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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.

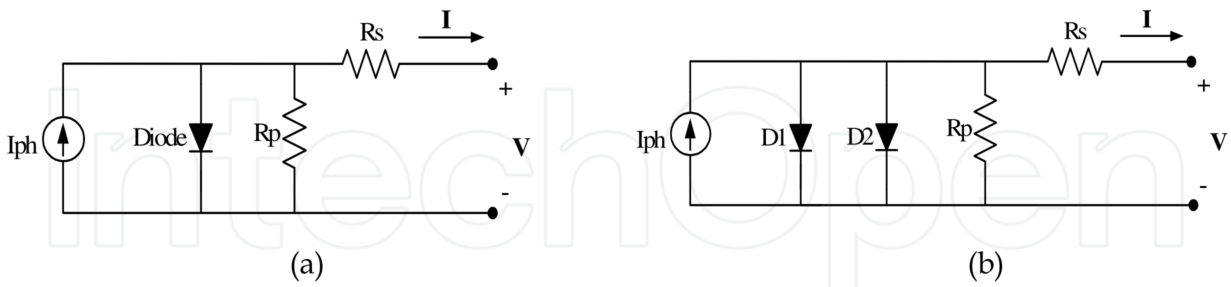


Fig. 1. The equivalent circuits of one-diode and two-diode models of a solar cell.

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

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

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

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/m² 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.

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

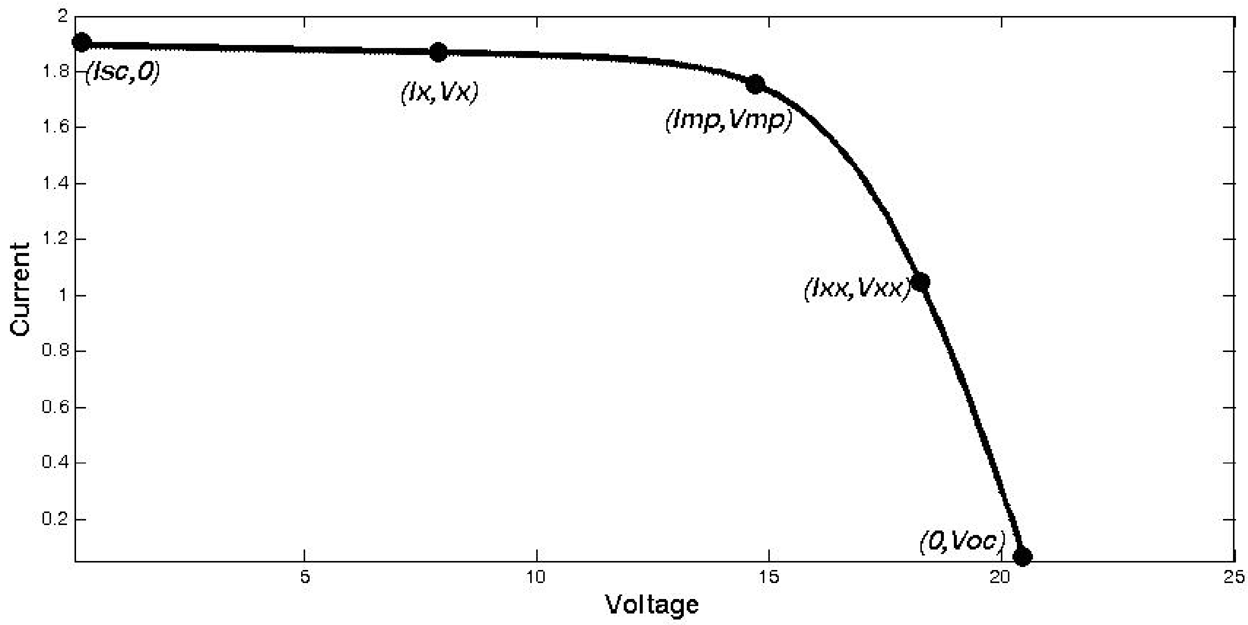


Fig. 2. Five points on the I-V curve of a solar panel are used to solve the nonlinear equations.

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 $V_f = \frac{V_{mp} + 2V_{oc}}{3}$.

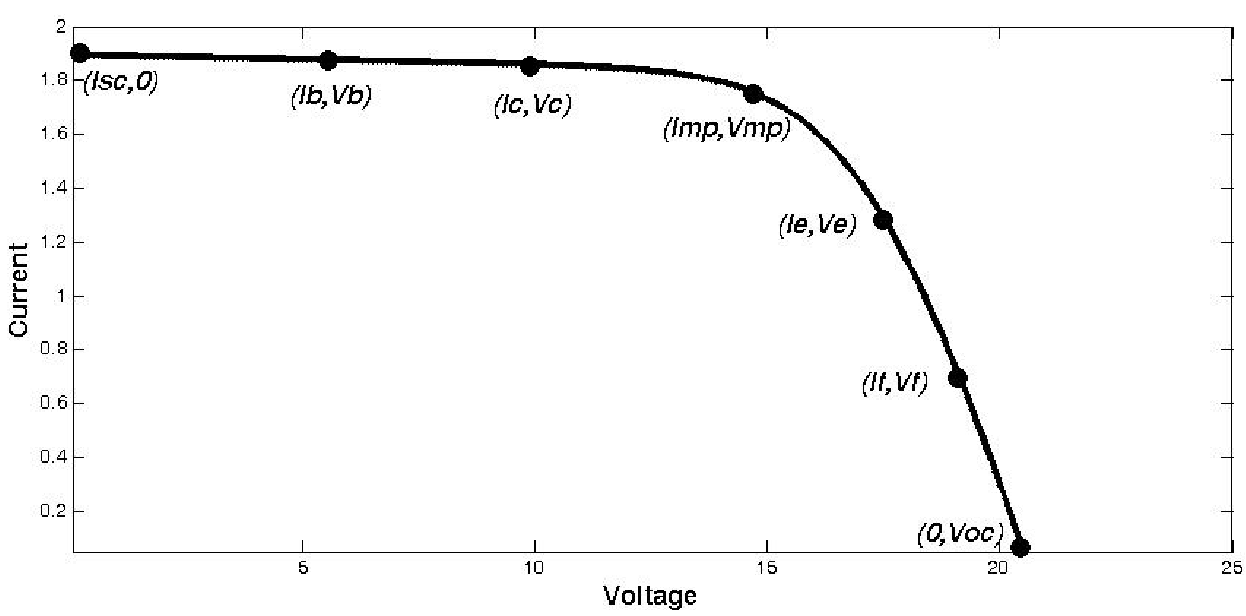


Fig. 3. Seven points on the I-V curve of a solar panel to solve the nonlinear equations.

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.

$$
\begin{gathered}
G_j = -i_j + I_{ph} - I_{01}(e^{\frac{v+iR_s}{a_1}} - 1) - I_{02}(e^{\frac{v+iR_s}{a_2}} - 1) - \frac{v + iR_s}{R_p}, \\
a_k = \frac{n_k kT}{q}, \qquad k = 1,2 \;,\; j = 1,2,\ldots,7
\end{gathered} \tag{4}
$$

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_{sc} (A)		2.98
V_{oc} (V)		20.5
I_{mpp} (A)		2.73
V_{mpp} (V)		16.5
P_{mpp} (W)		45
n_s		36
n_p		1
k_i (%/°C)		0.07
k_v (mv/°C)		-0.038

Table 1. Datasheet information of the under investigation solar panel

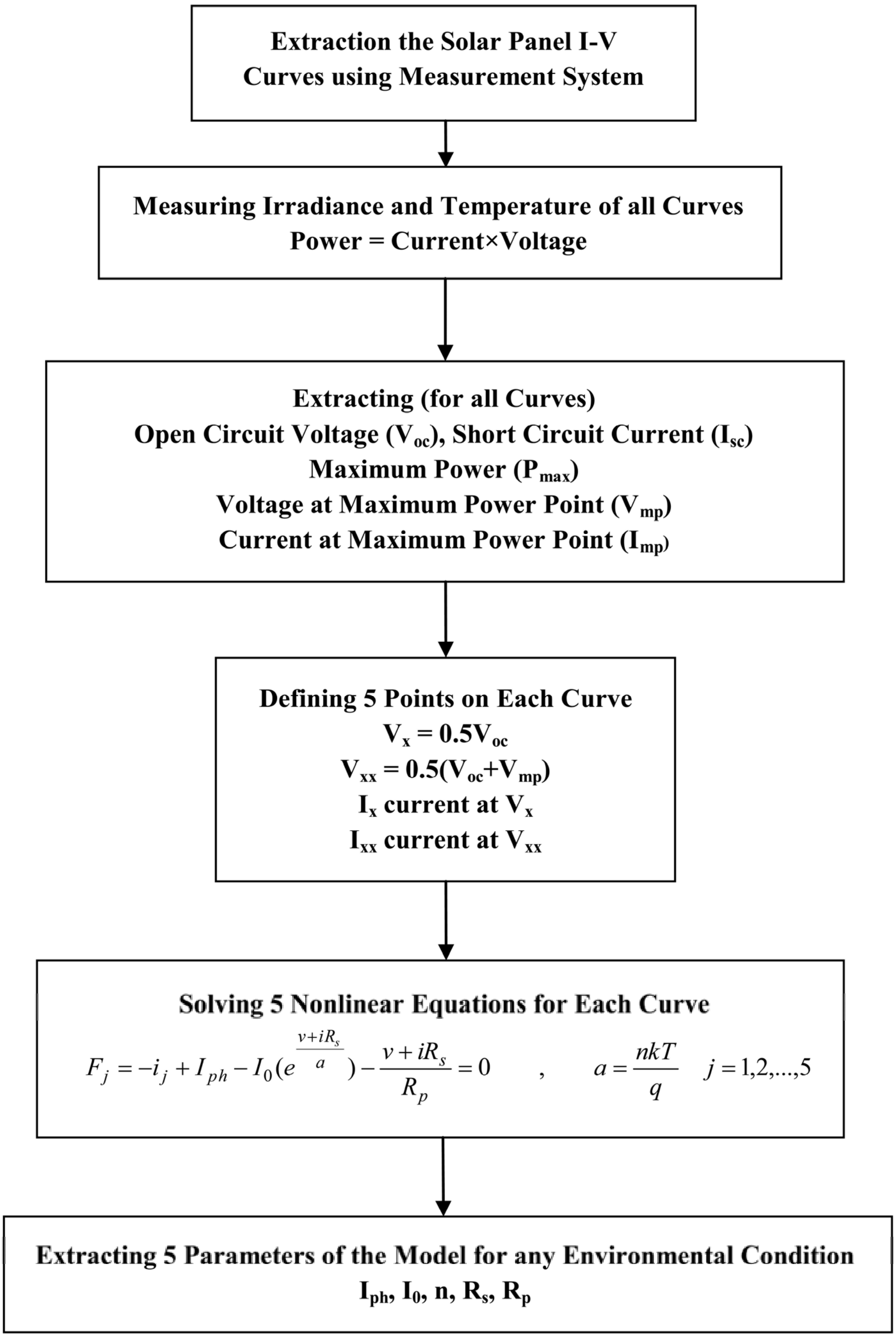


Fig. 4. Flowchart of extraction the one-diode model parameters

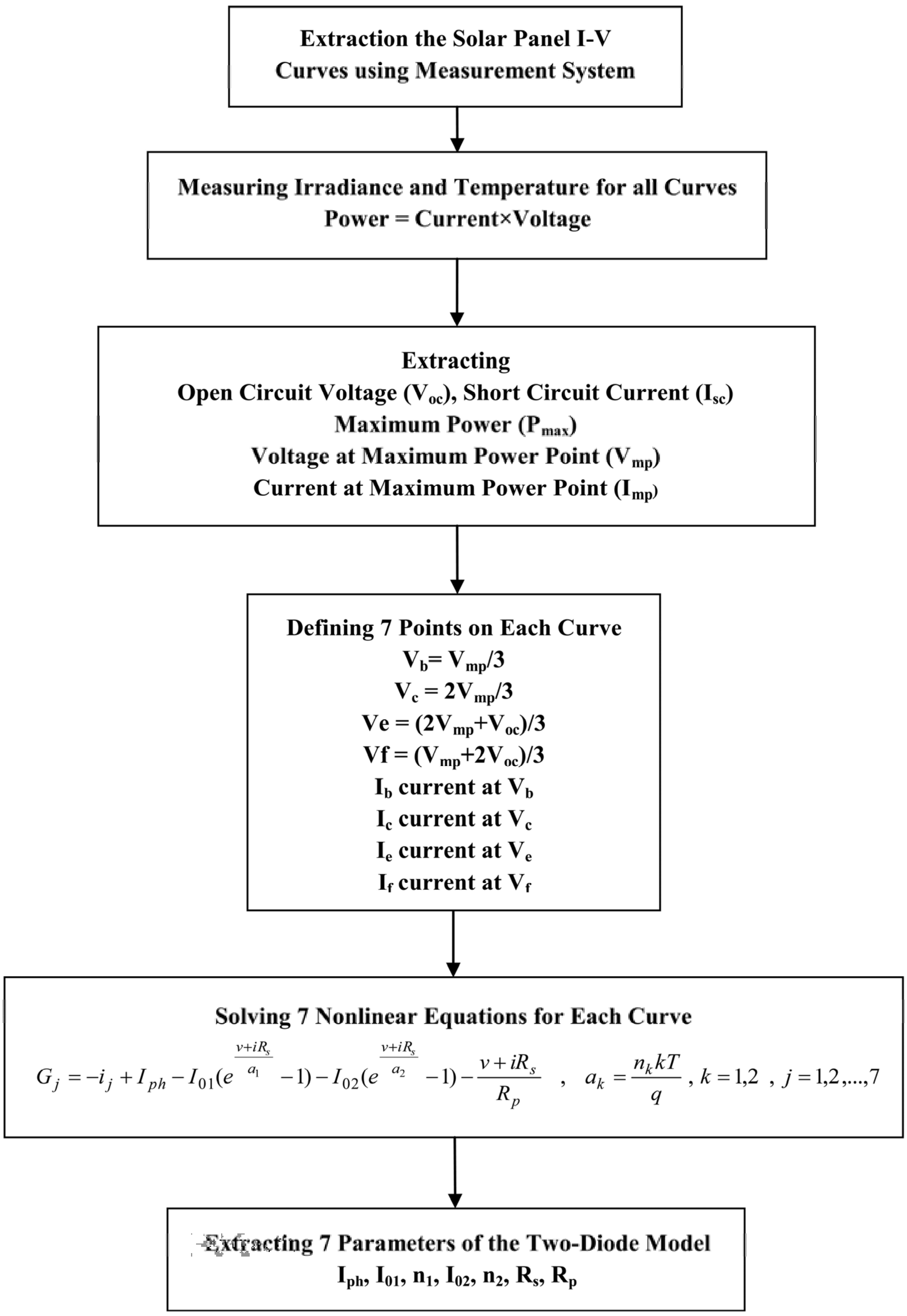


Fig. 5. Flowchart of extraction the two-diode model parameters

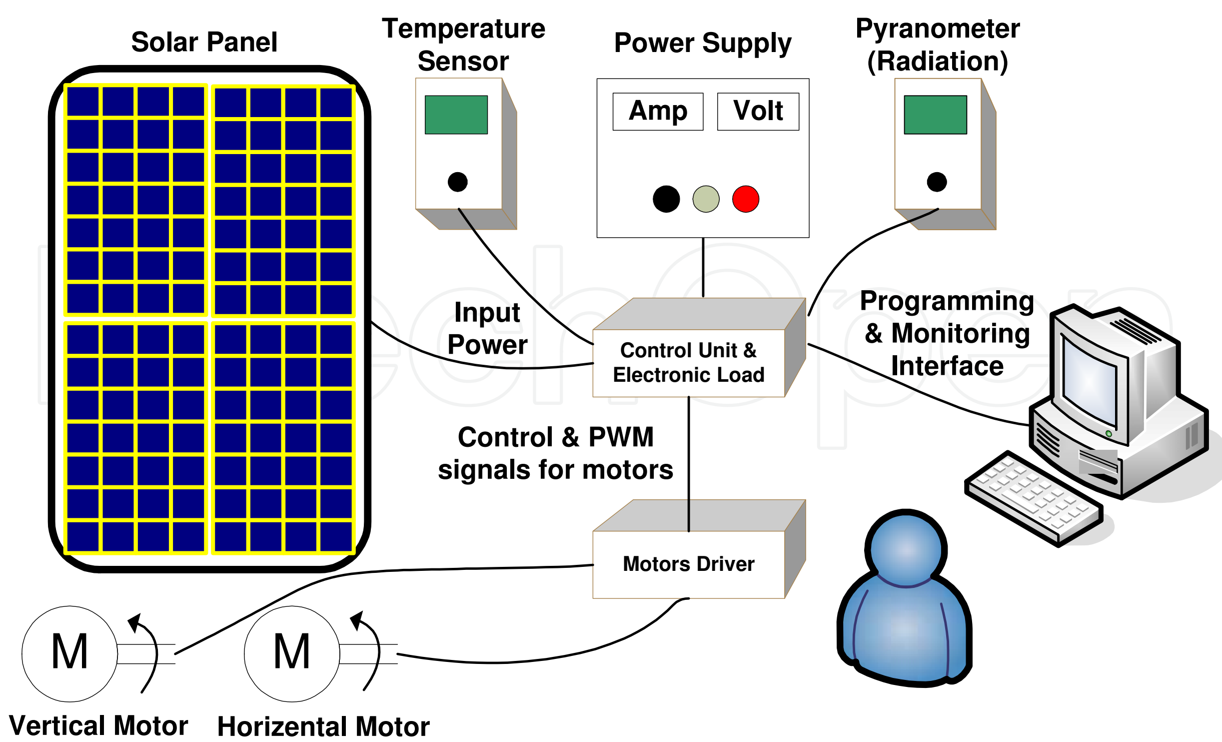


Fig. 6. Block diagram of the proposed measurement system

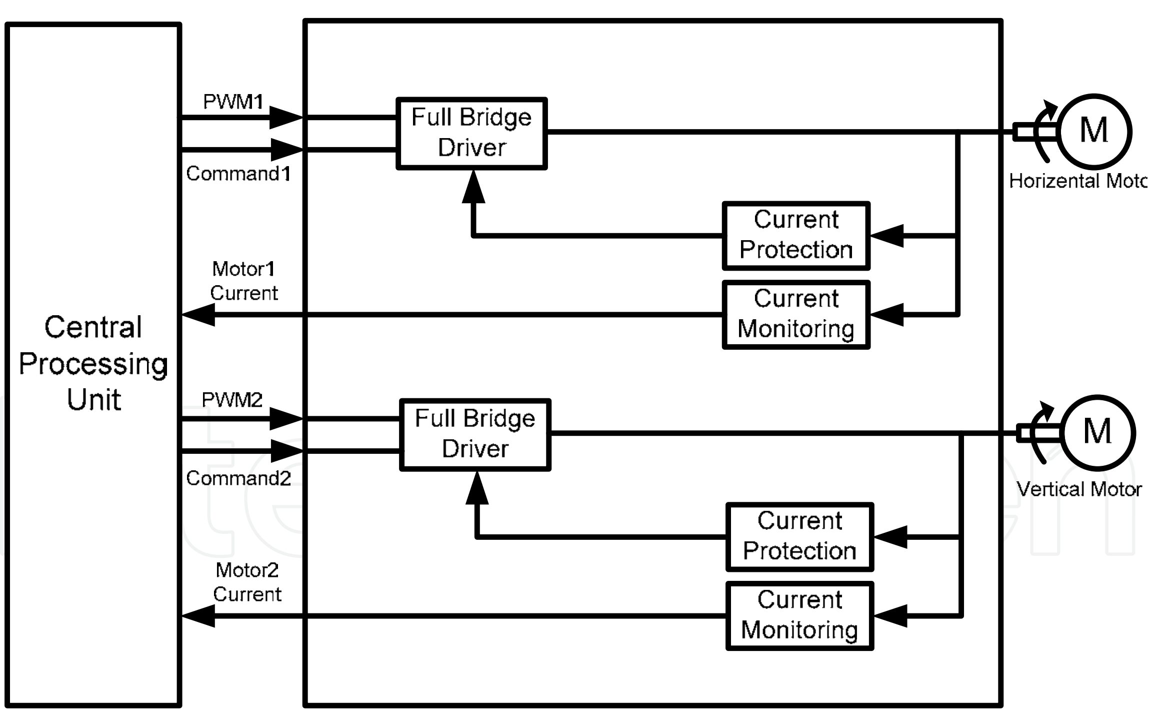


Fig. 7. Motor driver block diagram

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.

$$R_n = \frac{1}{2} R_{n-1} \tag{5}$$

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.

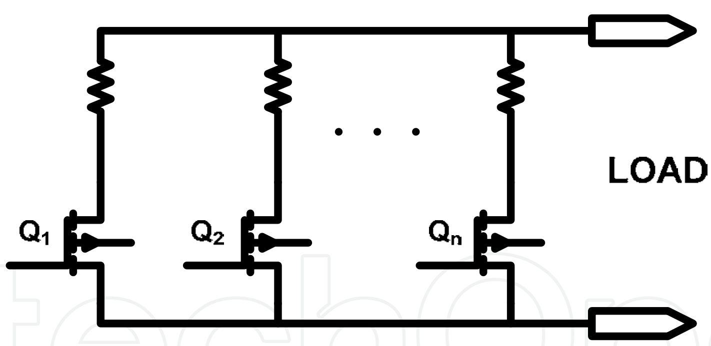


Fig. 8. The proposed switching load circuit

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).

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

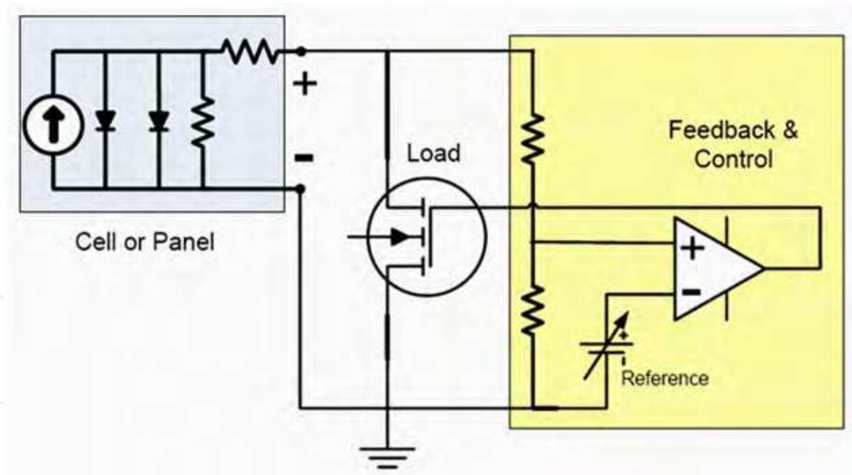


Fig. 9. The proposed continuous electronic load

In this equation, L is channel length, W is channel width, ε is electric permittivity, μ 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.

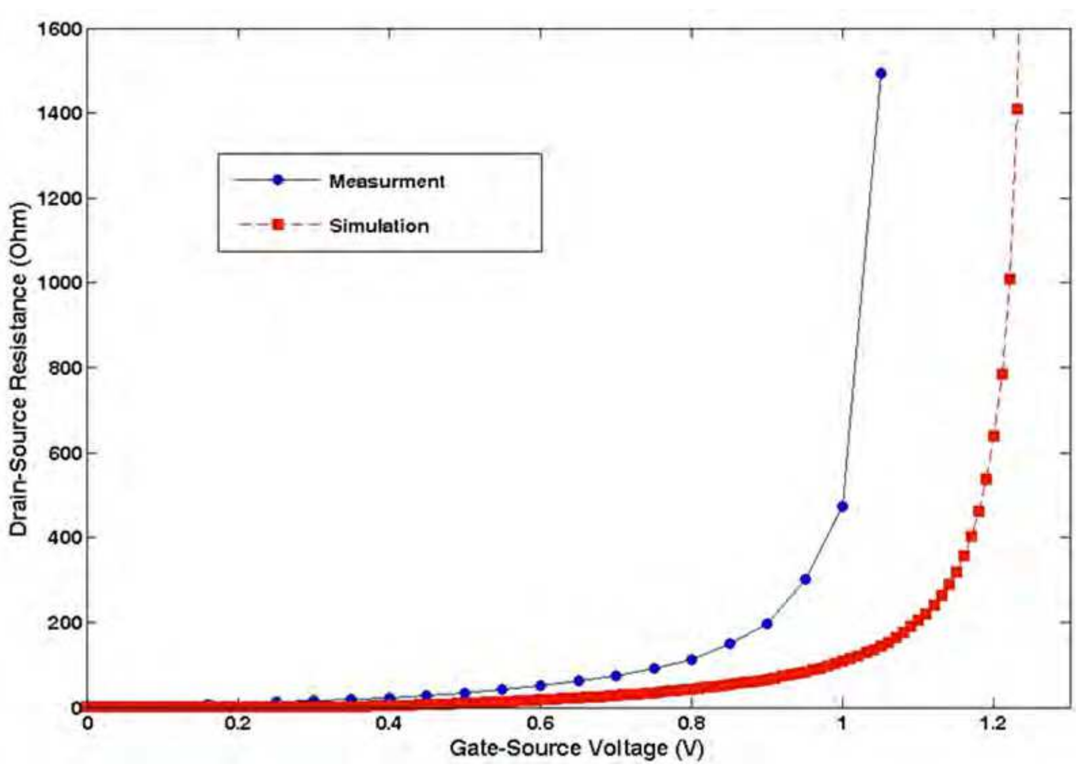


Fig. 10. Experimental data and simulation results of continuous electronic load profile

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

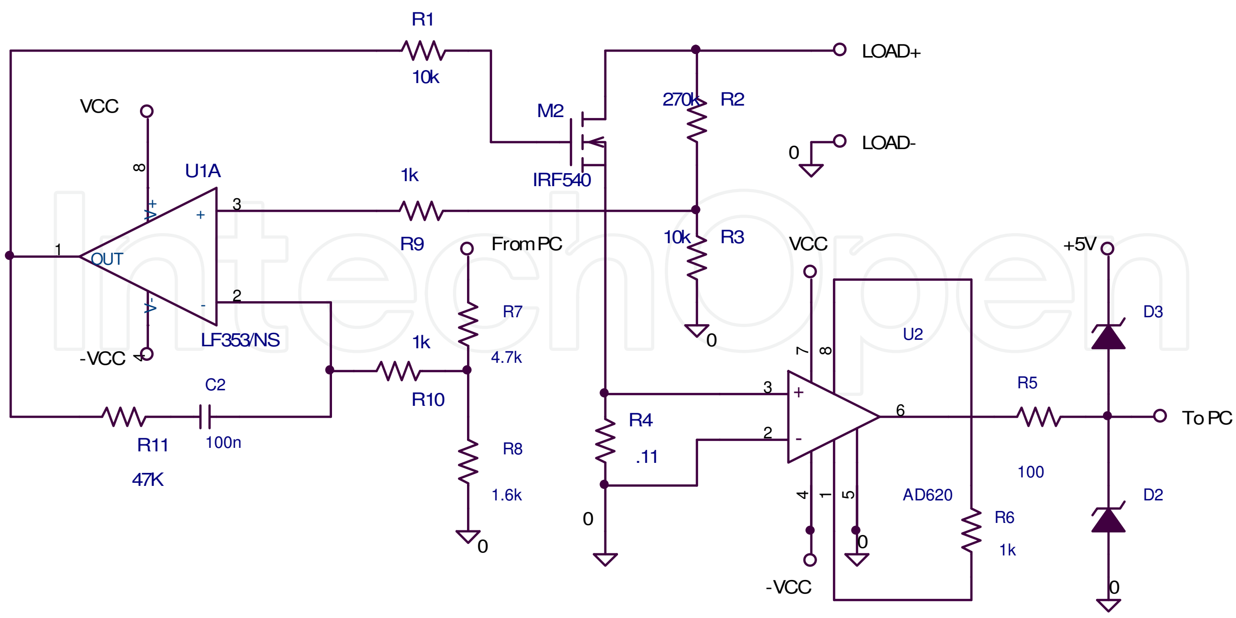


Fig. 11. The schematic diagram of continuous electronic load

Fig. 12 shows a typical extracted I-V and P-V curves by this method in the following conditions; irradiance = 500 w/m² 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.

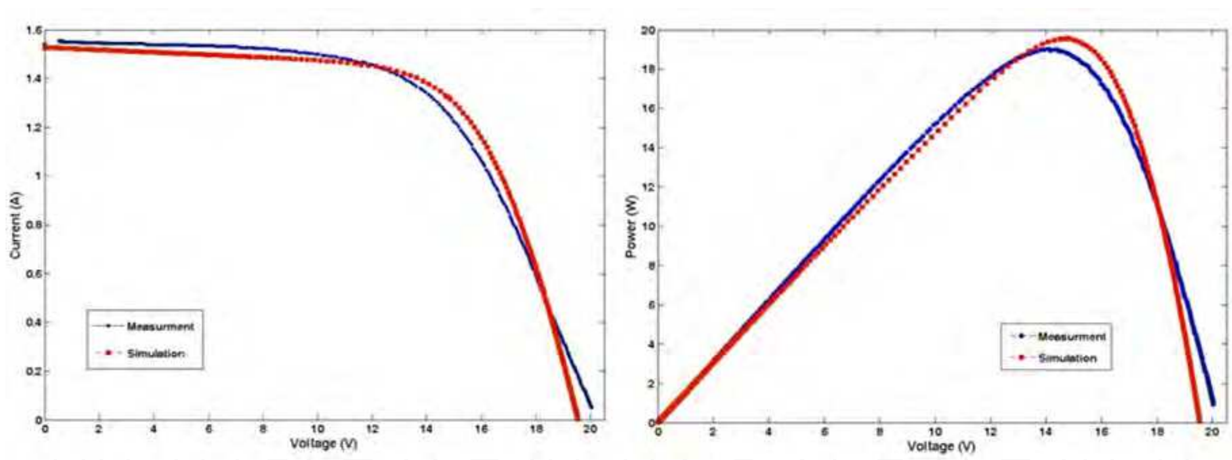


Fig. 12. A typical extracted solar panel's I-V curve

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 Curves	Environmental Conditions		V_{oc} (V)	I_{sc} (A)	V_{mp} (V)	I_{mp} (A)
	Irradiance (W/m^2)	Temperature (°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 Curves	Environmental Conditions		V_{oc} (V)	I_{sc} (A)	V_{mp} (V)	I_{mp} (A)
	Irradiance (W/m²)	Temperature (°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_{oc} (V)	I_{sc} (A)	V_{mp} (V)	I_{mp} (A)
	Irradiance (W/m²)	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/m²)	Temperature (°C)	I_{ph} (A)	I_0 (A)	a	Rs(Ω)	Rp(Ω)
1	644.30	22.95	1.9054	1.3645×10^{-7}	1.2544	1.2078	279.6413
2	657.70	24.00	1.9406	2.0381×10^{-7}	1.2807	1.1805	287.2463
3	662.18	24.50	1.9579	1.0977×10^{-7}	1.2311	1.2276	252.0760

	Irradiance (W/m^2)	Temperature (°C)	I_{ph} (A)	I_0 (A)	a	Rs(Ω)	Rp(Ω)
4	665.16	25.20	1.9738	9.0465×10^{-8}	1.2164	1.2520	255.1335
5	668.85	25.20	1.9776	1.4502×10^{-7}	1.2513	1.2238	253.4728
6	456.36	15.20	1.3443	2.0084×10^{-7}	1.3468	1.0289	475.3187
7	467.55	14.50	1.3822	5.7962×10^{-8}	1.2489	1.1676	303.7811
8	478.00	14.15	1.4235	5.2113×10^{-8}	1.2401	1.1492	228.1600
9	558.50	17.80	1.6448	1.6758×10^{-7}	1.3089	1.1391	488.4681
10	529.50	17.90	1.5640	1.3622×10^{-7}	1.2908	1.1252	305.8098
11	575.00	17.40	1.6993	1.4140×10^{-7}	1.2872	1.1635	280.1520
12	601.00	18.10	1.7753	1.0810×10^{-7}	1.2614	1.1667	252.2827
13	605.50	18.45	1.7854	1.8325×10^{-7}	1.3034	1.1494	313.9411
14	474.25	13.65	1.3814	2.0780×10^{-7}	1.3435	0.9994	307.3284
15	495.15	14.20	1.4413	2.1472×10^{-7}	1.3430	1.0062	275.3528
16	528.00	18.30	1.5321	2.1087×10^{-7}	1.3087	1.0844	307.3237
17	528.00	18.45	1.54442	1.8252×10^{-7}	1.2961	1.1175	303.6138
18	537.00	18.30	1.5615	9.6833×10^{-8}	1.2447	1.1485	245.5091
19	557.80	21.00	1.6145	3.2875×10^{-7}	1.3193	1.1212	354.5386
20	548.80	22.00	1.5919	2.1440×10^{-7}	1.2835	1.1649	305.2178
21	524.25	21.50	1.5309	5.5771×10^{-7}	1.3667	1.0884	474.5784
22	517.50	20.65	1.4714	3.9398×10^{-7}	1.3375	1.0842	405.6716
23	533.15	19.85	1.5753	2.1603×10^{-7}	1.2953	1.1464	805.5353
24	946.25	40.85	2.6666	8.9271×10^{-7}	1.2757	1.3558	146.2230
25	945.50	42.90	2.6574	1.2424×10^{-6}	1.3030	1.3219	150.3004
26	778.50	33.40	2.1973	3.1128×10^{-7}	1.2892	1.2567	515.2084
27	762.30	33.15	2.2171	5.3812×10^{-7}	1.3316	1.1894	210.1448
28	789.00	34.15	2.2886	3.9798×10^{-7}	1.3028	1.2315	214.3753
29	782.25	33.80	2.2765	5.0119×10^{-7}	1.3266	1.1978	212.4934
30	391.20	41.80	1.4409	2.2284×10^{-6}	1.3744	1.2030	357.0918
31	914.95	21.95	2.5657	2.9407×10^{-7}	1.2866	1.2771	178.6504
32	917.95	23.85	2.5853	4.0314×10^{-7}	1.2993	1.2704	179.9606
33	923.20	27.00	2.6220	5.5929×10^{-7}	1.3065	1.2800	142.9452
34	1004.50	34.60	2.8279	1.2215×10^{-6}	1.3071	1.3467	155.7048
35	1004.50	35.15	2.8362	1.5357×10^{-6}	1.3258	1.3260	151.6557
36	994.75	34.25	2.8140	1.2354×10^{-6}	1.3051	1.3258	141.9868
37	900.80	34.90	2.6385	2.1545×10^{-6}	1.3585	1.3032	170.0669
38	899.30	35.55	2.6449	1.5551×10^{-6}	1.3278	1.3082	152.1797
39	808.30	36.40	2.4663	1.5142×10^{-6}	1.3214	1.3244	186.9949
40	811.30	36.80	2.4866	8.9032×10^{-7}	1.2740	1.3574	152.6324
41	630.90	36.10	2.1335	7.5213×10^{-7}	1.2650	1.3213	179.3817
42	633.85	36.20	2.1493	1.4614×10^{-6}	1.3279	1.2659	172.9979
43	637.55	35.85	2.1526	1.3956×10^{-6}	1.3272	1.2720	181.0577
44	406.40	34.10	1.5971	1.7433×10^{-6}	1.3672	1.1656	253.3236
45	412.35	33.00	1.6220	1.0427×10^{-6}	1.3288	1.1815	221.4351

	Irradiance (W/m²)	Temperature (°C)	I_{ph} (A)	I_0 (A)	a	Rs(Ω)	Rp(Ω)
46	1006.70	33.05	2.8445	7.7494×10^{-7}	1.2922	1.3580	132.0408
47	1014.20	33.20	2.8548	9.1903×10^{-7}	1.3001	1.3490	162.1626
48	1014.90	33.95	2.8757	7.7393×10^{-7}	1.2816	1.3650	135.7198
49	599.50	44.10	2.0093	3.2553×10^{-6}	1.3443	1.3202	193.5047
50	756.85	50.55	2.2630	2.0566×10^{-6}	1.2958	1.3584	98.4074
51	776.20	50.35	2.3183	9.4350×10^{-6}	1.4552	1.3151	131.0878
52	759.90	50.10	2.3446	1.3496×10^{-6}	1.2650	1.4109	86.7692
53	769.55	49.55	2.3492	3.1359×10^{-6}	1.3436	1.3764	173.6641
54	590.60	48.20	1.9461	1.7518×10^{-6}	1.2990	1.3753	152.9589
55	392.25	45.35	1.4551	7.3811×10^{-6}	1.4749	1.1449	513.8872
56	701.00	36.40	2.1809	6.3023×10^{-7}	1.2744	1.3197	181.3692
57	822.55	36.55	2.4333	1.4581×10^{-6}	1.3457	1.2695	154.6094
58	815.00	36.25	2.3989	8.6293×10^{-7}	1.2995	1.3051	148.3509
59	937.35	35.90	2.6353	7.8507×10^{-7}	1.2924	1.3333	140.9158
60	948.10	35.40	2.6281	6.5875×10^{-7}	1.2819	1.3362	198.5875
61	458.65	37.40	1.7341	2.3307×10^{-7}	1.2435	1.2222	202.9395
62	455.65	37.60	1.7262	2.9317×10^{-7}	1.2605	1.2122	202.2739
63	602.50	38.40	2.0061	2.2729×10^{-7}	1.2318	1.2910	179.7304
64	706.90	38.45	2.1841	6.2885×10^{-7}	1.3100	1.2227	176.9047
65	705.40	36.60	2.1762	3.4172×10^{-7}	1.2607	1.2898	185.8031
66	703.90	38.70	2.1727	4.4171×10^{-7}	1.2803	1.2778	178.6681
67	780.75	37.00	2.2865	2.7213×10^{-7}	1.2499	1.2911	155.5827
68	777.75	36.40	2.2661	6.4822×10^{-7}	1.3257	1.2351	196.1866
69	777.00	35.80	2.2597	3.5896×10^{-7}	1.2797	1.2661	180.5390
70	886.60	44.45	2.4968	5.9216×10^{-7}	1.2747	1.2546	153.3574
71	879.15	44.25	2.4217	1.7378×10^{-6}	1.3740	1.2205	360.6990
72	830.70	40.05	2.4218	6.8898×10^{-7}	1.3016	1.2563	247.4058
73	818.80	40.30	2.4188	7.9099×10^{-7}	1.3181	1.2113	137.7473
74	749.45	38.95	2.2718	6.9207×10^{-7}	1.3136	1.2329	232.5429
75	746.45	38.70	2.2801	5.1192×10^{-7}	1.2905	1.2244	168.6507
76	604.75	45.95	2.0164	1.5572×10^{-6}	1.2660	1.3880	165.8156
77	987.30	48.80	2.7459	3.1186×10^{-6}	1.3124	1.4018	115.7579
78	981.05	50.00	2.7064	4.3017×10^{-6}	1.3400	1.4091	151.9670
79	519.00	33.70	1.7947	5.8455×10^{-7}	1.2951	1.2475	281.8090
80	516.00	34.90	1.8017	4.0818×10^{-7}	1.2618	1.2594	205.2749
81	615.95	36.35	2.0075	6.1718×10^{-7}	1.2774	1.2940	218.7826
82	615.20	36.50	2.0152	4.5464×10^{-7}	1.2507	1.3113	168.6899
83	648.75	37.90	2.0960	4.6946×10^{-7}	1.2710	1.2501	148.6441
84	778.50	35.70	2.3769	3.8760×10^{-7}	1.2713	1.2666	160.5721
85	836.70	25.00	2.4144	2.1683×10^{-7}	1.2840	1.2112	228.6814
86	850.10	25.40	2.4656	1.6939×10^{-7}	1.2639	1.2282	180.5302
87	839.65	23.15	2.4409	2.2484×10^{-7}	1.2938	1.1793	183.7797

	Irradiance (W/m²)	Temperature (°C)	I_{ph} (A)	I_0 (A)	a	Rs(Ω)	Rp(Ω)
88	838.16	23.05	2.4333	1.6491×10^{-7}	1.2697	1.1971	181.9877
89	844.15	23.35	2.4391	1.0187×10^{-7}	1.2337	1.2319	168.4823
90	781.50	20.80	2.2502	2.4789×10^{-7}	1.3180	1.1315	249.5637
91	775.50	20.45	2.2299	1.8167×10^{-7}	1.2934	1.1539	269.1192
92	612.25	15.55	1.7732	1.1189×10^{-7}	1.2958	1.0877	317.2956
93	609.25	15.00	1.7761	2.6497×10^{-8}	1.1944	1.1797	232.1886
94	601.75	14.75	1.7631	5.0466×10^{-8}	1.2390	1.1252	252.8796
95	240.85	31.40	1.0841	2.8277×10^{-6}	1.4522	0.8406	328.3110
96	241.60	31.65	1.0842	2.9811×10^{-6}	1.4494	0.8720	323.0246
97	876.20	35.40	2.4382	5.6696×10^{-7}	1.2564	1.3492	157.0273
98	873.25	36.45	2.4151	1.3653×10^{-6}	1.3337	1.3058	180.0039
99	453.40	34.10	1.6490	1.1006×10^{-6}	1.3337	1.1999	245.1651
100	617.40	38.50	2.0113	3.5727×10^{-7}	1.2650	1.2431	213.8478
101	620.40	37.40	2.0119	4.5098×10^{-7}	1.2847	1.2074	196.3093
102	453.40	37.00	1.6437	1.0425×10^{-6}	1.3602	1.1132	275.7352
103	678.60	14.75	1.8721	1.7176×10^{-7}	1.3306	1.1480	837.2890
104	718.10	13.15	2.0527	7.0015×10^{-8}	1.2647	1.2034	427.2372
105	615.20	33.10	2.0934	1.15866×10^{-7}	1.2124	1.2524	113.7532
106	589.10	33.55	1.9420	3.2678×10^{-7}	1.2673	1.2389	257.1990
107	649.50	37.85	2.1063	6.5590×10^{-7}	1.2966	1.2533	163.5833
108	648.05	37.90	2.0915	1.5511×10^{-6}	1.3355	1.2439	198.8860
109	653.95	38.15	2.0951	1.2615×10^{-6}	1.3138	1.2757	209.6240
110	665.20	39.20	2.1463	1.0031×10^{-6}	1.2899	1.3034	166.9648
111	947.05	42.55	2.6799	1.6611×10^{-6}	1.3274	1.3070	133.4828
112	454.90	37.75	1.6428	2.2538×10^{-6}	1.3913	1.1596	331.7340
113	458.65	36.10	1.6525	2.1133×10^{-6}	1.3810	1.1576	251.5761

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

	Irradiance (W/m²)	Temperature (°C)	I_{ph} (A)	I_{01} (A)	a_1	I_{02} (A)	a_2	Rs (Ω)	Rp(Ω)
1	644.30	22.95	1.9043	3.0432×10^{-8}	1.1883	1.3697×10^{-7}	1.3197	1.2341	294.5317
2	657.70	24.00	1.9446	2.0588×10^{-8}	1.1240	2.0918×10^{-7}	1.5696	1.3141	254.2053
3	662.18	24.50	1.9536	1.3177×10^{-7}	1.3606	4.0695×10^{-7}	1.3606	1.1380	318.7178
4	665.16	25.20	1.9729	2.9981×10^{-8}	1.1706	1.7914×10^{-7}	1.3537	1.2339	248.5131
5	668.85	25.20	1.9745	2.8887×10^{-8}	1.2215	2.0565×10^{-7}	1.3069	1.2181	281.0450
6	456.36	15.20	1.3453	2.4504×10^{-8}	1.2271	2.6436×10^{-7}	1.4485	1.0603	474.6605
7	467.55	14.50	1.3809	2.7889×10^{-8}	1.2443	1.4274×10^{-7}	1.3800	1.1122	340.2013
8	478.00	14.15	1.4212	2.7554×10^{-8}	1.2449	1.6846×10^{-7}	1.3907	1.0636	250.2702
9	558.50	17.80	1.6464	2.9720×10^{-8}	1.2208	1.6773×10^{-7}	1.3810	1.1662	443.9569
10	529.50	17.90	1.5654	3.4963×10^{-9}	1.0648	7.7917×10^{-7}	1.6272	1.2959	306.1568
11	575.00	17.40	1.7003	2.2433×10^{-8}	1.1666	2.1302×10^{-7}	1.5016	1.2351	268.6247
12	601.00	18.10	1.7728	2.8641×10^{-8}	1.2150	1.8419×10^{-7}	1.3616	1.1607	275.4929

	Irradiance (W/m²)	Temperature (°C)	I_{ph} (A)	I_{01} (A)	a_1	I_{02} (A)	a_2	Rs (Ω)	Rp(Ω)
13	605.50	18.45	1.7850	2.5508×10^{-8}	1.1760	1.8028×10^{-7}	1.4433	1.2442	316.8041
14	474.25	13.65	1.3797	3.0408×10^{-8}	1.3842	2.9990×10^{-7}	1.3846	0.9578	312.5028
15	495.15	14.20	1.4398	2.7505×10^{-8}	1.2616	1.9085×10^{-7}	1.3710	1.0181	268.2193
16	528.00	18.30	1.5321	2.3850×10^{-8}	1.1597	1.9136×10^{-7}	1.4811	1.2332	302.4667
17	528.00	18.45	1.5458	5.7239×10^{-9}	1.0782	6.9380×10^{-7}	1.5793	1.2685	298.4500
18	537.00	18.30	1.5612	2.8985×10^{-8}	1.1918	1.8355×10^{-7}	1.3790	1.1295	254.8772
19	557.80	21.00	1.6153	2.9673×10^{-8}	1.2465	2.6445×10^{-7}	1.3220	1.1547	356.6941
20	548.80	22.00	1.5912	2.9889×10^{-8}	1.1972	1.6498×10^{-7}	1.3094	1.1999	289.9760
21	524.25	21.50	1.5337	2.4210×10^{-8}	1.1624	3.3020×10^{-7}	1.4010	1.1874	396.9221
22	517.50	20.65	1.4707	2.9247×10^{-8}	1.1909	2.4577×10^{-7}	1.3534	1.1742	395.9226
23	533.15	19.85	1.5767	2.9454×10^{-8}	1.1883	1.9557×10^{-7}	1.3592	1.1708	611.9569
24	946.25	40.85	2.6531	2.5017×10^{-6}	1.4644	3.6255×10^{-6}	1.4643	1.2576	222.6724
25	945.50	42.90	2.6524	2.4917×10^{-7}	1.3377	1.5983×10^{-6}	1.3396	1.3038	165.3972
26	778.50	33.40	2.1998	1.1948×10^{-8}	1.0729	1.4190×10^{-6}	1.7427	1.3897	355.8168
27	762.30	33.15	2.2196	2.7598×10^{-8}	1.1455	2.8448×10^{-7}	1.3577	1.2938	200.6356
28	789.00	34.15	2.2859	2.8133×10^{-8}	1.2301	4.0767×10^{-7}	1.3213	1.2504	226.2728
29	782.25	33.80	2.2787	1.9512×10^{-8}	1.1067	4.2830×10^{-7}	1.4745	1.3242	187.2231
30	391.20	41.80	1.4425	2.5260×10^{-7}	1.3334	1.5355×10^{-6}	1.3554	1.2526	350.9833
31	914.95	21.95	2.5641	2.9959×10^{-8}	1.2141	2.4595×10^{-7}	1.2967	1.3091	195.5702
32	917.95	23.85	2.5827	5.4386×10^{-8}	1.3181	5.0320×10^{-7}	1.3275	1.2698	199.2378
33	923.20	27.00	2.6221	9.0452×10^{-9}	1.0543	1.2920×10^{-6}	1.4846	1.3512	137.6304
34	1004.50	34.60	2.8311	6.8694×10^{-8}	1.1262	9.0237×10^{-7}	1.3614	1.4110	152.6305
35	1004.50	35.15	2.8410	6.4888×10^{-8}	1.1394	8.3690×10^{-7}	1.3241	1.3880	142.3507
36	994.75	34.25	2.8144	1.1388×10^{-7}	1.2995	1.0543×10^{-6}	1.2999	1.3414	148.7050
37	900.80	34.90	2.6371	2.5877×10^{-7}	1.3474	1.7108×10^{-6}	1.3502	1.3179	171.1347
38	899.30	35.55	2.6451	7.9309×10^{-8}	1.2414	6.1660×10^{-7}	1.2594	1.3682	150.0456
39	808.30	36.40	2.4660	1.4170×10^{-7}	1.3019	1.1481×10^{-6}	1.3073	1.3361	184.8603
40	811.30	36.80	2.4842	1.8339×10^{-7}	1.3129	1.1981×10^{-6}	1.3128	1.3281	159.9860
41	630.90	36.10	2.1256	2.5422×10^{-6}	1.4743	3.6746×10^{-6}	1.4743	1.1656	248.2853
42	633.85	36.20	2.1413	2.2951×10^{-6}	1.4692	3.4374×10^{-6}	1.4690	1.1719	217.3854
43	637.55	35.85	2.1516	9.4216×10^{-8}	1.3134	1.1090×10^{-6}	1.3134	1.3044	184.2421
44	406.40	34.10	1.5958	2.9422×10^{-7}	1.3599	1.3358×10^{-6}	1.3611	1.1440	237.6602
45	412.35	33.00	1.6175	1.2768×10^{-6}	1.4603	2.4944×10^{-6}	1.4605	1.0597	258.8879
46	1006.70	33.05	2.8442	5.6206×10^{-8}	1.1902	6.3607×10^{-7}	1.3014	1.3825	134.8388
47	1014.20	33.20	2.8506	2.0098×10^{-7}	1.3564	1.5479×10^{-6}	1.3583	1.3247	197.6830
48	1014.90	33.95	2.8735	1.1218×10^{-7}	1.3243	1.1483×10^{-6}	1.3243	1.3351	140.4835
49	599.50	44.10	2.0076	9.6057×10^{-7}	1.3467	2.3573×10^{-6}	1.3467	1.3091	178.8528
50	756.85	50.55	2.2601	1.9992×10^{-6}	1.3906	3.3102×10^{-6}	1.3904	1.3121	108.5623
51	776.20	50.35	2.3243	6.7891×10^{-7}	1.3131	2.3084×10^{-6}	1.3385	1.4005	110.3408
52	759.90	50.10	2.3479	1.6993×10^{-7}	1.1701	5.8437×10^{-7}	1.2368	1.4630	84.6207
53	769.55	49.55	2.3457	2.2463×10^{-6}	1.4075	3.5604×10^{-6}	1.4074	1.3535	201.9657
54	590.60	48.20	1.9409	5.6130×10^{-7}	1.3287	1.8279×10^{-6}	1.3287	1.3952	158.5665

	Irradiance (W/m^2)	Temperature (°C)	I_{ph} (A)	I_{01} (A)	a_1	I_{02} (A)	a_2	Rs (Ω)	Rp(Ω)
55	392.25	45.35	1.4567	6.3763×10^{-7}	1.3514	2.1097×10^{-6}	1.3685	1.2832	449.1823
56	701.00	36.40	2.1796	5.9120×10^{-8}	1.2659	6.4841×10^{-7}	1.2862	1.3258	185.9257
57	822.55	36.55	2.4292	8.8912×10^{-8}	1.3149	9.5018×10^{-7}	1.3149	1.2908	148.4283
58	815.00	36.25	2.3942	7.8008×10^{-8}	1.3071	8.6383×10^{-7}	1.3071	1.3137	158.4158
59	937.35	35.90	2.6380	5.6508×10^{-8}	1.1643	5.8327×10^{-7}	1.3081	1.3438	125.1391
60	948.10	35.40	2.6253	7.7330×10^{-8}	1.3167	9.1644×10^{-7}	1.3172	1.3343	238.5130
61	458.65	37.40	1.7340	2.0356×10^{-8}	1.0972	4.2763×10^{-7}	1.4106	1.2842	196.2692
62	455.65	37.60	1.7239	3.0959×10^{-8}	1.1392	4.4560×10^{-7}	1.3674	1.2573	216.5685
63	602.50	38.40	2.0035	3.1412×10^{-8}	1.1813	4.8461×10^{-7}	1.3212	1.2244	180.2013
64	706.90	38.45	2.1800	5.4562×10^{-8}	1.3504	9.3287×10^{-7}	1.3503	1.2132	194.9991
65	705.40	36.60	2.1695	2.9715×10^{-8}	1.3401	8.3436×10^{-7}	1.3401	1.2273	210.6548
66	703.90	38.70	2.1708	2.9240×10^{-8}	1.3187	6.6092×10^{-7}	1.3187	1.2416	177.3929
67	780.75	37.00	2.2875	1.2985×10^{-8}	1.0604	1.8326×10^{-6}	1.6166	1.3705	151.6619
68	777.75	36.40	2.2669	7.9289×10^{-8}	1.0395	2.0258×10^{-6}	1.6016	1.3944	189.5926
69	777.00	35.80	2.2613	1.0495×10^{-8}	1.0530	2.1107×10^{-6}	1.6648	1.3922	174.3726
70	886.60	44.45	2.4906	5.3519×10^{-8}	1.1734	5.0326×10^{-7}	1.2961	1.2738	151.7814
71	879.15	44.25	2.4246	4.7363×10^{-8}	1.2251	8.2091×10^{-7}	1.3194	1.2895	317.8984
72	830.70	40.05	2.4173	2.0975×10^{-7}	1.3619	1.1345×10^{-6}	1.3619	1.2276	289.4507
73	818.80	40.30	2.4138	4.3268×10^{-8}	1.3130	7.0331×10^{-7}	1.3130	1.2228	141.9730
74	749.45	38.95	2.2701	8.8746×10^{-8}	1.3359	9.5496×10^{-7}	1.3522	1.1952	238.7603
75	746.45	38.70	2.2769	3.4376×10^{-8}	1.3022	6.5867×10^{-7}	1.3174	1.2048	173.1026
76	604.75	45.95	2.0155	2.1057×10^{-7}	1.2517	1.4359×10^{-6}	1.2742	1.3825	166.8131
77	987.30	48.80	2.7327	3.8961×10^{-6}	1.4222	5.1035×10^{-6}	1.4221	1.3555	150.1287
78	981.05	50.00	2.7015	2.1267×10^{-6}	1.3779	4.0844×10^{-6}	1.3779	1.4000	164.3968
79	519.00	33.70	1.7890	3.6873×10^{-7}	1.4160	1.7341×10^{-6}	1.4160	1.1666	388.5935
80	516.00	34.90	1.7966	2.8663×10^{-7}	1.3823	1.2693×10^{-6}	1.3824	1.1770	259.5067
81	615.95	36.35	2.0065	5.4318×10^{-8}	1.2134	5.3810×10^{-7}	1.2844	1.2897	206.7961
82	615.20	36.50	2.0134	5.5856×10^{-8}	1.1890	4.8161×10^{-7}	1.2822	1.3032	171.1018
83	648.75	37.90	2.0925	4.2362×10^{-8}	1.1432	5.3933×10^{-7}	1.3437	1.2704	149.7204
84	778.50	35.70	2.3755	3.8038×10^{-8}	1.1490	4.7462×10^{-7}	1.3515	1.2931	161.9807
85	836.70	25.00	2.4100	3.0253×10^{-8}	1.3337	3.7734×10^{-7}	1.3361	1.1797	260.1578
86	850.10	25.40	2.4609	3.0968×10^{-8}	1.3033	2.4821×10^{-7}	1.3033	1.2173	195.0512
87	839.65	23.15	2.4396	$2.5111\times10^{-}$	1.1490	1.9083×10^{-7}	1.4551	1.2452	169.0755
88	838.16	23.05	2.4322	2.4870×10^{-8}	1.1509	2.0781×10^{-7}	1.4440	1.2393	172.6510
89	844.15	23.35	2.4427	1.2633×10^{-8}	1.0985	1.0025×10^{-9}	1.7022	1.3270	152.1720
90	781.50	20.80	2.2524	9.4105×10^{-9}	1.1001	1.4127×10^{-6}	1.7709	1.2685	219.9114
91	775.50	20.45	2.2298	1.6292×10^{-8}	1.1488	4.3632×10^{-7}	1.4821	1.1884	260.3549
92	612.25	15.55	1.7738	2.4899×10^{-8}	1.1970	1.3638×10^{-7}	1.5022	1.1488	289.5701
93	609.25	15.00	1.7733	2.9613×10^{-8}	1.2056	6.0005×10^{-8}	1.5044	1.1616	247.4696
94	601.75	14.75	1.7590	2.7260×10^{-8}	1.2505	1.9787×10^{-7}	1.3990	1.0152	277.5651
95	240.85	31.40	1.0832	7.6864×10^{-7}	1.4388	1.7435×10^{-6}	1.4391	0.9077	320.8844
96	241.60	31.65	1.0832	1.0096×10^{-6}	1.4575	2.1944×10^{-6}	1.4580	0.8800	315.9751

	Irradiance (W/m^2)	Temperature (°C)	I_{ph} (A)	I_{01} (A)	a_1	I_{02} (A)	a_2	Rs (Ω)	Rp(Ω)
97	876.20	35.40	2.4400	5.9112×10^{-8}	1.1237	6.9247×10^{-7}	1.3634	1.3776	148.9166
98	873.25	36.45	2.4181	5.7254×10^{-8}	1.1237	6.8324×10^{-7}	1.3591	1.3861	154.3058
99	453.40	34.10	1.6455	4.0638×10^{-7}	1.3908	1.5872×10^{-6}	1.3921	1.1546	268.8136
100	617.40	38.50	2.0073	3.2293×10^{-8}	1.2287	4.8840×10^{-7}	1.3040	1.2366	241.8706
101	620.40	37.40	2.0146	2.7671×10^{-8}	1.0959	4.7090×10^{-7}	1.4730	1.3276	181.4589
102	453.40	37.00	1.6427	4.6296×10^{-8}	1.3259	6.7511×10^{-7}	1.3262	1.1444	253.0705
103	678.60	14.75	1.8738	2.7386×10^{-8}	1.2386	1.8163×10^{-7}	1.4012	1.1645	756.5171
104	718.10	13.15	2.0557	1.1487×10^{-8}	1.1480	9.7984×10^{-7}	1.8497	1.2781	404.3674
105	615.20	33.10	2.0924	2.7213×10^{-8}	1.1383	6.1137×10^{-7}	1.3848	1.1947	116.7962
106	589.10	33.55	1.9408	2.9259×10^{-8}	1.1168	3.8318×10^{-7}	1.4000	1.3141	242.0028
107	649.50	37.85	2.1087	3.3872×10^{-8}	1.1031	7.3445×10^{-7}	1.4255	1.3455	152.8020
108	648.05	37.90	2.0881	9.7714×10^{-7}	1.4012	2.0786×10^{-6}	1.4040	1.1869	209.7529
109	653.95	38.15	2.0926	2.2252×10^{-7}	1.3486	1.6059×10^{-6}	1.3486	1.2456	228.6922
110	665.20	39.20	2.1417	2.5978×10^{-7}	1.3349	1.3822×10^{-6}	1.3349	1.2873	185.4866
111	947.05	42.55	2.6777	4.5174×10^{-7}	1.3483	1.7329×10^{-6}	1.3546	1.2946	139.3115
112	454.90	37.75	1.6429	8.0987×10^{-8}	1.3366	1.3234×10^{-6}	1.3447	1.2234	311.6319
113	458.65	36.10	1.6527	1.3443×10^{-7}	1.3189	1.2103×10^{-6}	1.3386	1.2193	244.6175

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

5. Results and their commentary

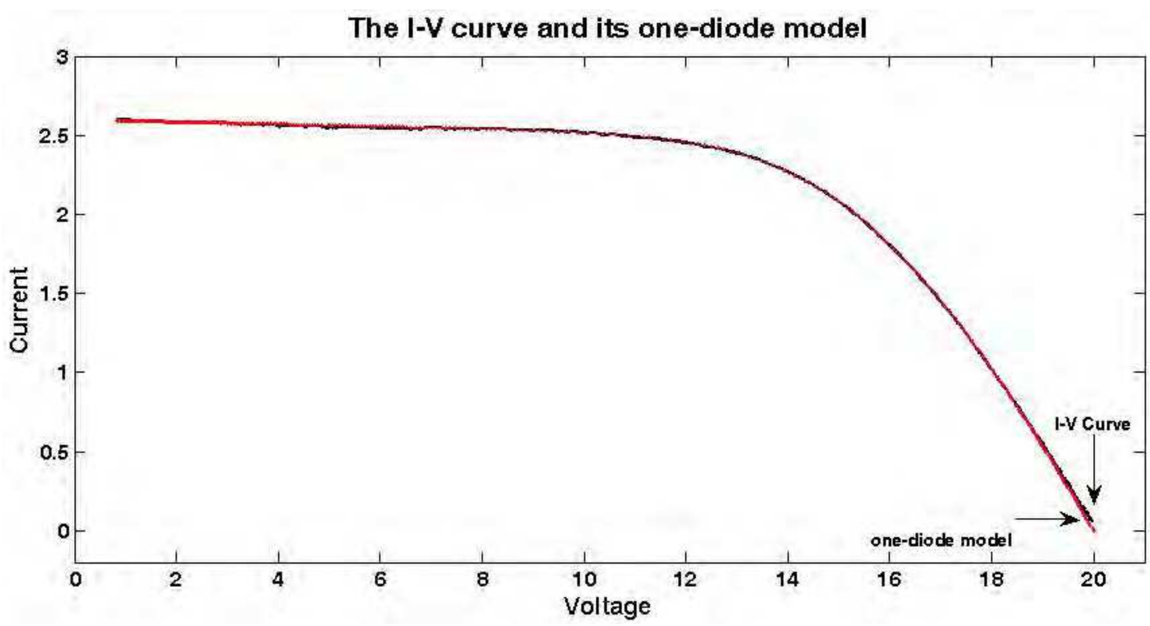
As discussed earlier, Tables 3 and 4 show the models parameters for the poly-crystalline silicon solar panel. It is easily seen any parameters in both models is not equal together. There are many interesting observations that could be made upon examination of the models. Figs. 13 and 14 show the I-V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

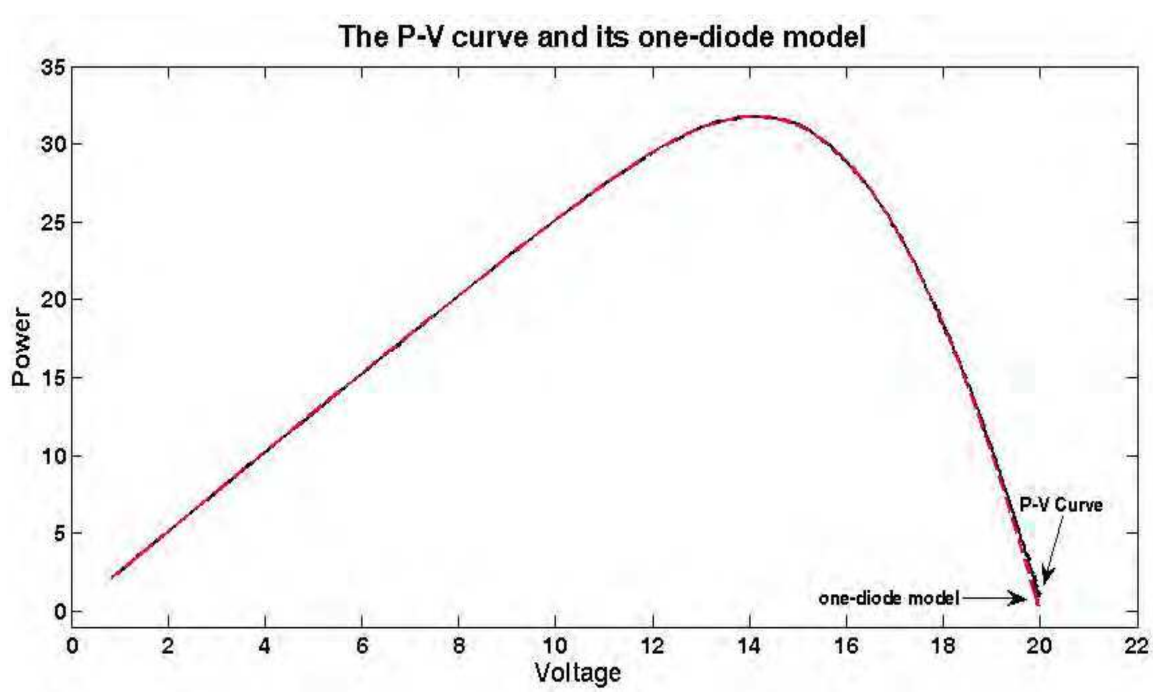
Table 5 shows the main characteristics (P_{max}, V_{oc}, I_{sc} and Fill Factor) of the solar panel for several measured curves and the corresponding one-diode and two-diode models corresponding parameters. The Fill Factor is described by Equation (7) [1].

$$FF = \frac{V_{mp}I_{mp}}{V_{oc}I_{sc}} \tag{7}$$

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_{ph} 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.

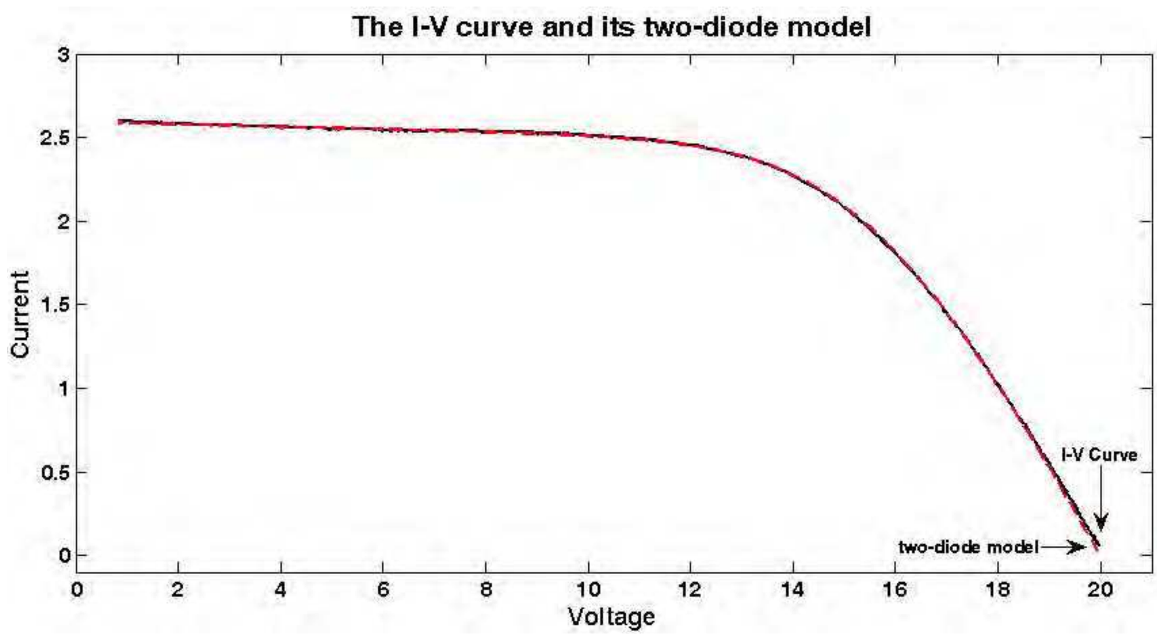


(a)

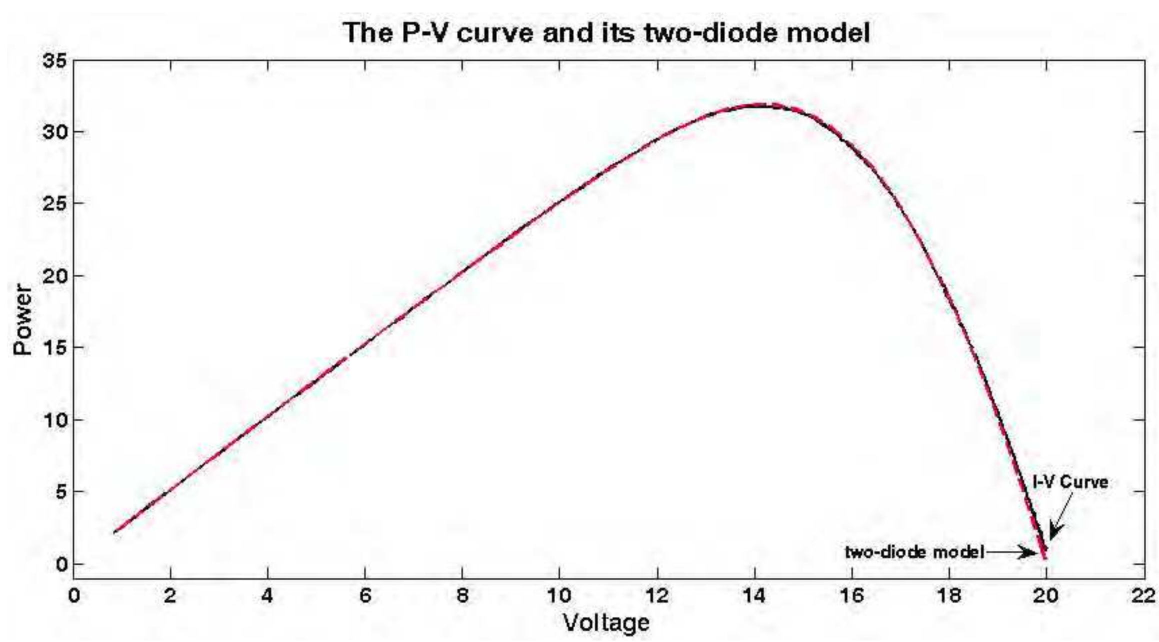


(b)

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.	$P_{max}(W)$			$I_{sc}(A)$			$V_{oc}(V)$		
	Measurements	*1-diode model*	*2-diode model*	*Measurements*	*1-diode model*	*2-diode model*	*Measurements*	*1-diode model*	*2-diod mode*
33	31.8064	31.8	31.9203	2.5993	2.5929	2.5908	19.9972	19.9972	19.997
63	25.1194	25.1201	25.0915	1.9918	1.9884	1.9866	19.6316	19.6316	19.631
79	22.4528	22.4681	22.3444	1.7867	1.7848	1.7822	19.2940	19.2940	19.294
90	31.0414	31.0373	31.1237	2.2443	2.2371	2.2362	21.066	21.066	21.06

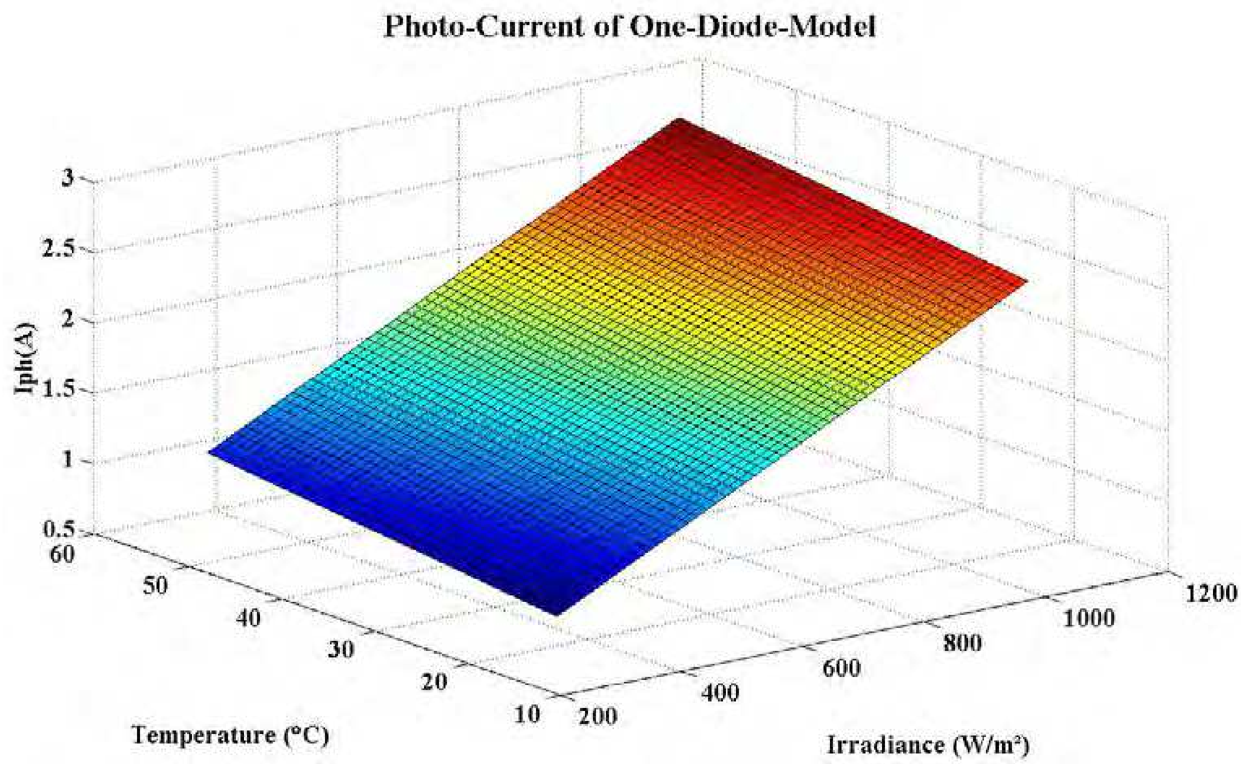


Fig. 15. Fitted sheet on photo-current of one-diode model by MATLAB.

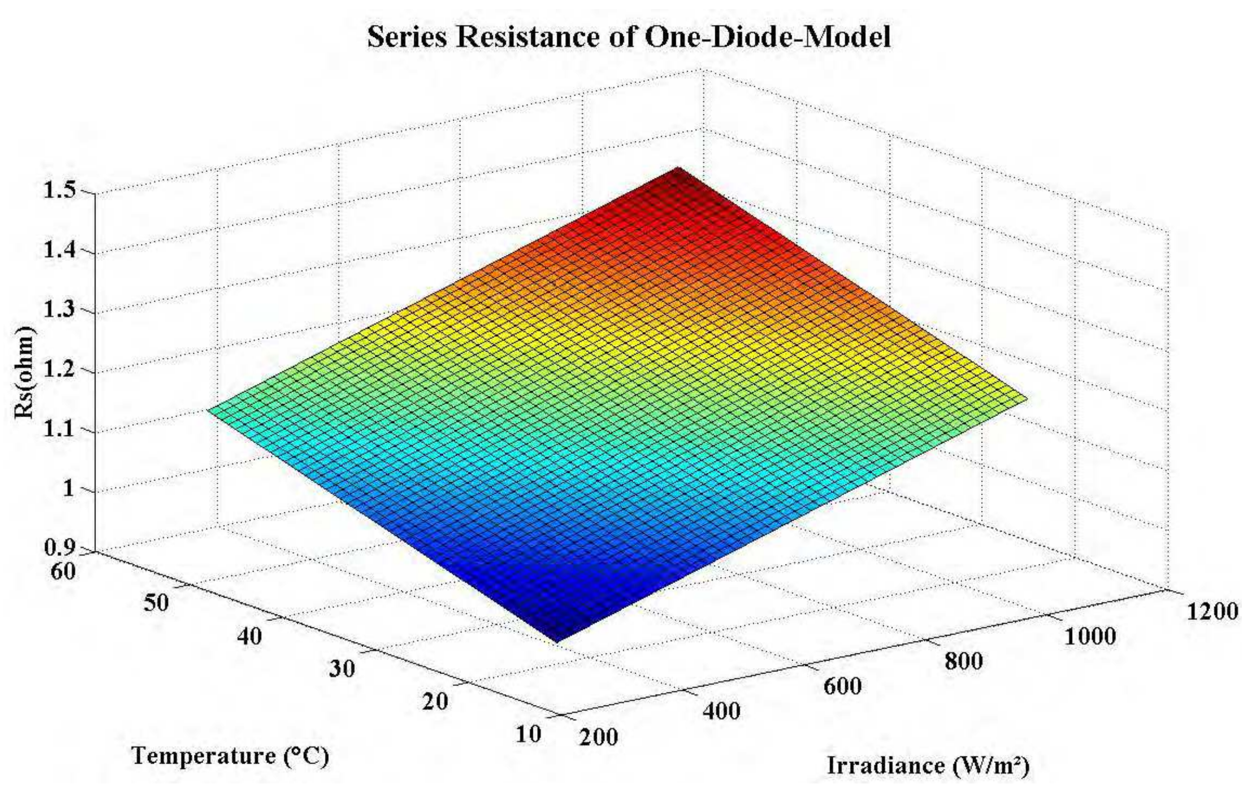


Fig. 16. Fitted sheet on series resistance of one-diode model by MATLAB.

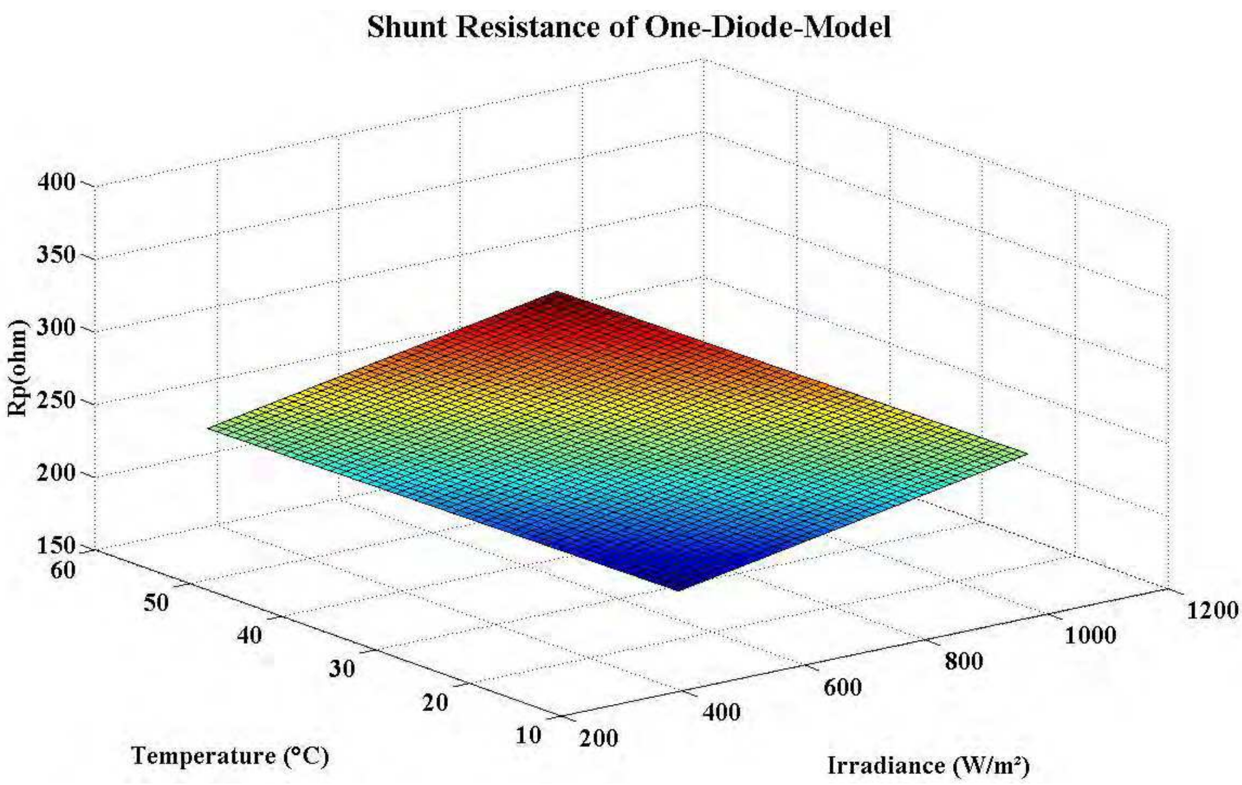


Fig. 17. Fitted sheet on shunt resistance of one-diode model by MATLAB.

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 form 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.

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

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

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

$$I_x = I_{ph} - I_0 e^{\frac{V_x+I_xR_s}{V_T}} - \frac{V_x+I_xR_s}{R_p} \tag{11}$$

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

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.

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

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 δx is described based on the Eq. (13) and consequently Eq. (14) states the new estimation for the root of the equations.

$$J^k \delta x^k = -R^k \tag{13}$$

$$x_{new} = x_{old} + \delta x \tag{14}$$

Finally, the above iteration is repeated by the new start point (x_{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).

$$x_{new} = x_{old} + \alpha \times \delta x \tag{15}$$

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

8. Acknowledgment

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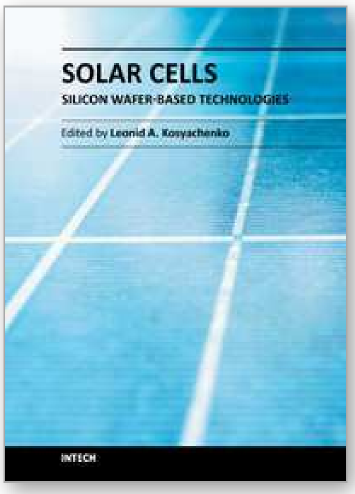

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