Modeling and Parameter Extraction of PV Cell Using Single- and Two-Diode Model

B. Benabdelkrim [1,2], A. Benatillah[2]

[1] *Department of Material Sciences, Institute of Science and Technology, University of Ahmed Draia, Adrar, ALGERIA*
[2] *Laboratory of Energy, Environment and Systems of Information (LEESI), University Ahmed Draia Adrar, ALGERIA*
benaekbouchra01@gmail.com

Abstract – *Photovoltaic modules operate under a large range of conditions. This combined with the fact that manufacturers provide electrical parameters at specific conditions (STC). The present study proposes a comparison between single and double diode models of solar PV system and ensures the best suited model under specific environmental condition for accurate performance prediction. An important feature of these models is that its parameters can be determined using data commonly provided by module manufacturers on their published datasheets. Accurate determination of these parameters which arose from a diversification of models and methods dedicated to their estimations is still a challenge for researchers. In this paper the single and two diode models have been studied by mathematical methods based on simulated Newton-Raphson iteration method. Newton-Raphson iteration method is solved by MATLAB simulation.*

I. Introduction

The rapid growth of PV system utilizations is due to its availability everywhere which avoids transmission costs and losses, free, abundant and pollution free. Silicon is the basic material required for the production of solar cells based crystalline or thin film technology.

The photovoltaic (PV) modules are generally rated under standard test conditions (STC) with the solar radiation of 1000 W/m2, cell temperature of 25°C, and solar spectrum of 1.5 by the manufacturers. The parameters required for the input of the PV modules are relying on the meteorological conditions of the area. The climatic conditions are unpredictable due to the random nature of their occurrence. These uncertainties lead to either over- or underestimation of energy yield from PV modules. An overestimation up to 40% was reported as compared to the rated power output of PV modules [1, 2]. The growing demand of photovoltaic technologies led to research in the various aspects of its components from cell technology to the modeling, size optimization, and system performance [3–5].

There are various PV cell modules studied by researchers in the literature. One of the simplest is single diode model. [6] In broad sense this model is derived by three parameters: Short Circuit Current (I_{sc}), Open Circuit Voltage (V_{oc}), and Diode Ideality Factor (A). When the parameter series resistance (R_s)

is added in this model, the accuracy of model gets improved. One drawback of this model is that it is not capable of temperature (T) variation handling. Parameter shunt resistance (R_{sh}) significantly improves the model efficiency. [7] This model is having a drawback of reduced accuracy under low irradiance (G) level, especially at open circuit voltage (V_{oc}). Additional diode design is added to the model for the recombination loss in the depletion region of the cell of solar module. [8] This is double- diode model. This model has more parameters to calculate. This model gives more accuracy because this model is more practical especially under low voltages.

In this paper, a comparative analysis details the behavioral I-V characteristics of a single-diode using analytical four and five parameter model and two-diode model. The accuracy of the simulation results is verified by comparing it with published data provided by manufacturers of six PV modules of different types (mono-crystalline, poly-crystalline and thin-film).

II. Mathematical models of PV module

II.1 Single-diode model

An electrical circuit with a single diode (single exponential) is considered as the equivalent

photovoltaic cell in the present article. Two different models drawn from the equivalent electrical-circuit are studied: namely four- and five-parameter models.
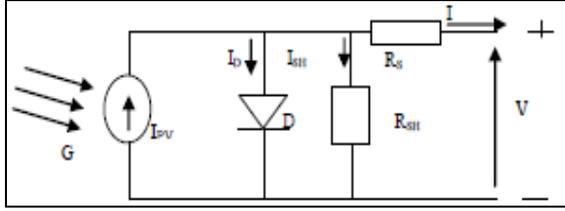
Figure1. PV-cell equivalent-circuit models: single-diode model [9].

An output current equation of I-V characteristic using this model can be written as:

$$I = I_{pv} - I_0 \cdot \left(\exp\left(\frac{V + R_s.I}{V_T} \right) - 1 \right) - \left(\frac{V + R_s.I}{R_{sh}} \right) \tag{1}$$

Where

I_{pv}	Photocurrent
I_0	Cell saturation current
R_{sh}	Shunt resistance
R_s	Series resistance
V_T	the thermal voltage (V_T=a.Ns.k.T/q)
N_s	Number of cells in series
a	Ideal factor of the PV diode
q	Electron charge (1.60281×10^{-19} C)
k	Boltzmann's constant=1.38066×10^{-23} J/K
T	Cell operating temperature

II.1.1 Four-parameter model

The four-parameter model studied in this work has been used elsewhere [10, 11]. Assuming R_{sh} as infinite and neglecting it in Equation (1), the four-parameter model is obtained as follows:

$$I = I_{pv} - I_0 \cdot \left(\exp\left(\frac{V + R_s.I}{V_T} \right) - 1 \right) \tag{2}$$

The unknown parameters are denoted at STC as I_{pvn}, I_{0n}, a_n and R_{sn} ; where the "n" subscript refers to the reference operating conditions. The short circuit current can be found when V=0

$$I_{scn} = I_{pvn} \tag{3}$$

The following equations are used to calculate the other parameters at STC [10].

$$a_n = \frac{K_v - \frac{V_{ocn}}{T_n}}{V_{Tn} \cdot \left(\frac{K_i}{I_{pvn}} - \frac{3}{T_n} - \frac{E_g}{k T_n^2} \right)} \tag{4}$$

$$I_{0n} = \frac{I_{pvn}}{\exp\left(\frac{V_{ocn}}{V_{Tn}} \right) - 1} \tag{5}$$

$$R_{sn} = \frac{V_{Tn} \cdot \ln(1 - \frac{I_{mpn}}{I_{pvn}}) + V_{ocn} - V_{mpn}}{I_{mpn}} \tag{6}$$

Where Eg is the band gap of the material The parameters can be found at any other operating conditions by using following equations:

$$I_{pv} = \frac{G}{G_n} \left[I_{pvn} + K_i (T - T_n) \right] \tag{7}$$

$$I_O = I_{On} \left(\frac{T}{T_n} \right)^3 \exp\left[\left(\frac{q.E_g}{a.k} \right) \left(\frac{1}{T_n} - \frac{1}{T} \right) \right] \tag{8}$$

$$R_s = R_{sn} \tag{9}$$

$$a = a_n \cdot \frac{T}{T_n} \tag{10}$$

This model is implemented as follows: Eqs. (3)–(6) are used to find values of the four parameters under reference conditions. These four parameters are corrected for environmental conditions using Eqs. (7)–(10) and used in Eq. (2), which relates cell current to cell voltage. From Eq. (2) either cell current or voltage could be calculated provided that the other is known. Alternatively, cell current and voltage could both be calculated at the maximum-power point.

II.1.2 Five-parameter model

As given in Eq. (1), the five-parameter model is an implicit non-linear equation, which can be solved with a numerical iterative method such as Newton Raphson method [12]. However, this requires a close approximation of initial parameter values to attain convergence. Alternatively, the parameters may be extracted by means of analytical methods. Some of the analytical methods are studied elsewhere [12-15]. The five parameters I_{pv}, I_o, R_s, R_{sh}, and m are calculated at a particular temperature and solar-irradiance level from the limiting conditions of V_{oc}, I_{sc}, V_{mp}, I_{mp} and using the following definitions of R_{so} and R_{sho}:

$$R_{s0} = -\frac{dV}{dI} \bigg|_{V = V_{oc}} \tag{11}$$

$$R_{sh0} = -\frac{dV}{dI} \bigg|_{I = I_{sc}} \tag{12}$$

Where R_{s0} and R_{sh0} are the reciprocals of the slopes at the open-circuit point and short-circuit point, respectively. The values of these resistances are not usually provided by module manufacturers. The other parameters are calculated as follows. The following equations are used to calculate the five parameters required.

$$I_{pv} = I_{sc} \left(1 + \frac{R_s}{R_{sh}} \right) + I_0 \cdot \left(\exp\left(\frac{I_{sc}.R_s}{V_T} \right) - 1 \right) \tag{13}$$

$$I_0 = \left(I_{sc} - \frac{V_{oc}}{R_{sh}} \right).\exp\left(-\frac{V_{oc}}{V_T} \right) \qquad (14)$$

The value of the diode ideality factor (a) may be arbitrarily chosen. Many authors discuss ways to estimate the correct value of this constant.

Usually, $1 \leq a \leq 2$ and the chosen value depend on other parameters of the I–V model. As it's given in [16], there are different opinions about the best way to choose (a). Because (a) expresses the degree of ideality of the diode and it is totally empirical, any initial value of (a) can be chosen in order to adjust the model.

The R_s and R_{sh} resistances are calculated by iterative methods. The relation between R_s and R_{sh}, may be found by making the maximum power calculated by the I–V model, equal to the maximum experimental power from the datasheet ($P_{max,m} = P_{max,e}$) at the (V_m; I_m) point. In the iterative process, R_s must be slowly incremented starting from $R_s = 0$ and for every iteration, the value of R_{sh} is calculated simultaneously:

$$P_{max,m} = V_{mp} \times \left\{ I_{pv} - I_0 \cdot \left(\exp\left(\frac{V_{mp} + R_s.I_{mp}}{V_T} \right) - 1 \right) - \left(\frac{V_{mp} + R_s.I_{mp}}{R_{sh}} \right) \right\} = P_{max,e} \qquad (15)$$

$$R_s = R_{s0} - \frac{V_T}{I_0} \exp\left(-\frac{V_{oc}}{V_T} \right) \qquad (16)$$

$$R_{sh} = \frac{V_{mp} + R_s.I_{mp}}{I_{pv} - I_0 \cdot \left(\exp\left(\frac{V_{mp} + R_s.I_{mp}}{V_T} \right) - 1 \right) - \frac{P_{max,e}}{V_{mp}}} \qquad (17)$$

The initial condition for the shunt resistance R_{sh} can be found when considering the initial value of $R_s=0$ [17, 18]

$$R_{sh,min} = \frac{V_{mp}}{I_{sc} - I_{mp}} - \frac{V_{oc} - V_{mp}}{I_{mp}} \qquad (18)$$

In the proposed iterative method, the series resistance must be slowly incremented starting from a null value. Adjusting the I-V curve to match the cell reference condition requires finding the curve for several values of series and equivalent shunt resistances. The Newton–Raphson method was used in the proposed iterative method due to the ability to overcome undesired behaviors [19].

II.2 Two-diode model

The two diode model (Fig.2) equation of the I–V curve is expressed as [20]:

$$I = I_{pv} - I_{01} \cdot \left(\exp\left(\frac{V + R_s.I}{V_{T1}} \right) - 1 \right) - I_{02} \cdot \left(\exp\left(\frac{V + R_s.I}{V_{T2}} \right) - 1 \right) - \left(\frac{V + R_s.I}{R_{sh}} \right) \qquad (19)$$
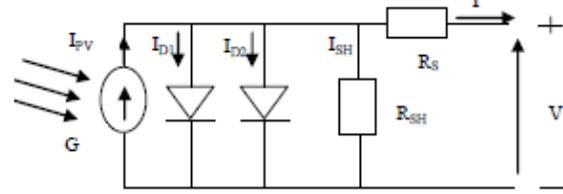
Figure2. PV-cell equivalent-circuit models: two-diode model

Where the diode factors $a_1=1$ and a_2 can be derived from:

$$\frac{a_1 + a_2}{p} \geq 1 \qquad (20)$$

Where, p can be chosen greater than 2.2.

The rest of parameters can be deduced from the following equations [20]:

$$I_{pv} = I_{sc} \qquad (21)$$

$$I_{01} = I_{02} = \frac{I_{sc} + K_i.\Delta T}{\exp\left(\frac{q.(V_{oc} + K_v.\Delta T)}{kT.(a_1 + a_2)/p} \right) - 1} \qquad (22)$$

Rs and R_{sh} are calculated by iterative method, similar to the procedure proposed by [21], where the relation between R_s and R_{sh} is chosen to verify that the calculated maximum power is equal to the experimental one ($P_{max,m} = P_{max,e}$) at (V_m, I_m) point. The R_s value is found by a slow incrementation by the same manner as the above subsection.

The expression of R_{sh} can be written as:

$$R_{sh} = \frac{V_{mp} + R_s.I_{mp}}{I_{pv} - I_{01} \cdot \left(\exp\left(q \frac{V_{mp} + R_s.I_{mp}}{kT} \right) + \exp\left(q \frac{V_{mp} + R_s.I_{mp}}{(p-1)kT} \right) + 2 \right) - \frac{P_{max,e}}{V_{mp}}} \qquad (23)$$

III. Results and discussion

The modeling methods described in this paper are validated by measured parameters of selected PV modules. The experimental (V,I) data are extracted from the manufacturer's datasheet. Three different modules of different brands/ models are utilized for verification; these include the multi- and mono crystalline as well as thin-film types. The specifications of these modules are summarized in Table 1

Table1. Specification of the PV modules

Modules	Isc (A)	Voc (V)	Imp (A)	Vmp (V)	Ki(Isc) (mA/°C)	Kv(Voc) (mV/°C)	Ns
Poly-cristallin							
Kyocera KC200GT	8.21	32.9	7.61	26.3	3.18	-123	54
Shell S70	4.5	21.2	4.12	17	2	-76	36
Mono-cristallin							
Shell SQ150	4.8	43.4	4.4	34	1.4	-161	72
Shell SP70	4.7	21.4	4.25	16.5	2	-76	36
Thin-Film							
Shell ST40	2.68	23.3	2.41	16.6	0.35	-100	36
PVL-136	5.1	46.2	4.1	33	5.1	-176	66

Figures (3-5) shows the I-V curves for modules for different levels of irradiance and temperature. It can be seen that for varying irradiance, despite the modeling curves do not match experimental data in all points, the tow diode model strongly agrees to experimental data than the four-parameter and five-parameter models for all types of modules, except for the thin-film (ST40) module at low irradiance of about 200W/m² where the five-parameter modeled curve is closer to the experimental data than four-parameter and tow diode models.

In the case of the varying temperature, G is kept constant at 1000 W/m². It can be noted that all three methods show good general agreement with the experimental data. However, a close inspection reveals that the tow-diode model yields the most accurate results at all temperature.
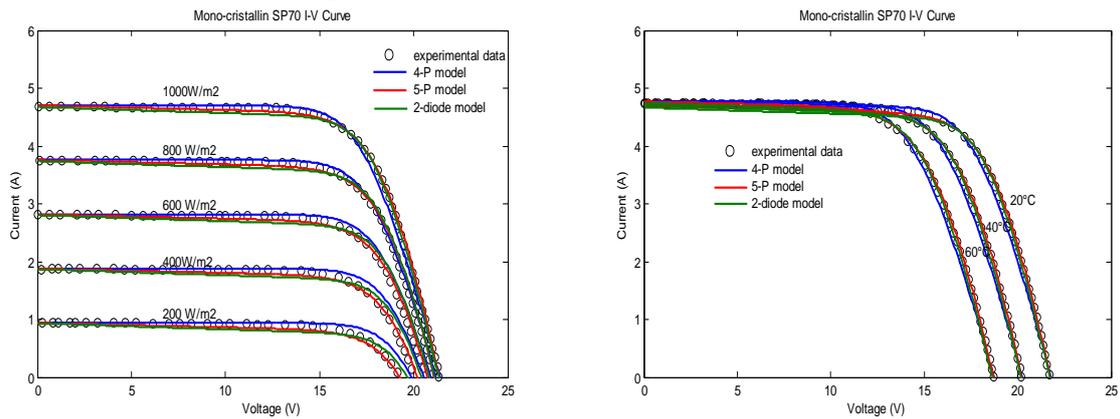
Figure3. The I-V characteristics of SP70 module at varying irradiance and temperature.
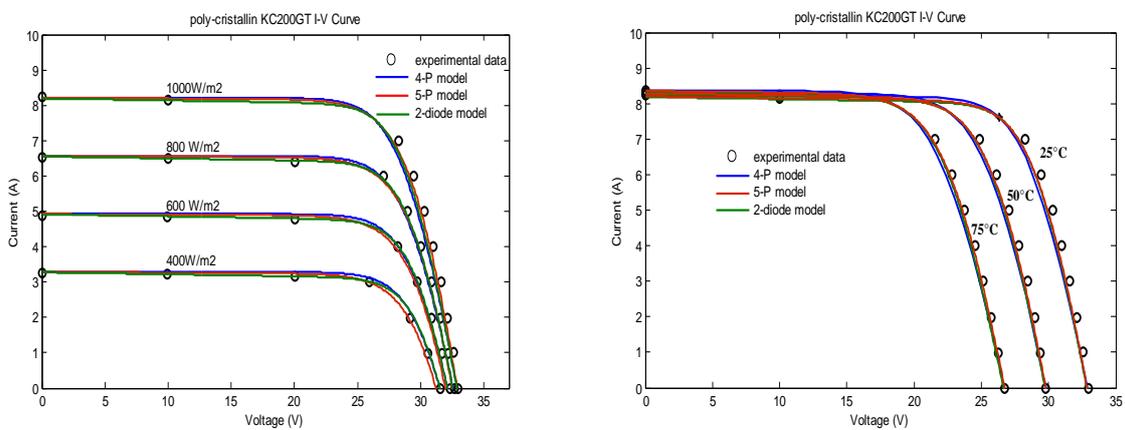
Figure4. The I-V characteristics of KC200GT module at varying irradiance and temperature.
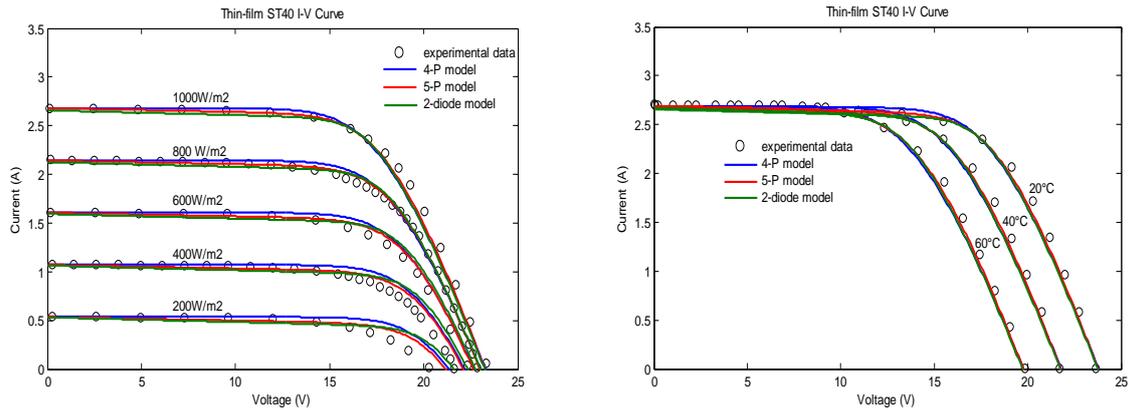
Figure5. The I-V characteristics of ST40 module at varying irradiance and temperature.

Table 2-4 shows the parameters used for three models. Four parameters are calculated namely, I_0, I_{PV}, ideality factor (a) and Rs for the 4-P model. In the five parameter model, the additional calculated parameter is the shunt resistance; Rsh. and the two-diode model has more variables, the actual number of parameters computed is four because $I_{01}=I_{02}=I_0$ while

a1=1 and p can be chosen arbitrarily, i.e. $p \geq 2.2$. The two-diode model and the five parameter model exhibit similar results at STC. This is to be expected because both models use the similar max power matching algorithm to evaluate the model parameters at STC. However, at low irradiance, more accurate results are obtained from the two-diode model.

Table2.Parameters extracted for the four parameter model

Module	Poly-crystalline		Mono-crystalline		Thin-Film	
	KC200GT	S70	SP70	SQ150-PC	ST40	PVL-136
Ipv	8.2100	4.5000	4.7000	4.8000	2.6800	5.1000
a	1.0758	1.0177	1.0222	1.0594	1.3219	1.2573
Rs	0.3541	0.4547	0.6310	1.0296	1.6156	2.3723
Io	2.1954e-9	7.4460e-10	6.9528e-10	1.1570e-9	1.4202e-8	1.9783e-9

Table3. Parameters extracted for the five parameter model

Module	Poly-crystalline		Mono-crystalline		Thin-Film	
	KC200GT	S70	SP70	SQ150-PC	ST40	PVL-136
Ipv	8.2146	4.5055	4.7150	4.8073	2.6961	5.2942
a	1.3000	1.3000	1.3000	1.3000	1.3000	1.3000
Rs	0.2300	0.2200	0.4000	0.6700	1.5100	1.6800
Rsh	601.3368	189.0262	133.1309	466.4639	266.5478	44.1667
Io	9.8252e-8	9.9101e-8	8.7645e-8	6.9745e-8	1.0292e-8	4.0336e-9

Table4. Parameters extracted for the two-diode model

Module	Poly-crystalline		Mono-crystalline		Thin-Film	
	KC200GT	S70	SP70	SQ150-PC	ST40	PVL-136
Ipv	8.2100	4.5000	4.7000	4.8000	2.6800	5.1000
a_1	1	1	1	1	1	1
a_2	1.2000	1.2000	1.2000	1.2000	1.2000	1.2000
Rs	0.3300	0.3400	0.5100	0.9100	1.7100	1.9600
Rsh	174.1551	119.5882	94.9643	275.2625	204.8492	54.2497
$Io_1=Io_2$	4.1280e-10	4.9996e-10	4.2065e-10	3.1059e-10	3.0748e-11	7.5012e-12

Tables 5–8 show the relative errors for P_{max}, Voc and Isc at varying irradiance and temperature of SP70 and ST40 modules. The relative error is defined as:

$$E_{relative}\left(X\right) = \left(\frac{abs\left(X_{data} - X_{calcul}\right)}{X_{data}}\right) * 100 \quad (24)$$

The irradiance is maintained constant at STC. From the data it can be concluded, more accurate results are obtained from the two-diode model for the crystalline silicon technologies.

Table5. Relative errors of three models at different irradiances (T =25°C) for SP70 module.

Irradiance (W/m²)	Parameters	Measured data	4-P model	Error %	5-P model	Error %	2D model	Error %
1000	Pmax	70.07	70.5	0.61	70.11	0.057	70.22	0.21
	Voc	21.33	21.39	0.28	21.35	0.094	21.34	0.047
	Isc	4.682	4.7	0.38	4.7	0.38	4.675	0.15
800	Pmax	56.13	57.61	2.64	55.95	0.32	56.38	0.45
	Voc	21.03	21.18	0.71	21.07	0.19	21.13	0.48
	Isc	3.752	3.76	0.21	3.76	0.21	3.74	0.32
600	Pmax	41.89	43.96	4.94	41.46	1.026	41.99	0.24
	Voc	20.5	20.91	2.00	20.72	1.073	20.84	1.66
	Isc	2.815	2.82	0.18	2.82	0.18	2.805	0.36
400	Pmax	27.53	29.62	7.59	26.76	2.79	27.12	1.49
	Voc	19.92	20.53	3.06	20.19	4.92	20.43	2.56
	Isc	1.882	1.88	0.11	1.88	0.11	1.87	0.64
200	Pmax	13.17	14.72	11.76	12.08	8.28	11.99	8.96
	Voc	19.12	19.81	3.61	19.25	0.68	19.65	2.77
	Isc	0.9472	0.94	0.76	0.94	0.76	0.935	1.29

Table6: Relative errors of three models at different temperatures (E =1000 W/m²) for SP70 module.

Temperature (°C)	Parameters	Measured data	4-P model	Error %	5-P model	Error %	2D model	Error %
20	Pmax	71.54	72.23	0.96	71.76	0.31	71.82	0.39
	Voc	21.71	21.77	0.28	21.70	0.046	21.70	0.046
	Isc	4.743	4.69	1.12	4.69	1.12	4.665	1.64
40	Pmax	64.77	65.29	0.80	65.15	0.59	65.38	0.94
	Voc	20.18	20.26	0.39	20.25	0.35	20.24	0.29
	Isc	4.736	4.73	0.13	4.73	0.13	4.705	0.65
60	Pmax	57.94	58.34	0.69	58.54	1.036	58.86	1.59
	Voc	18.71	18.69	0.11	18.68	0.16	18.67	0.21
	Isc	4.743	4.77	0.57	4.77	0.57	4.745	0.042

Table7. Relative errors of three models at different irradiances (T =25°C) for ST40 module.

Irradiance (W/m²)	Parameters	Measured data	4-P model	Error %	5-P model	Error %	2D model	Error %
1000	Pmax	40.21	40.03	0.45	39.99	0.55	40.04	0.42|
	Voc	23.29	23.30	0.04	23.27	0.086	23.26	0.13
	Isc	2.677	2.68	0.11	2.68	0.11	2.658	0.71
800	Pmax	31.71	33.04	4.19	32.68	3.06	32.97	3.97
	Voc	22.85	23.02	0.74	22.99	0.61	23.04	0.83
	Isc	2.149	2.144	0.23	2.144	0.23	2.126	1.07
600	Pmax	23.52	25.44	8.16	24.80	5.44	25.17	7.02
	Voc	22.33	22.67	1.52	22.62	1.30	22.76	1.92
	Isc	1.607	1.608	0.062	1.608	0.062	1.595	0.75
400	Pmax	15.34	17.26	12.52	16.4	6.91	16.7	8.86
	Voc	21.63	22.17	2.49	22.11	2.22	22.35	3.33
	Isc	1.074	1.072	0.19	1.072	0.19	1.063	1.02

200	Pmax	6.967	8.611	23.59	7.615	9.30	7.655	9.87
	Voc	20.28	21.33	5.18	21.17	4.39	21.61	6.56
	Isc	0.537	0.536	0.19	0.536	0.19	0.5316	1.01

Table8: Relative errors of three models at different temperatures (E =1000 W/m^2) for ST40 module.

Tempetaure (°C)	Parameters	Measured data	4-P model	Error %	5-P model	Error %	2D model	Error %
20	Pmax	41.29	41.36	0.33	41.27	0.048	41.3	0.024
	Voc	23.65	23.80	0.63	23.76	0.46	23.75	0.42
	Isc	2.702	2.678	0.89	2.678	0.89	2.656	1.70
40	Pmax	36.36	36.09	0.74	36.19	0.47	36.29	0.19
	Voc	21.7	21.79	0.41	21.77	0.32	21.75	0.23
	Isc	2.702	2.685	0.63	2.685	0.63	2.663	1.44
60	Pmax	31.49	30.93	1.78	31.21	0.89	31.34	0.48
	Voc	19.87	19.77	0.50	19.76	0.55	19.75	0.60
	Isc	2.706	2.692	0.52	2.692	0.52	2.67	1.33

Figure.6 and 8 shows the analysis for relative error of Voc and the P$_{max}$ for ST40 module at different irradiance levels. As can be seen at STC irradiance, there is a very small difference in the Voc values among the three models. However as the irradiance is reduced, there is a significant deviation of Voc calculated using the 4-P, 5-P and two-diode models. Similar results can be observed for the P$_{max}$.

Figure.7 shows the performance of the three models at different temperature for ST40 module. There is no significant difference between three models for Voc. However the four-parameter model exhibits poor performance for P$_{max}$ calculations.

Figure.9 shows the performance of the three models at different temperature for SP70 module.

We note that the two-diode model and the five-parameter model are the least accurate at the three remarkable points at 60 °C compared to the four-parameter models. This is logical because the value of the ideality factor is assumed to be fixed in the five-parameter model and the two-diode model and in the other hand the values of the recombination and diffusion saturation current are assumed to be equal in the two-diode model.
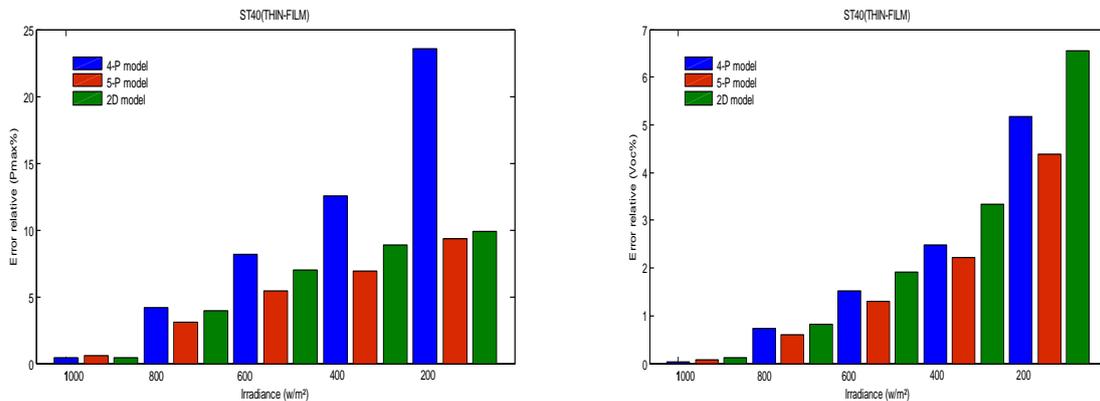
Figure.6. Relative error of P$_{max}$ (a) and Voc (b) at varying irradiance for ST40 PV module
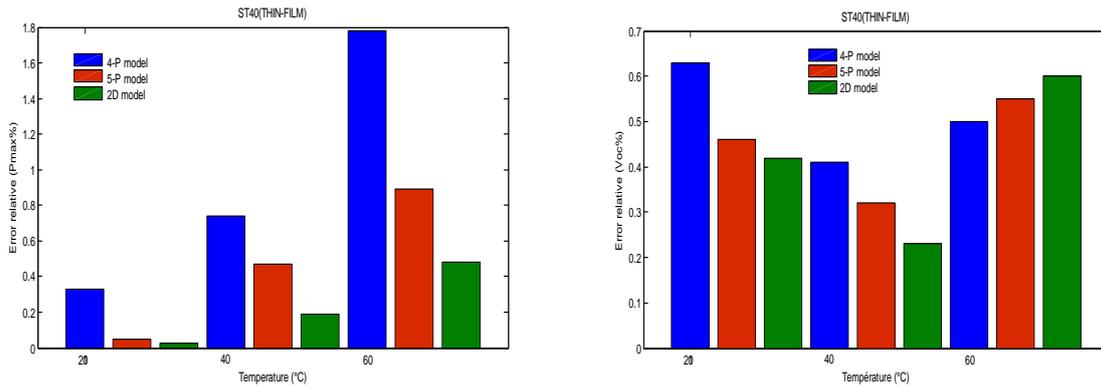
Figure.7. Relative error of P$_{max}$ (a) and Voc (b) at varying temperature for ST40 PV module
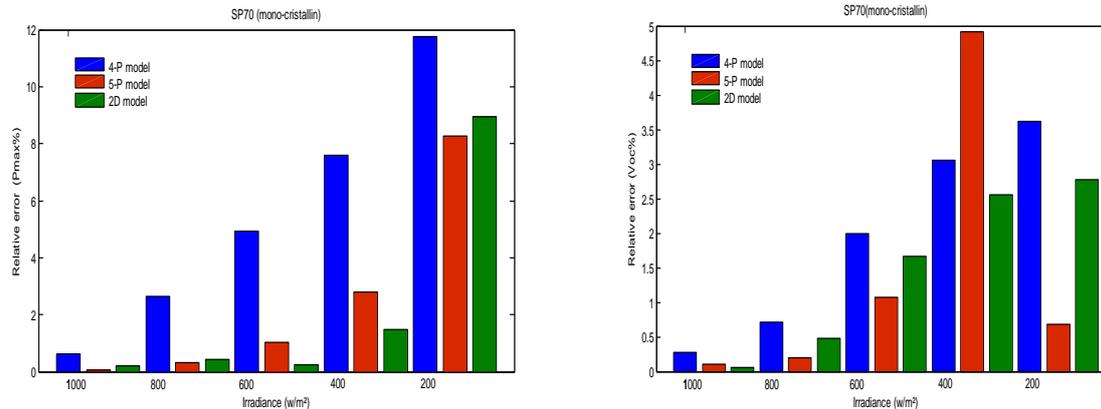
Figure.8. Relative error of P$_{max}$ (a) and Voc (b) at varying irradiance for SP70 PV module
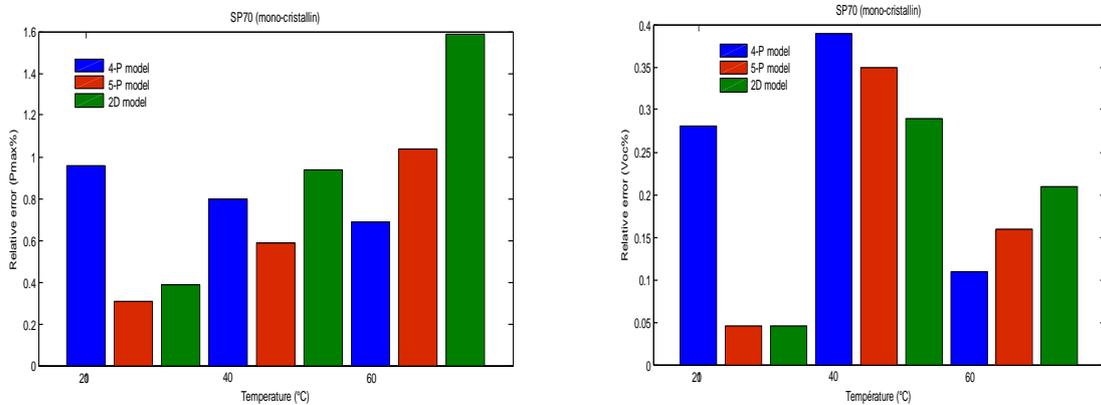
Figure.9. Relative error of P$_{max}$ (a) and Voc (b) at varying temperature for SP70 PV module

IV.   Conclusion

The present paper has proposed the comparison between the four-parameter, five-parameter and tow-diode models. These models used to predict the electrical response of illuminated six PV modules for various operating conditions. The accuracy of the three models is evaluated using practical data from manufacturers of different types of PV modules. Its performances are compared with the experimental values given by the constructors. It has been found that, the tow-diode model is better when subjected to variations in irradiance and temperature.

And gives better accuracy for reconstructing the electrical characteristics of mono-crystalline and poly-crystalline PV modules, but for thin-film PV module the five parameter model is closer to the experimental data at the low irradiance.

References

[1] W. Durisch, D. Tille, A. Worz, and W. Plapp, "Characterisation ¨ of photovoltaic generators," *Applied Energy*, vol. 65, no. 1–4, 2000, pp. 273–284.

[2] A. Q. Jakhrani, A. K. Othman, A. R. H. Rigit, S. R. Samo, and S. R. Kamboh, "A novel analytical model

for optimal sizing of standalone photovoltaic systems," *Energy*, vol. 46, no. 1,2012, pp. 675– 682.

[3] A. N. Celik, "A simplifed model based on clearness index for estimating yearly performance of hybrid pv energy systems," *Progress in Photovoltaics: Research and Applications*, vol. 10, no. 8, 2002, pp. 545–554.

[4] A. H. Fanney and B. P. Dougherty, "Building integrated photovoltaic test facility," *Journal of Solar Energy Engineering*, vol. 123, no. 3, 2001, pp. 194–199.

[5] M. A. Green, "Short communication: price/efciency correlations for 2004 photovoltaic modules," *Progress in Photovoltaics: Research and Applications*, vol. 13, 2005, pp. 85–87.

[6] Glass M. C., 'Improved Solar Array Power Point Model with SPICE Realization of Generalized', IECEC, Vol. 1,1996, pp. 286-291.

[7] Kajihara A and Harakawa A. T., 'Model of Photovoltaic Cell Circuits Under Partial Shading', ICIT, 2005, pp. 866-870.

[8] Tan Y. T., Kirschen D. S., and Jenkins N., 'A Model of PV Generation Suitable for Stability Analysis', IEEE Trans. Energy Converts, Vol. 19, No. 4, 2004, pp. 748-755.

[9] A. Chatterjee, A. Keyhani, and D. Kapoor, "Identification of Photovoltaic Source Models," *Energy Conversion, IEEE Transactions on,* vol. PP, 2011, pp1-7.

[10] Celik, A. N. and Acikgoz, N. "Modelling and experimental verification of the operating current of mono-crystalline photovoltaic modules using four- and five-parameter models", Applied Energy, 84, 2007, pp 1–15.

[11] Arab, A. H., Chenlo, F., Benghanem, M.,. "Loss- of-load probability of photovoltaic water pumping systems", Solar Energy, 76, 2004, pp713–723.

[12] Phang JCH, Chan DSH, Philips JR. Accurate analytical method for the extraction of solar-cell model parameters. Electron Letters, 20, 1984, pp406–408.

[13] Blas MA, Torres JL, Prieto E, Garcia A. Selecting a suitable model for characterizing photovoltaic devices. Renewable Energy, 25, 2002, pp371–380.

[14] Kou Q, Klein A, Beckman WA. A method for estimating the long-term performance of direct-coupled PV pumping systems. Solar Energy, 64, 1998, pp 33–40.

[15] Chenlo F, Fabero F, Alonso MC. Testing, norms, reliability and harmonization: a comparative study between indoor and outdoor measurement. Agencia EUREC, Joule. JOUII-CT92-0178, Brussels: European Commission, 1996.

[16] Marcelo G. Villalva, Jonas R. Gazoli, and Ernesto R. Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays ", IEEE Transactions on Power Electronics, 24, 2009, pp 1198 - 1208.

[17] Villalva, M.G., Gazoli, J.R., Filho, E.R. Comprehensive approach to modeling and simulation of photovoltaic arrays. IEEE Trans. Power Electron. 24, 2009, pp1198–1208

[18] Ishaque, K., Salam, Z., Taheri, H., Shamsudin, A. A critical evaluation of EA computational methods for photovoltaic cell parameter extraction based on two diode model. Sol. Energy, 85, 2011, pp 1768–1779.

[19] Walker, G.R.: Evaluating MPPT topologies using a Matlab PV model. Journal of Electrical & Electronics Engineering, 21, 2001, pp 49-56.

[20] Ishaque, K., Salam, Z., Taheri, H. Simple, fast and accurate two diode model for photovoltaic modules. Sol. Energy Mater. Sol. Cells, 95 (2), 2011a, pp 586–594.

[21] Villalva, M.G., Gazoli, J.R., Filho, E.R. Comprehensive approach to modeling and simulation of photovoltaic arrays. IEEE Trans. Power Electron. 24, 2009, pp 1198–1208.