | 1.2993 | 1.2704 | 179.9606 |
| 33 | 923.20                            | 27.00               | 2.6220              | 5.5929×10 <sup>-7</sup> | 1.3065 | 1.2800 | 142.9452 |
| 34 | 1004.50                           | 34.60               | 2.8279              | 1.2215×10 <sup>-6</sup> | 1.3071 | 1.3467 | 155.7048 |
| 35 | 1004.50                           | 35.15               | 2.8362              | 1.5357×10 <sup>-6</sup> | 1.3258 | 1.3260 | 151.6557 |
| 36 | 994.75                            | 34.25               | 2.8140              | 1.2354×10 <sup>-6</sup> | 1.3051 | 1.3258 | 141.9868 |
| 37 | 900.80                            | 34.90               | 2.6385              | 2.1545×10 <sup>-6</sup> | 1.3585 | 1.3032 | 170.0669 |
| 38 | 899.30                            | 35.55               | 2.6449              | 1.5551×10 <sup>-6</sup> | 1.3278 | 1.3082 | 152.1797 |
| 39 | 808.30                            | 36.40               | 2.4663              | 1.5142×10 <sup>-6</sup> | 1.3214 | 1.3244 | 186.9949 |
| 40 | 811.30                            | 36.80               | 2.4866              | 8.9032×10 <sup>-7</sup> | 1.2740 | 1.3574 | 152.6324 |
| 41 | 630.90                            | 36.10               | 2.1335              | 7.5213×10 <sup>-7</sup> | 1.2650 | 1.3213 | 179.3817 |
| 42 | 633.85                            | 36.20               | 2.1493              | 1.4614×10 <sup>-6</sup> | 1.3279 | 1.2659 | 172.9979 |
| 43 | 637.55                            | 35.85               | 2.1526              | 1.3956×10 <sup>-6</sup> | 1.3272 | 1.2720 | 181.0577 |
| 44 | 406.40                            | 34.10               | 1.5971              | 1.7433×10 <sup>-6</sup> | 1.3672 | 1.1656 | 253.3236 |
| 45 | 412.35                            | 33.00               | 1.6220              | 1.0427×10 <sup>-6</sup> | 1.3288 | 1.1815 | 221.4351 |



|    | Irradiance<br>(W/m <sup>2</sup> ) | Temperature<br>(°C) | I <sub>ph</sub> (A) | I <sub>0</sub> (A)      | a      | Rs(Ω)  | Rp(Ω)    |
|----|-----------------------------------|---------------------|---------------------|-------------------------|--------|--------|----------|
| 46 | 1006.70                           | 33.05               | 2.8445              | 7.7494×10 <sup>-7</sup> | 1.2922 | 1.3580 | 132.0408 |
| 47 | 1014.20                           | 33.20               | 2.8548              | 9.1903×10 <sup>-7</sup> | 1.3001 | 1.3490 | 162.1626 |
| 48 | 1014.90                           | 33.95               | 2.8757              | 7.7393×10 <sup>-7</sup> | 1.2816 | 1.3650 | 135.7198 |
| 49 | 599.50                            | 44.10               | 2.0093              | 3.2553×10 <sup>-6</sup> | 1.3443 | 1.3202 | 193.5047 |
| 50 | 756.85                            | 50.55               | 2.2630              | 2.0566×10 <sup>-6</sup> | 1.2958 | 1.3584 | 98.4074  |
| 51 | 776.20                            | 50.35               | 2.3183              | 9.4350×10 <sup>-6</sup> | 1.4552 | 1.3151 | 131.0878 |
| 52 | 759.90                            | 50.10               | 2.3446              | 1.3496×10 <sup>-6</sup> | 1.2650 | 1.4109 | 86.7692  |
| 53 | 769.55                            | 49.55               | 2.3492              | 3.1359×10 <sup>-6</sup> | 1.3436 | 1.3764 | 173.6641 |
| 54 | 590.60                            | 48.20               | 1.9461              | 1.7518×10 <sup>-6</sup> | 1.2990 | 1.3753 | 152.9589 |
| 55 | 392.25                            | 45.35               | 1.4551              | 7.3811×10 <sup>-6</sup> | 1.4749 | 1.1449 | 513.8872 |
| 56 | 701.00                            | 36.40               | 2.1809              | 6.3023×10 <sup>-7</sup> | 1.2744 | 1.3197 | 181.3692 |
| 57 | 822.55                            | 36.55               | 2.4333              | 1.4581×10 <sup>-6</sup> | 1.3457 | 1.2695 | 154.6094 |
| 58 | 815.00                            | 36.25               | 2.3989              | 8.6293×10 <sup>-7</sup> | 1.2995 | 1.3051 | 148.3509 |
| 59 | 937.35                            | 35.90               | 2.6353              | 7.8507×10 <sup>-7</sup> | 1.2924 | 1.3333 | 140.9158 |
| 60 | 948.10                            | 35.40               | 2.6281              | 6.5875×10 <sup>-7</sup> | 1.2819 | 1.3362 | 198.5875 |
| 61 | 458.65                            | 37.40               | 1.7341              | 2.3307×10 <sup>-7</sup> | 1.2435 | 1.2222 | 202.9395 |
| 62 | 455.65                            | 37.60               | 1.7262              | 2.9317×10 <sup>-7</sup> | 1.2605 | 1.2122 | 202.2739 |
| 63 | 602.50                            | 38.40               | 2.0061              | 2.2729×10 <sup>-7</sup> | 1.2318 | 1.2910 | 179.7304 |
| 64 | 706.90                            | 38.45               | 2.1841              | 6.2885×10 <sup>-7</sup> | 1.3100 | 1.2227 | 176.9047 |
| 65 | 705.40                            | 36.60               | 2.1762              | 3.4172×10 <sup>-7</sup> | 1.2607 | 1.2898 | 185.8031 |
| 66 | 703.90                            | 38.70               | 2.1727              | 4.4171×10 <sup>-7</sup> | 1.2803 | 1.2778 | 178.6681 |
| 67 | 780.75                            | 37.00               | 2.2865              | 2.7213×10 <sup>-7</sup> | 1.2499 | 1.2911 | 155.5827 |
| 68 | 777.75                            | 36.40               | 2.2661              | 6.4822×10 <sup>-7</sup> | 1.3257 | 1.2351 | 196.1866 |
| 69 | 777.00                            | 35.80               | 2.2597              | 3.5896×10 <sup>-7</sup> | 1.2797 | 1.2661 | 180.5390 |
| 70 | 886.60                            | 44.45               | 2.4968              | 5.9216×10 <sup>-7</sup> | 1.2747 | 1.2546 | 153.3574 |
| 71 | 879.15                            | 44.25               | 2.4217              | 1.7378×10 <sup>-6</sup> | 1.3740 | 1.2205 | 360.6990 |
| 72 | 830.70                            | 40.05               | 2.4218              | 6.8898×10 <sup>-7</sup> | 1.3016 | 1.2563 | 247.4058 |
| 73 | 818.80                            | 40.30               | 2.4188              | 7.9099×10 <sup>-7</sup> | 1.3181 | 1.2113 | 137.7473 |
| 74 | 749.45                            | 38.95               | 2.2718              | 6.9207×10 <sup>-7</sup> | 1.3136 | 1.2329 | 232.5429 |
| 75 | 746.45                            | 38.70               | 2.2801              | 5.1192×10 <sup>-7</sup> | 1.2905 | 1.2244 | 168.6507 |
| 76 | 604.75                            | 45.95               | 2.0164              | 1.5572×10 <sup>-6</sup> | 1.2660 | 1.3880 | 165.8156 |
| 77 | 987.30                            | 48.80               | 2.7459              | 3.1186×10 <sup>-6</sup> | 1.3124 | 1.4018 | 115.7579 |
| 78 | 981.05                            | 50.00               | 2.7064              | 4.3017×10 <sup>-6</sup> | 1.3400 | 1.4091 | 151.9670 |
| 79 | 519.00                            | 33.70               | 1.7947              | 5.8455×10 <sup>-7</sup> | 1.2951 | 1.2475 | 281.8090 |
| 80 | 516.00                            | 34.90               | 1.8017              | 4.0818×10 <sup>-7</sup> | 1.2618 | 1.2594 | 205.2749 |
| 81 | 615.95                            | 36.35               | 2.0075              | 6.1718×10 <sup>-7</sup> | 1.2774 | 1.2940 | 218.7826 |
| 82 | 615.20                            | 36.50               | 2.0152              | 4.5464×10 <sup>-7</sup> | 1.2507 | 1.3113 | 168.6899 |
| 83 | 648.75                            | 37.90               | 2.0960              | 4.6946×10 <sup>-7</sup> | 1.2710 | 1.2501 | 148.6441 |
| 84 | 778.50                            | 35.70               | 2.3769              | 3.8760×10 <sup>-7</sup> | 1.2713 | 1.2666 | 160.5721 |
| 85 | 836.70                            | 25.00               | 2.4144              | 2.1683×10 <sup>-7</sup> | 1.2840 | 1.2112 | 228.6814 |
| 86 | 850.10                            | 25.40               | 2.4656              | 1.6939×10 <sup>-7</sup> | 1.2639 | 1.2282 | 180.5302 |
| 87 | 839.65                            | 23.15               | 2.4409              | 2.2484×10 <sup>-7</sup> | 1.2938 | 1.1793 | 183.7797 |

|     | Irradiance<br>(W/m <sup>2</sup> ) | Temperature<br>(°C) | I <sub>ph</sub> (A) | I <sub>0</sub> (A)       | a      | Rs(Ω)  | Rp(Ω)    |
|-----|-----------------------------------|---------------------|---------------------|--------------------------|--------|--------|----------|
| 88  | 838.16                            | 23.05               | 2.4333              | 1.6491×10 <sup>-7</sup>  | 1.2697 | 1.1971 | 181.9877 |
| 89  | 844.15                            | 23.35               | 2.4391              | 1.0187×10 <sup>-7</sup>  | 1.2337 | 1.2319 | 168.4823 |
| 90  | 781.50                            | 20.80               | 2.2502              | 2.4789×10 <sup>-7</sup>  | 1.3180 | 1.1315 | 249.5637 |
| 91  | 775.50                            | 20.45               | 2.2299              | 1.8167×10 <sup>-7</sup>  | 1.2934 | 1.1539 | 269.1192 |
| 92  | 612.25                            | 15.55               | 1.7732              | 1.1189×10 <sup>-7</sup>  | 1.2958 | 1.0877 | 317.2956 |
| 93  | 609.25                            | 15.00               | 1.7761              | 2.6497×10 <sup>-8</sup>  | 1.1944 | 1.1797 | 232.1886 |
| 94  | 601.75                            | 14.75               | 1.7631              | 5.0466×10 <sup>-8</sup>  | 1.2390 | 1.1252 | 252.8796 |
| 95  | 240.85                            | 31.40               | 1.0841              | 2.8277×10 <sup>-6</sup>  | 1.4522 | 0.8406 | 328.3110 |
| 96  | 241.60                            | 31.65               | 1.0842              | 2.9811×10 <sup>-6</sup>  | 1.4494 | 0.8720 | 323.0246 |
| 97  | 876.20                            | 35.40               | 2.4382              | 5.6696×10 <sup>-7</sup>  | 1.2564 | 1.3492 | 157.0273 |
| 98  | 873.25                            | 36.45               | 2.4151              | 1.3653×10 <sup>-6</sup>  | 1.3337 | 1.3058 | 180.0039 |
| 99  | 453.40                            | 34.10               | 1.6490              | 1.1006×10 <sup>-6</sup>  | 1.3337 | 1.1999 | 245.1651 |
| 100 | 617.40                            | 38.50               | 2.0113              | 3.5727×10 <sup>-7</sup>  | 1.2650 | 1.2431 | 213.8478 |
| 101 | 620.40                            | 37.40               | 2.0119              | 4.5098×10 <sup>-7</sup>  | 1.2847 | 1.2074 | 196.3093 |
| 102 | 453.40                            | 37.00               | 1.6437              | 1.0425×10 <sup>-6</sup>  | 1.3602 | 1.1132 | 275.7352 |
| 103 | 678.60                            | 14.75               | 1.8721              | 1.7176×10 <sup>-7</sup>  | 1.3306 | 1.1480 | 837.2890 |
| 104 | 718.10                            | 13.15               | 2.0527              | 7.0015×10 <sup>-8</sup>  | 1.2647 | 1.2034 | 427.2372 |
| 105 | 615.20                            | 33.10               | 2.0934              | 1.15866×10 <sup>-7</sup> | 1.2124 | 1.2524 | 113.7532 |
| 106 | 589.10                            | 33.55               | 1.9420              | 3.2678×10 <sup>-7</sup>  | 1.2673 | 1.2389 | 257.1990 |
| 107 | 649.50                            | 37.85               | 2.1063              | 6.5590×10 <sup>-7</sup>  | 1.2966 | 1.2533 | 163.5833 |
| 108 | 648.05                            | 37.90               | 2.0915              | 1.5511×10 <sup>-6</sup>  | 1.3355 | 1.2439 | 198.8860 |
| 109 | 653.95                            | 38.15               | 2.0951              | 1.2615×10 <sup>-6</sup>  | 1.3138 | 1.2757 | 209.6240 |
| 110 | 665.20                            | 39.20               | 2.1463              | 1.0031×10 <sup>-6</sup>  | 1.2899 | 1.3034 | 166.9648 |
| 111 | 947.05                            | 42.55               | 2.6799              | 1.6611×10 <sup>-6</sup>  | 1.3274 | 1.3070 | 133.4828 |
| 112 | 454.90                            | 37.75               | 1.6428              | 2.2538×10 <sup>-6</sup>  | 1.3913 | 1.1596 | 331.7340 |
| 113 | 458.65                            | 36.10               | 1.6525              | 2.1133×10 <sup>-6</sup>  | 1.3810 | 1.1576 | 251.5761 |

Table 3. One-diode model parameters in different environmental conditions

|    | Irradiance<br>(W/m <sup>2</sup> ) | Temperature<br>(°C) | I <sub>ph</sub> (A) | I <sub>01</sub> (A)     | a <sub>1</sub> | I <sub>02</sub> (A)     | a <sub>2</sub> | Rs (Ω) | Rp(Ω)    |
|----|-----------------------------------|---------------------|---------------------|-------------------------|----------------|-------------------------|----------------|--------|----------|
| 1  | 644.30                            | 22.95               | 1.9043              | 3.0432×10 <sup>-8</sup> | 1.1883         | 1.3697×10 <sup>-7</sup> | 1.3197         | 1.2341 | 294.5317 |
| 2  | 657.70                            | 24.00               | 1.9446              | 2.0588×10 <sup>-8</sup> | 1.1240         | 2.0918×10 <sup>-7</sup> | 1.5696         | 1.3141 | 254.2053 |
| 3  | 662.18                            | 24.50               | 1.9536              | 1.3177×10 <sup>-7</sup> | 1.3606         | 4.0695×10 <sup>-7</sup> | 1.3606         | 1.1380 | 318.7178 |
| 4  | 665.16                            | 25.20               | 1.9729              | 2.9981×10 <sup>-8</sup> | 1.1706         | 1.7914×10 <sup>-7</sup> | 1.3537         | 1.2339 | 248.5131 |
| 5  | 668.85                            | 25.20               | 1.9745              | 2.8887×10 <sup>-8</sup> | 1.2215         | 2.0565×10 <sup>-7</sup> | 1.3069         | 1.2181 | 281.0450 |
| 6  | 456.36                            | 15.20               | 1.3453              | 2.4504×10 <sup>-8</sup> | 1.2271         | 2.6436×10 <sup>-7</sup> | 1.4485         | 1.0603 | 474.6605 |
| 7  | 467.55                            | 14.50               | 1.3809              | 2.7889×10 <sup>-8</sup> | 1.2443         | 1.4274×10 <sup>-7</sup> | 1.3800         | 1.1122 | 340.2013 |
| 8  | 478.00                            | 14.15               | 1.4212              | 2.7554×10 <sup>-8</sup> | 1.2449         | 1.6846×10 <sup>-7</sup> | 1.3907         | 1.0636 | 250.2702 |
| 9  | 558.50                            | 17.80               | 1.6464              | 2.9720×10 <sup>-8</sup> | 1.2208         | 1.6773×10 <sup>-7</sup> | 1.3810         | 1.1662 | 443.9569 |
| 10 | 529.50                            | 17.90               | 1.5654              | 3.4963×10 <sup>-9</sup> | 1.0648         | 7.7917×10 <sup>-7</sup> | 1.6272         | 1.2959 | 306.1568 |
| 11 | 575.00                            | 17.40               | 1.7003              | 2.2433×10 <sup>-8</sup> | 1.1666         | 2.1302×10 <sup>-7</sup> | 1.5016         | 1.2351 | 268.6247 |
| 12 | 601.00                            | 18.10               | 1.7728              | 2.8641×10 <sup>-8</sup> | 1.2150         | 1.8419×10 <sup>-7</sup> | 1.3616         | 1.1607 | 275.4929 |

|    | Irradiance<br>(W/m <sup>2</sup> ) | Temperature<br>(°C) | I <sub>ph</sub> (A) | I <sub>01</sub> (A)     | a <sub>1</sub> | I <sub>02</sub> (A)     | a <sub>2</sub> | Rs (Ω) | Rp(Ω)    |
|----|-----------------------------------|---------------------|---------------------|-------------------------|----------------|-------------------------|----------------|--------|----------|
| 13 | 605.50                            | 18.45               | 1.7850              | 2.5508×10 <sup>-8</sup> | 1.1760         | 1.8028×10 <sup>-7</sup> | 1.4433         | 1.2442 | 316.8041 |
| 14 | 474.25                            | 13.65               | 1.3797              | 3.0408×10 <sup>-8</sup> | 1.3842         | 2.9990×10 <sup>-7</sup> | 1.3846         | 0.9578 | 312.5028 |
| 15 | 495.15                            | 14.20               | 1.4398              | 2.7505×10 <sup>-8</sup> | 1.2616         | 1.9085×10 <sup>-7</sup> | 1.3710         | 1.0181 | 268.2193 |
| 16 | 528.00                            | 18.30               | 1.5321              | 2.3850×10 <sup>-8</sup> | 1.1597         | 1.9136×10 <sup>-7</sup> | 1.4811         | 1.2332 | 302.4667 |
| 17 | 528.00                            | 18.45               | 1.5458              | 5.7239×10 <sup>-9</sup> | 1.0782         | 6.9380×10 <sup>-7</sup> | 1.5793         | 1.2685 | 298.4500 |
| 18 | 537.00                            | 18.30               | 1.5612              | 2.8985×10 <sup>-8</sup> | 1.1918         | 1.8355×10 <sup>-7</sup> | 1.3790         | 1.1295 | 254.8772 |
| 19 | 557.80                            | 21.00               | 1.6153              | 2.9673×10 <sup>-8</sup> | 1.2465         | 2.6445×10 <sup>-7</sup> | 1.3220         | 1.1547 | 356.6941 |
| 20 | 548.80                            | 22.00               | 1.5912              | 2.9889×10 <sup>-8</sup> | 1.1972         | 1.6498×10 <sup>-7</sup> | 1.3094         | 1.1999 | 289.9760 |
| 21 | 524.25                            | 21.50               | 1.5337              | 2.4210×10 <sup>-8</sup> | 1.1624         | 3.3020×10 <sup>-7</sup> | 1.4010         | 1.1874 | 396.9221 |
| 22 | 517.50                            | 20.65               | 1.4707              | 2.9247×10 <sup>-8</sup> | 1.1909         | 2.4577×10 <sup>-7</sup> | 1.3534         | 1.1742 | 395.9226 |
| 23 | 533.15                            | 19.85               | 1.5767              | 2.9454×10 <sup>-8</sup> | 1.1883         | 1.9557×10 <sup>-7</sup> | 1.3592         | 1.1708 | 611.9569 |
| 24 | 946.25                            | 40.85               | 2.6531              | 2.5017×10 <sup>-6</sup> | 1.4644         | 3.6255×10 <sup>-6</sup> | 1.4643         | 1.2576 | 222.6724 |
| 25 | 945.50                            | 42.90               | 2.6524              | 2.4917×10 <sup>-7</sup> | 1.3377         | 1.5983×10 <sup>-6</sup> | 1.3396         | 1.3038 | 165.3972 |
| 26 | 778.50                            | 33.40               | 2.1998              | 1.1948×10 <sup>-8</sup> | 1.0729         | 1.4190×10 <sup>-6</sup> | 1.7427         | 1.3897 | 355.8168 |
| 27 | 762.30                            | 33.15               | 2.2196              | 2.7598×10 <sup>-8</sup> | 1.1455         | 2.8448×10 <sup>-7</sup> | 1.3577         | 1.2938 | 200.6356 |
| 28 | 789.00                            | 34.15               | 2.2859              | 2.8133×10 <sup>-8</sup> | 1.2301         | 4.0767×10 <sup>-7</sup> | 1.3213         | 1.2504 | 226.2728 |
| 29 | 782.25                            | 33.80               | 2.2787              | 1.9512×10 <sup>-8</sup> | 1.1067         | 4.2830×10 <sup>-7</sup> | 1.4745         | 1.3242 | 187.2231 |
| 30 | 391.20                            | 41.80               | 1.4425              | 2.5260×10 <sup>-7</sup> | 1.3334         | 1.5355×10 <sup>-6</sup> | 1.3554         | 1.2526 | 350.9833 |
| 31 | 914.95                            | 21.95               | 2.5641              | 2.9959×10 <sup>-8</sup> | 1.2141         | 2.4595×10 <sup>-7</sup> | 1.2967         | 1.3091 | 195.5702 |
| 32 | 917.95                            | 23.85               | 2.5827              | 5.4386×10 <sup>-8</sup> | 1.3181         | 5.0320×10 <sup>-7</sup> | 1.3275         | 1.2698 | 199.2378 |
| 33 | 923.20                            | 27.00               | 2.6221              | 9.0452×10 <sup>-9</sup> | 1.0543         | 1.2920×10 <sup>-6</sup> | 1.4846         | 1.3512 | 137.6304 |
| 34 | 1004.50                           | 34.60               | 2.8311              | 6.8694×10 <sup>-8</sup> | 1.1262         | 9.0237×10 <sup>-7</sup> | 1.3614         | 1.4110 | 152.6305 |
| 35 | 1004.50                           | 35.15               | 2.8410              | 6.4888×10 <sup>-8</sup> | 1.1394         | 8.3690×10 <sup>-7</sup> | 1.3241         | 1.3880 | 142.3507 |
| 36 | 994.75                            | 34.25               | 2.8144              | 1.1388×10 <sup>-7</sup> | 1.2995         | 1.0543×10 <sup>-6</sup> | 1.2999         | 1.3414 | 148.7050 |
| 37 | 900.80                            | 34.90               | 2.6371              | 2.5877×10 <sup>-7</sup> | 1.3474         | 1.7108×10 <sup>-6</sup> | 1.3502         | 1.3179 | 171.1347 |
| 38 | 899.30                            | 35.55               | 2.6451              | 7.9309×10 <sup>-8</sup> | 1.2414         | 6.1660×10 <sup>-7</sup> | 1.2594         | 1.3682 | 150.0456 |
| 39 | 808.30                            | 36.40               | 2.4660              | 1.4170×10 <sup>-7</sup> | 1.3019         | 1.1481×10 <sup>-6</sup> | 1.3073         | 1.3361 | 184.8603 |
| 40 | 811.30                            | 36.80               | 2.4842              | 1.8339×10 <sup>-7</sup> | 1.3129         | 1.1981×10 <sup>-6</sup> | 1.3128         | 1.3281 | 159.9860 |
| 41 | 630.90                            | 36.10               | 2.1256              | 2.5422×10 <sup>-6</sup> | 1.4743         | 3.6746×10 <sup>-6</sup> | 1.4743         | 1.1656 | 248.2853 |
| 42 | 633.85                            | 36.20               | 2.1413              | 2.2951×10 <sup>-6</sup> | 1.4692         | 3.4374×10 <sup>-6</sup> | 1.4690         | 1.1719 | 217.3854 |
| 43 | 637.55                            | 35.85               | 2.1516              | 9.4216×10 <sup>-8</sup> | 1.3134         | 1.1090×10 <sup>-6</sup> | 1.3134         | 1.3044 | 184.2421 |
| 44 | 406.40                            | 34.10               | 1.5958              | 2.9422×10 <sup>-7</sup> | 1.3599         | 1.3358×10 <sup>-6</sup> | 1.3611         | 1.1440 | 237.6602 |
| 45 | 412.35                            | 33.00               | 1.6175              | 1.2768×10 <sup>-6</sup> | 1.4603         | 2.4944×10 <sup>-6</sup> | 1.4605         | 1.0597 | 258.8879 |
| 46 | 1006.70                           | 33.05               | 2.8442              | 5.6206×10 <sup>-8</sup> | 1.1902         | 6.3607×10 <sup>-7</sup> | 1.3014         | 1.3825 | 134.8388 |
| 47 | 1014.20                           | 33.20               | 2.8506              | 2.0098×10 <sup>-7</sup> | 1.3564         | 1.5479×10 <sup>-6</sup> | 1.3583         | 1.3247 | 197.6830 |
| 48 | 1014.90                           | 33.95               | 2.8735              | 1.1218×10 <sup>-7</sup> | 1.3243         | 1.1483×10 <sup>-6</sup> | 1.3243         | 1.3351 | 140.4835 |
| 49 | 599.50                            | 44.10               | 2.0076              | 9.6057×10 <sup>-7</sup> | 1.3467         | 2.3573×10 <sup>-6</sup> | 1.3467         | 1.3091 | 178.8528 |
| 50 | 756.85                            | 50.55               | 2.2601              | 1.9992×10 <sup>-6</sup> | 1.3906         | 3.3102×10 <sup>-6</sup> | 1.3904         | 1.3121 | 108.5623 |
| 51 | 776.20                            | 50.35               | 2.3243              | 6.7891×10 <sup>-7</sup> | 1.3131         | 2.3084×10 <sup>-6</sup> | 1.3385         | 1.4005 | 110.3408 |
| 52 | 759.90                            | 50.10               | 2.3479              | 1.6993×10 <sup>-7</sup> | 1.1701         | 5.8437×10 <sup>-7</sup> | 1.2368         | 1.4630 | 84.6207  |
| 53 | 769.55                            | 49.55               | 2.3457              | 2.2463×10 <sup>-6</sup> | 1.4075         | 3.5604×10 <sup>-6</sup> | 1.4074         | 1.3535 | 201.9657 |
| 54 | 590.60                            | 48.20               | 1.9409              | 5.6130×10 <sup>-7</sup> | 1.3287         | 1.8279×10 <sup>-6</sup> | 1.3287         | 1.3952 | 158.5665 |

|    | Irradiance<br>(W/m <sup>2</sup> ) | Temperature<br>(°C) | I <sub>ph</sub> (A) | I <sub>01</sub> (A)      | a <sub>1</sub> | I <sub>02</sub> (A)     | a <sub>2</sub> | Rs (Ω) | Rp(Ω)    |
|----|-----------------------------------|---------------------|---------------------|--------------------------|----------------|-------------------------|----------------|--------|----------|
| 55 | 392.25                            | 45.35               | 1.4567              | 6.3763×10 <sup>-7</sup>  | 1.3514         | 2.1097×10 <sup>-6</sup> | 1.3685         | 1.2832 | 449.1823 |
| 56 | 701.00                            | 36.40               | 2.1796              | 5.9120×10 <sup>-8</sup>  | 1.2659         | 6.4841×10 <sup>-7</sup> | 1.2862         | 1.3258 | 185.9257 |
| 57 | 822.55                            | 36.55               | 2.4292              | 8.8912×10 <sup>-8</sup>  | 1.3149         | 9.5018×10 <sup>-7</sup> | 1.3149         | 1.2908 | 148.4283 |
| 58 | 815.00                            | 36.25               | 2.3942              | 7.8008×10 <sup>-8</sup>  | 1.3071         | 8.6383×10 <sup>-7</sup> | 1.3071         | 1.3137 | 158.4158 |
| 59 | 937.35                            | 35.90               | 2.6380              | 5.6508×10 <sup>-8</sup>  | 1.1643         | 5.8327×10 <sup>-7</sup> | 1.3081         | 1.3438 | 125.1391 |
| 60 | 948.10                            | 35.40               | 2.6253              | 7.7330×10 <sup>-8</sup>  | 1.3167         | 9.1644×10 <sup>-7</sup> | 1.3172         | 1.3343 | 238.5130 |
| 61 | 458.65                            | 37.40               | 1.7340              | 2.0356×10 <sup>-8</sup>  | 1.0972         | 4.2763×10 <sup>-7</sup> | 1.4106         | 1.2842 | 196.2692 |
| 62 | 455.65                            | 37.60               | 1.7239              | 3.0959×10 <sup>-8</sup>  | 1.1392         | 4.4560×10 <sup>-7</sup> | 1.3674         | 1.2573 | 216.5685 |
| 63 | 602.50                            | 38.40               | 2.0035              | 3.1412 ×10 <sup>-8</sup> | 1.1813         | 4.8461×10 <sup>-7</sup> | 1.3212         | 1.2244 | 180.2013 |
| 64 | 706.90                            | 38.45               | 2.1800              | 5.4562×10 <sup>-8</sup>  | 1.3504         | 9.3287×10 <sup>-7</sup> | 1.3503         | 1.2132 | 194.9991 |
| 65 | 705.40                            | 36.60               | 2.1695              | 2.9715×10 <sup>-8</sup>  | 1.3401         | 8.3436×10 <sup>-7</sup> | 1.3401         | 1.2273 | 210.6548 |
| 66 | 703.90                            | 38.70               | 2.1708              | 2.9240×10 <sup>-8</sup>  | 1.3187         | 6.6092×10 <sup>-7</sup> | 1.3187         | 1.2416 | 177.3929 |
| 67 | 780.75                            | 37.00               | 2.2875              | 1.2985×10 <sup>-8</sup>  | 1.0604         | 1.8326×10 <sup>-6</sup> | 1.6166         | 1.3705 | 151.6619 |
| 68 | 777.75                            | 36.40               | 2.2669              | 7.9289×10 <sup>-8</sup>  | 1.0395         | 2.0258×10 <sup>-6</sup> | 1.6016         | 1.3944 | 189.5926 |
| 69 | 777.00                            | 35.80               | 2.2613              | 1.0495×10 <sup>-8</sup>  | 1.0530         | 2.1107×10 <sup>-6</sup> | 1.6648         | 1.3922 | 174.3726 |
| 70 | 886.60                            | 44.45               | 2.4906              | 5.3519×10 <sup>-8</sup>  | 1.1734         | 5.0326×10 <sup>-7</sup> | 1.2961         | 1.2738 | 151.7814 |
| 71 | 879.15                            | 44.25               | 2.4246              | 4.7363×10 <sup>-8</sup>  | 1.2251         | 8.2091×10 <sup>-7</sup> | 1.3194         | 1.2895 | 317.8984 |
| 72 | 830.70                            | 40.05               | 2.4173              | 2.0975×10 <sup>-7</sup>  | 1.3619         | 1.1345×10 <sup>-6</sup> | 1.3619         | 1.2276 | 289.4507 |
| 73 | 818.80                            | 40.30               | 2.4138              | 4.3268×10 <sup>-8</sup>  | 1.3130         | 7.0331×10 <sup>-7</sup> | 1.3130         | 1.2228 | 141.9730 |
| 74 | 749.45                            | 38.95               | 2.2701              | 8.8746×10 <sup>-8</sup>  | 1.3359         | 9.5496×10 <sup>-7</sup> | 1.3522         | 1.1952 | 238.7603 |
| 75 | 746.45                            | 38.70               | 2.2769              | 3.4376×10 <sup>-8</sup>  | 1.3022         | 6.5867×10 <sup>-7</sup> | 1.3174         | 1.2048 | 173.1026 |
| 76 | 604.75                            | 45.95               | 2.0155              | 2.1057×10 <sup>-7</sup>  | 1.2517         | 1.4359×10 <sup>-6</sup> | 1.2742         | 1.3825 | 166.8131 |
| 77 | 987.30                            | 48.80               | 2.7327              | 3.8961×10 <sup>-6</sup>  | 1.4222         | 5.1035×10 <sup>-6</sup> | 1.4221         | 1.3555 | 150.1287 |
| 78 | 981.05                            | 50.00               | 2.7015              | 2.1267×10 <sup>-6</sup>  | 1.3779         | 4.0844×10 <sup>-6</sup> | 1.3779         | 1.4000 | 164.3968 |
| 79 | 519.00                            | 33.70               | 1.7890              | 3.6873×10 <sup>-7</sup>  | 1.4160         | 1.7341×10 <sup>-6</sup> | 1.4160         | 1.1666 | 388.5935 |
| 80 | 516.00                            | 34.90               | 1.7966              | 2.8663×10 <sup>-7</sup>  | 1.3823         | 1.2693×10 <sup>-6</sup> | 1.3824         | 1.1770 | 259.5067 |
| 81 | 615.95                            | 36.35               | 2.0065              | 5.4318×10 <sup>-8</sup>  | 1.2134         | 5.3810×10 <sup>-7</sup> | 1.2844         | 1.2897 | 206.7961 |
| 82 | 615.20                            | 36.50               | 2.0134              | 5.5856×10 <sup>-8</sup>  | 1.1890         | 4.8161×10 <sup>-7</sup> | 1.2822         | 1.3032 | 171.1018 |
| 83 | 648.75                            | 37.90               | 2.0925              | 4.2362×10 <sup>-8</sup>  | 1.1432         | 5.3933×10 <sup>-7</sup> | 1.3437         | 1.2704 | 149.7204 |
| 84 | 778.50                            | 35.70               | 2.3755              | 3.8038×10 <sup>-8</sup>  | 1.1490         | 4.7462×10 <sup>-7</sup> | 1.3515         | 1.2931 | 161.9807 |
| 85 | 836.70                            | 25.00               | 2.4100              | 3.0253×10 <sup>-8</sup>  | 1.3337         | 3.7734×10 <sup>-7</sup> | 1.3361         | 1.1797 | 260.1578 |
| 86 | 850.10                            | 25.40               | 2.4609              | 3.0968×10 <sup>-8</sup>  | 1.3033         | 2.4821×10 <sup>-7</sup> | 1.3033         | 1.2173 | 195.0512 |
| 87 | 839.65                            | 23.15               | 2.4396              | 2.5111×10 <sup>-7</sup>  | 1.1490         | 1.9083×10 <sup>-7</sup> | 1.4551         | 1.2452 | 169.0755 |
| 88 | 838.16                            | 23.05               | 2.4322              | 2.4870×10 <sup>-8</sup>  | 1.1509         | 2.0781×10 <sup>-7</sup> | 1.4440         | 1.2393 | 172.6510 |
| 89 | 844.15                            | 23.35               | 2.4427              | 1.2633×10 <sup>-8</sup>  | 1.0985         | 1.0025×10 <sup>-9</sup> | 1.7022         | 1.3270 | 152.1720 |
| 90 | 781.50                            | 20.80               | 2.2524              | 9.4105×10 <sup>-9</sup>  | 1.1001         | 1.4127×10 <sup>-6</sup> | 1.7709         | 1.2685 | 219.9114 |
| 91 | 775.50                            | 20.45               | 2.2298              | 1.6292×10 <sup>-8</sup>  | 1.1488         | 4.3632×10 <sup>-7</sup> | 1.4821         | 1.1884 | 260.3549 |
| 92 | 612.25                            | 15.55               | 1.7738              | 2.4899×10 <sup>-8</sup>  | 1.1970         | 1.3638×10 <sup>-7</sup> | 1.5022         | 1.1488 | 289.5701 |
| 93 | 609.25                            | 15.00               | 1.7733              | 2.9613×10 <sup>-8</sup>  | 1.2056         | 6.0005×10 <sup>-8</sup> | 1.5044         | 1.1616 | 247.4696 |
| 94 | 601.75                            | 14.75               | 1.7590              | 2.7260×10 <sup>-8</sup>  | 1.2505         | 1.9787×10 <sup>-7</sup> | 1.3990         | 1.0152 | 277.5651 |
| 95 | 240.85                            | 31.40               | 1.0832              | 7.6864×10 <sup>-7</sup>  | 1.4388         | 1.7435×10 <sup>-6</sup> | 1.4391         | 0.9077 | 320.8844 |
| 96 | 241.60                            | 31.65               | 1.0832              | 1.0096×10 <sup>-6</sup>  | 1.4575         | 2.1944×10 <sup>-6</sup> | 1.4580         | 0.8800 | 315.9751 |

|     | Irradiance<br>(W/m <sup>2</sup> ) | Temperature<br>(°C) | I <sub>ph</sub> (A) | I <sub>01</sub> (A)     | a <sub>1</sub> | I <sub>02</sub> (A)     | a <sub>2</sub> | Rs (Ω) | Rp(Ω)    |
|-----|-----------------------------------|---------------------|---------------------|-------------------------|----------------|-------------------------|----------------|--------|----------|
| 97  | 876.20                            | 35.40               | 2.4400              | 5.9112×10 <sup>-8</sup> | 1.1237         | 6.9247×10 <sup>-7</sup> | 1.3634         | 1.3776 | 148.9166 |
| 98  | 873.25                            | 36.45               | 2.4181              | 5.7254×10 <sup>-8</sup> | 1.1237         | 6.8324×10 <sup>-7</sup> | 1.3591         | 1.3861 | 154.3058 |
| 99  | 453.40                            | 34.10               | 1.6455              | 4.0638×10 <sup>-7</sup> | 1.3908         | 1.5872×10 <sup>-6</sup> | 1.3921         | 1.1546 | 268.8136 |
| 100 | 617.40                            | 38.50               | 2.0073              | 3.2293×10 <sup>-8</sup> | 1.2287         | 4.8840×10 <sup>-7</sup> | 1.3040         | 1.2366 | 241.8706 |
| 101 | 620.40                            | 37.40               | 2.0146              | 2.7671×10 <sup>-8</sup> | 1.0959         | 4.7090×10 <sup>-7</sup> | 1.4730         | 1.3276 | 181.4589 |
| 102 | 453.40                            | 37.00               | 1.6427              | 4.6296×10 <sup>-8</sup> | 1.3259         | 6.7511×10 <sup>-7</sup> | 1.3262         | 1.1444 | 253.0705 |
| 103 | 678.60                            | 14.75               | 1.8738              | 2.7386×10 <sup>-8</sup> | 1.2386         | 1.8163×10 <sup>-7</sup> | 1.4012         | 1.1645 | 756.5171 |
| 104 | 718.10                            | 13.15               | 2.0557              | 1.1487×10 <sup>-8</sup> | 1.1480         | 9.7984×10 <sup>-7</sup> | 1.8497         | 1.2781 | 404.3674 |
| 105 | 615.20                            | 33.10               | 2.0924              | 2.7213×10 <sup>-8</sup> | 1.1383         | 6.1137×10 <sup>-7</sup> | 1.3848         | 1.1947 | 116.7962 |
| 106 | 589.10                            | 33.55               | 1.9408              | 2.9259×10 <sup>-8</sup> | 1.1168         | 3.8318×10 <sup>-7</sup> | 1.4000         | 1.3141 | 242.0028 |
| 107 | 649.50                            | 37.85               | 2.1087              | 3.3872×10 <sup>-8</sup> | 1.1031         | 7.3445×10 <sup>-7</sup> | 1.4255         | 1.3455 | 152.8020 |
| 108 | 648.05                            | 37.90               | 2.0881              | 9.7714×10 <sup>-7</sup> | 1.4012         | 2.0786×10 <sup>-6</sup> | 1.4040         | 1.1869 | 209.7529 |
| 109 | 653.95                            | 38.15               | 2.0926              | 2.2252×10 <sup>-7</sup> | 1.3486         | 1.6059×10 <sup>-6</sup> | 1.3486         | 1.2456 | 228.6922 |
| 110 | 665.20                            | 39.20               | 2.1417              | 2.5978×10 <sup>-7</sup> | 1.3349         | 1.3822×10 <sup>-6</sup> | 1.3349         | 1.2873 | 185.4866 |
| 111 | 947.05                            | 42.55               | 2.6777              | 4.5174×10 <sup>-7</sup> | 1.3483         | 1.7329×10 <sup>-6</sup> | 1.3546         | 1.2946 | 139.3115 |
| 112 | 454.90                            | 37.75               | 1.6429              | 8.0987×10 <sup>-8</sup> | 1.3366         | 1.3234×10 <sup>-6</sup> | 1.3447         | 1.2234 | 311.6319 |
| 113 | 458.65                            | 36.10               | 1.6527              | 1.3443×10 <sup>-7</sup> | 1.3189         | 1.2103×10 <sup>-6</sup> | 1.3386         | 1.2193 | 244.6175 |

Table 4. Two-diode model parameters in different environmental conditions

5. Results and their commentary

As discussed earlier, Tables 3 and 4 show the models parameters for the poly-crystalline silicon solar panel. It is easily seen any parameters in both models is not equal together. There are many interesting observations that could be made upon examination of the models. Figs. 13 and 14 show the I-V and P-V characteristic curves of #33 and their corresponding one-diode and two-diode models.

Comparison among the extracted I-V curves show that the both models have high accuracy. It can be seen that the one-diode model with variable diode ideally factor (n) can also models the solar panel accurately. The mentioned approach was repeated for all the curves and similar results were obtained.

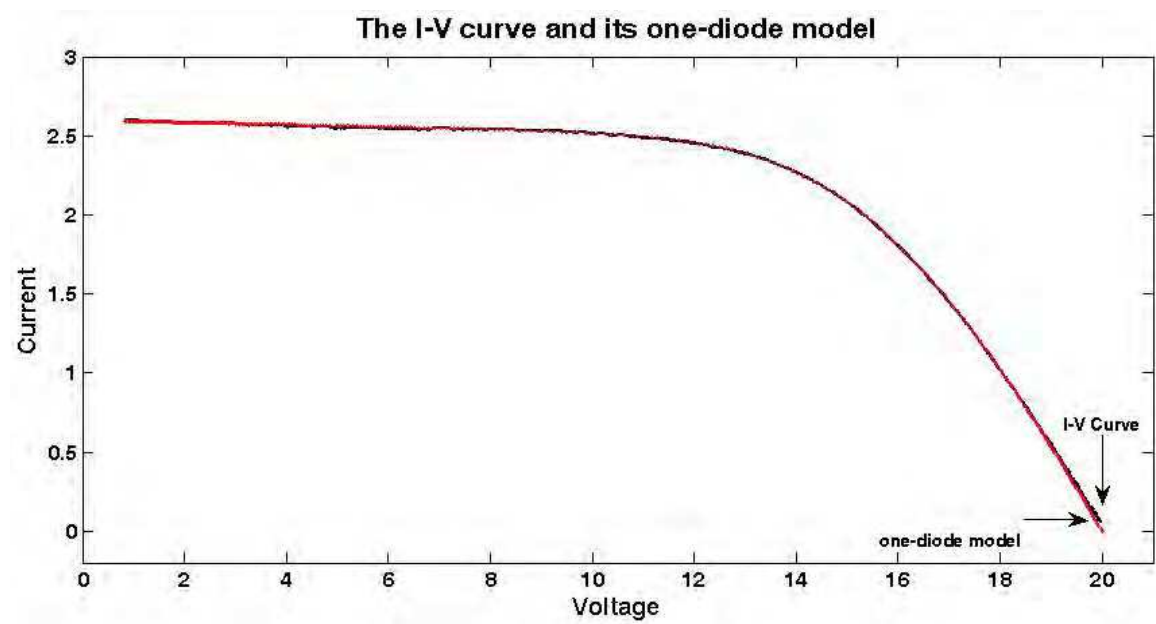
Table 5 shows the main characteristics (P<sub>max</sub>, V<sub>oc</sub>, I<sub>sc</sub> and Fill Factor) of the solar panel for several measured curves and the corresponding one-diode and two-diode models corresponding parameters. The Fill Factor is described by Equation (7) [1].

$$FF = \frac{V_{mp}I_{mp}}{V_{oc}I_{sc}}$$

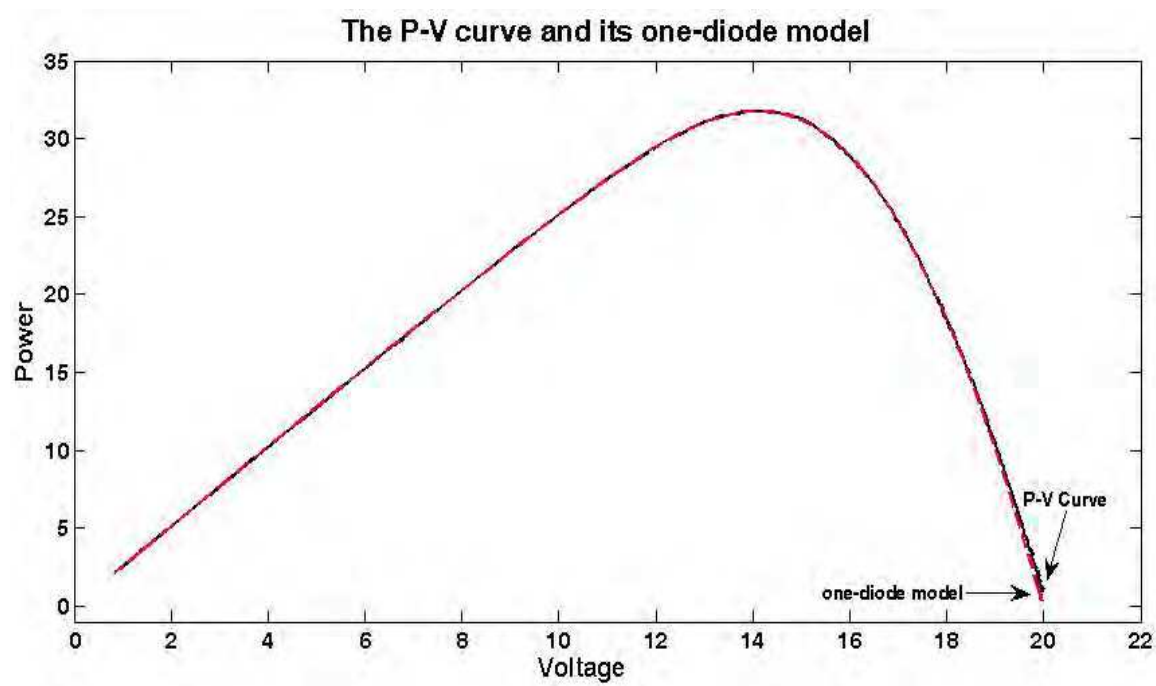
(7)

In continue dependency of the models parameters over environmental conditions is expressed. Figures 15, 16 and 17 show appropriate sheets fitted on the distribution data (i.e. some of one-diode model parameters) drawn by MATLAB (thin plate smoothing splint fitting). Dependency of the model parameters could be seen from the figures. It could be easily seen that the relation between I<sub>ph</sub> and irradiance is approximately increasing linear and its dependency with temperature is also the same behavior. Other commentaries could be expressed for other model parameters. Thin plate smoothing splint fitting could be also carried out for two-diode model.



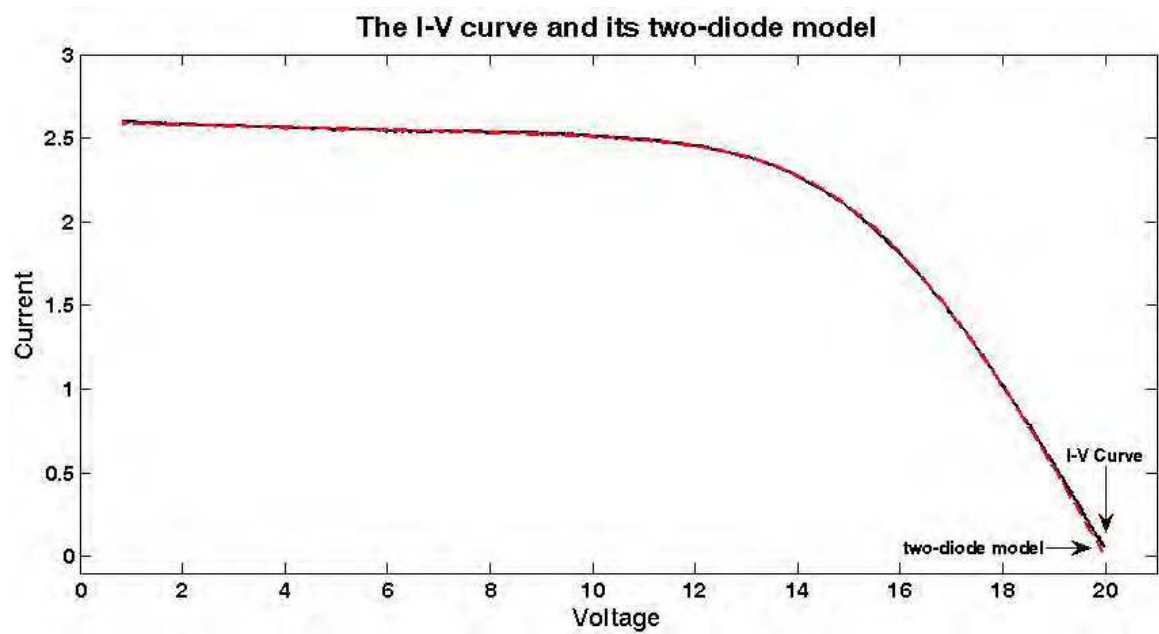


(a)

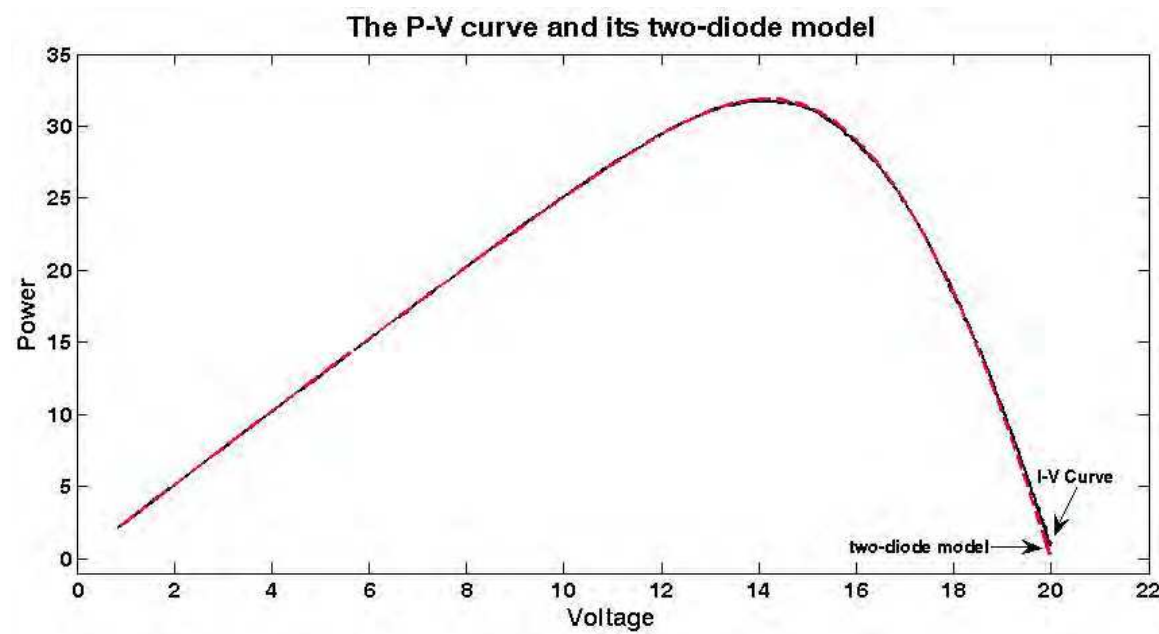


(b)

Fig. 13. The I-V curves #33 and its one-diode model



(a)



(b)

Fig. 14. The I-V curves #33 and its two-diode model

Table 5. The main characteristics of the solar panel

| Curve No. | P <sub>max</sub> (W) |               |               | I <sub>sc</sub> (A) |               |               | V <sub>oc</sub> (V) |               |               |
|-----------|----------------------|---------------|---------------|---------------------|---------------|---------------|---------------------|---------------|---------------|
|           | Measurements         | 1-diode model | 2-diode model | Measurements        | 1-diode model | 2-diode model | Measurements        | 1-diode model | 2-diode model |
| 33        | 31.8064              | 31.8          | 31.9203       | 2.5993              | 2.5929        | 2.5908        | 19.9972             | 19.9972       | 19.9972       |
| 63        | 25.1194              | 25.1201       | 25.0915       | 1.9918              | 1.9884        | 1.9866        | 19.6316             | 19.6316       | 19.6316       |
| 79        | 22.4528              | 22.4681       | 22.3444       | 1.7867              | 1.7848        | 1.7822        | 19.2940             | 19.2940       | 19.2940       |
| 90        | 31.0414              | 31.0373       | 31.1237       | 2.2443              | 2.2371        | 2.2362        | 21.066              | 21.066        | 21.066        |



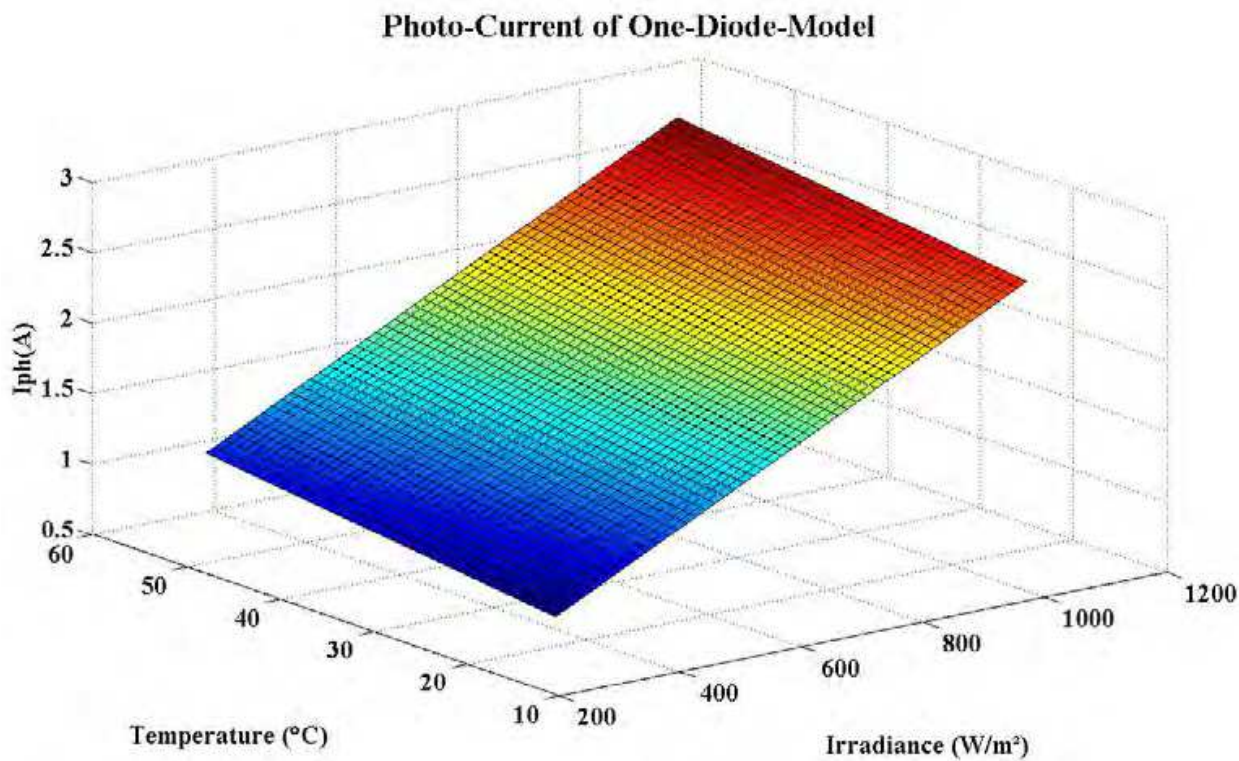


Fig. 15. Fitted sheet on photo-current of one-diode model by MATLAB.

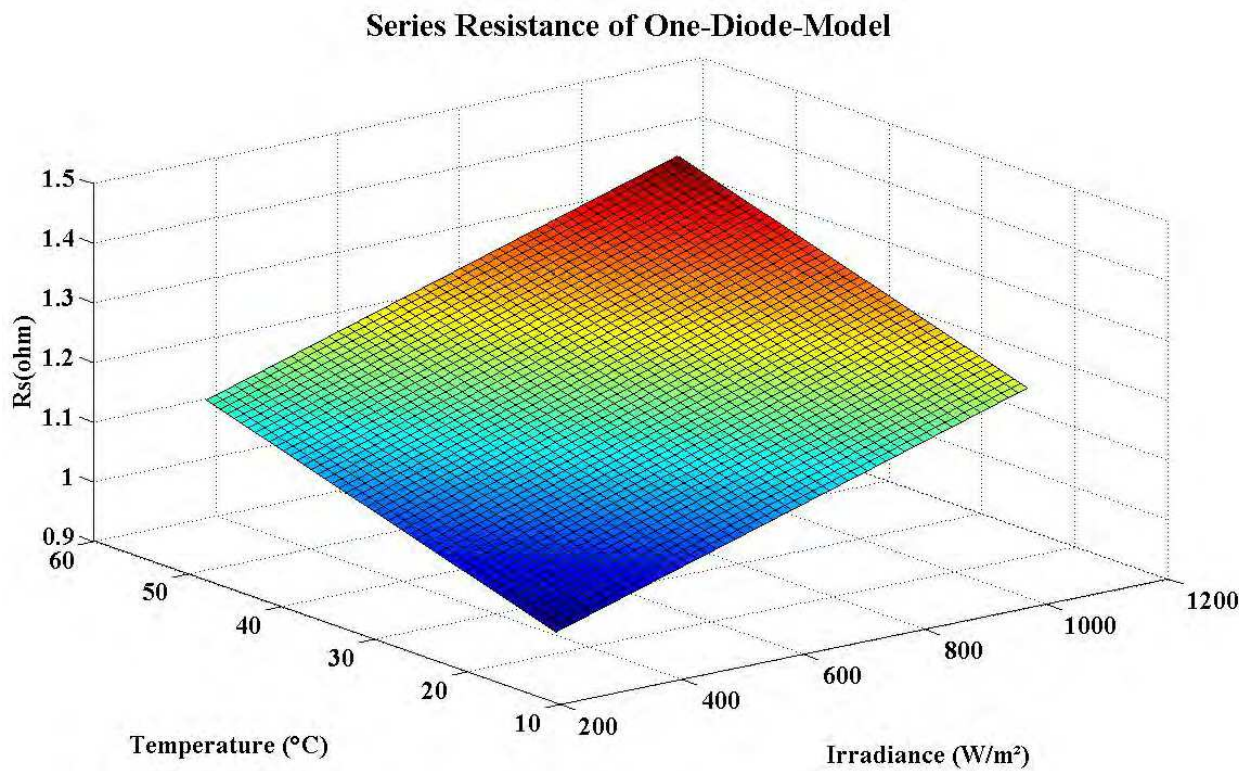


Fig. 16. Fitted sheet on series resistance of one-diode model by MATLAB.

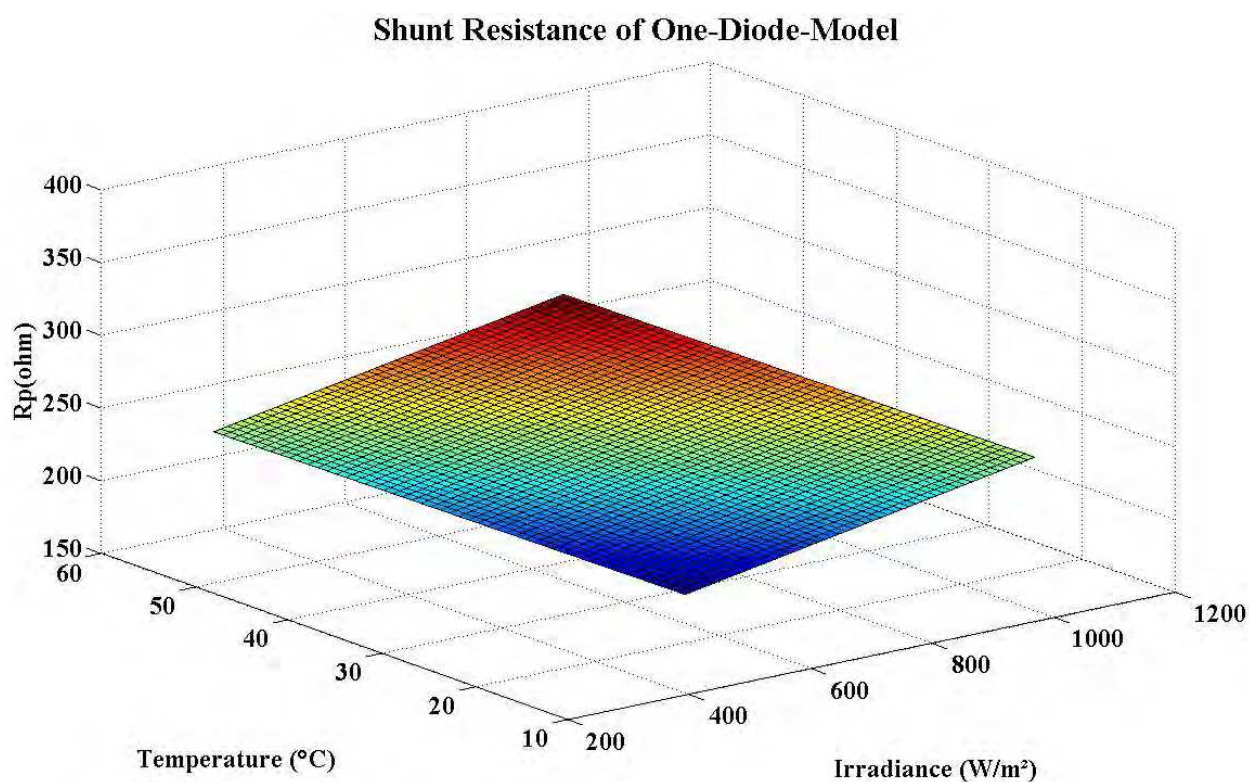


Fig. 17. Fitted sheet on shunt resistance of one-diode model by MATLAB.

## 6. Conclusion

In this research, a new approach to define one-diode and two-diode models of a solar panel were developed through using outdoor solar panel I-V curves measurement. For one-diode model five nonlinear equations and for two-diode model seven nonlinear equations were introduced. Solving the nonlinear equations lead us to define unknown parameters of the both models respectively. The Newton's method was chosen to solve the models nonlinear equations. A modification was also reported in the Newton's solving approach to attain the best convergence. Then, a comprehensive measurement system was developed and implemented to extract solar panel I-V curves in open air climate condition. To evaluate accuracy of the models, output characteristics of the solar panel provided from simulation results were compared with the data provided from experimental results. The comparison showed that the results from simulation are compatible with data from measurement for both models and the both proposed models have the same accuracy in the measurement range of environmental conditions approximately. Finally, it was shown that all parameters of the both models have dependency on environmental conditions which they were extracted by thin plates smoothing splint fitting. Extracting mathematical expression for dependency of the each parameter of the models over environmental conditions will carry out in our future research.

## 7. Appendix

Equations (8-12) state the one-diode model nonlinear equations for a solar panel. Five unknown parameters;  $I_{ph}$ ,  $I_0$ ,  $n$ ,  $R_s$  and  $R_p$  should be specified.

$$I_{sc} = I_{ph} - I_0 e^{\frac{I_{sc} R_s}{V_T}} - \frac{I_{sc} R_s}{R_p} \quad (8)$$

$$I_{oc} = 0 = I_{ph} - I_0 e^{\frac{V_{oc}}{V_T}} - \frac{V_{oc}}{R_p} \quad (9)$$

$$I_{mpp} = I_{ph} - I_0 e^{\frac{V_{mpp} + I_{mpp} R_s}{V_T}} - \frac{V_{mpp} + I_{mpp} R_s}{R_p} \quad (10)$$

$$I_x = I_{ph} - I_0 e^{\frac{V_x + I_x R_s}{V_T}} - \frac{V_x + I_x R_s}{R_p} \quad (11)$$

$$I_{xx} = I_{ph} - I_0 e^{\frac{V_{xx} + I_{xx} R_s}{V_T}} - \frac{V_{xx} + I_{xx} R_s}{R_p} \quad (12)$$

Therefore, the five aforementioned nonlinear equations must be solved to define the model. Newton's method is chosen to solve the equations which its foundation is based on using Jacobean matrix. MATLAB software environment is used to express the Jacobean matrix.

$$R = \begin{cases} f_1(I_{ph}, I_0, V_T, R_s, R_p) = 0 \\ f_2(I_{ph}, I_0, V_T, R_s, R_p) = 0 \\ f_3(I_{ph}, I_0, V_T, R_s, R_p) = 0 \\ f_4(I_{ph}, I_0, V_T, R_s, R_p) = 0 \\ f_5(I_{ph}, I_0, V_T, R_s, R_p) = 0 \end{cases}, \quad J = \begin{bmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \frac{\partial f_1}{\partial x_3} & \frac{\partial f_1}{\partial x_4} & \frac{\partial f_1}{\partial x_5} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \frac{\partial f_2}{\partial x_3} & \frac{\partial f_2}{\partial x_4} & \frac{\partial f_2}{\partial x_5} \\ \frac{\partial f_3}{\partial x_1} & \frac{\partial f_3}{\partial x_2} & \frac{\partial f_3}{\partial x_3} & \frac{\partial f_3}{\partial x_4} & \frac{\partial f_3}{\partial x_5} \\ \frac{\partial f_4}{\partial x_1} & \frac{\partial f_4}{\partial x_2} & \frac{\partial f_4}{\partial x_3} & \frac{\partial f_4}{\partial x_4} & \frac{\partial f_4}{\partial x_5} \\ \frac{\partial f_5}{\partial x_1} & \frac{\partial f_5}{\partial x_2} & \frac{\partial f_5}{\partial x_3} & \frac{\partial f_5}{\partial x_4} & \frac{\partial f_5}{\partial x_5} \end{bmatrix}$$

To solve the equations, a starting point  $x_0 = [I_{ph}, I_0, V_T, R_s, R_p]$  must be determined and both matrixes  $R$  &  $J$  are also examined at that point. Then  $\delta x$  is described based on the Eq. (13) and consequently Eq. (14) states the new estimation for the root of the equations.

$$J^k \delta x^k = -R^k \quad (13)$$



$$x_{\text{new}} = x_{\text{old}} + \delta x \quad (14)$$

Finally, the above iteration is repeated by the new start point ( $x_{\text{new}}$ ) while the error was less than an acceptable level. The above iterative numerical approach is implemented for the two-diode models with seven nonlinear equations system. It was seen that to have an appropriate convergence, a modification coefficient ( $0 < \alpha < 1$ ) is added to Eq. (14) and it leads to Eq. (15).

$$x_{\text{new}} = x_{\text{old}} + \alpha \times \delta x \quad (15)$$

The modified approach has good response to solve the models equations by tuning the proposed coefficient.

## 8. Acknowledgment

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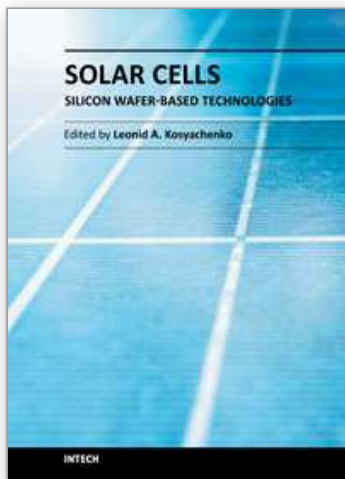
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The third book of four-volume edition of 'Solar Cells' is devoted to solar cells based on silicon wafers, i.e., the main material used in today's photovoltaics. The volume includes the chapters that present new results of research aimed to improve efficiency, to reduce consumption of materials and to lower cost of wafer-based silicon solar cells as well as new methods of research and testing of the devices. Light trapping design in c-Si and mc-Si solar cells, solar-energy conversion as a function of the geometric-concentration factor, design criteria for spacecraft solar arrays are considered in several chapters. A system for the micrometric characterization of solar cells, for identifying the electrical parameters of PV solar generators, a new model for extracting the physical parameters of solar cells, LBIC method for characterization of solar cells, non-idealities in the I-V characteristic of the PV generators are discussed in other chapters of the volume.

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