PV Parameters Estimation using a Developed Iterative Method

Tarek M. El-Sayed
Electronics Research Institute Cairo, Egypt
engtarekmoh@gmail.com

Abd El-Shafy A. Nafeh
Electronics Research Institute Cairo, Egypt
abdelshafyn@yahoo.com

Faten H. Fahmy
Electronics Research Institute Cairo, Egypt
fatenhf@yahoo.com

Hosam K. M. Yousef
faculty of Engineering, Cairo University
hosamkm@yahoo.com

Abstract - **This paper presents a developed iterative methodology to estimate the real parameters for a considered photovoltaic (PV) module. Thus, the estimated parameters can accurately model and simulate the actual performance of the considered PV module. The developed method is carried out by writing the appropriate Matlab code in an M-file, which takes the manufacturer specified data at standard test conditions as inputs. The resulted PV model has the capability to simulate both the current-voltage (I-V) and the power-voltage (P-V) characteristics of the PV module. The model is also able to study the effects of the parameters variations on the PV module performance such as operating temperature and solar irradiation. The model is simulated using Matlab/Simulink. Therefore, it has the capability to compare simulation results with experimental results. The resulted PV characteristics of the considered PV module are compared to those provided by the commercially available module's datasheet. Simulation results exhibit the high accuracy and validity of the simulated PV module.**

Keywords – **Photovoltaic Module, Solar Energy, Performance I–V Curves, Parameter Estimation.**

I. INTRODUCTION

A photovoltaic (PV) system directly converts sunlight into electricity. The basic device of a PV system is the PV cell. Cells may be grouped to form panels or arrays. The voltage and current available at the terminals of a PV device may directly feed small loads such as lighting systems and DC motors. More sophisticated applications require electronic converters to process the electricity from the PV device. These converters may be used to regulate the voltage or current at the load, to control the power flow in grid-connected systems, and mainly to track the maximum power point (MPP) of the device [1].

Solar panels are relatively expensive. Therefore experimenting with a prototype system would be costly. In addition, as the characteristics of the PV modules are highly dependent on environmental conditions [2]. Thus, studying the PV behavior through simulation is an important step before actually implementing a solar power system.

This paper presents a mathematical simulation model for a PV module, through estimating the parameters of the PV module using iterative method, and comparing it to an existing practical model. The developed model is able to simulate the curves of both the current-voltage (I-V) and the power-voltage (P-V) characteristics of the PV module. The developed model is used to study different parameters variation effects on the PV module including operating temperature and/or solar radiation level. This model can also be utilized to simulate maximum power point tracking (MPPT) performance for solar PV systems. Simulation results exhibit the high capability of the model in simulating the characteristics of the commercially available PV module.

II. MODELING OF PV DEVICES

The electrical power available from a PV device can be modeled with the well known equivalent circuit shown in Fig. 1. This circuit includes a series resistance and a diode in parallel with a shunt resistance. This circuit can be used either for an individual cell, for a module consisting of several cells, or for an array consisting of several modules [3].

The current–voltage relationship at a fixed cell temperature and solar radiation for the circuit in Fig. 1 is expressed in Eq. (1) [3].Thus, five parameters must be exactly known in order to accurately determine this current–voltage relationship. These parameters are the light- generated current I_{ph}, the diode reverse saturation current I_o, the series resistance R_s, the shunt resistance R_{sh}, and the ideality factor n. The electron charge q and Boltzmann's constant K are known, N_s is the number of cells connected in series and T is the absolute cell temperature [2]. Cells connected in parallel increase the current and cells connected in series provide greater output voltages. In Eq. (1), R_s is the equivalent series resistance of the module and R_{sh} is the equivalent shunt resistance. This equation originates the I–V curve shown in Fig. 2, where three remarkable points are highlighted which are short-circuit (0, I_{sc}), maximum power point (MPP) (V_{mp}, I_{mp}), and open circuit (V_{oc}, 0) [1]. Where, I_{sc} is the short-circuit current, V_{oc} is the open-circuit voltage, and

V_{mp} & I_{mp} are the voltage and current at MPP, respectively
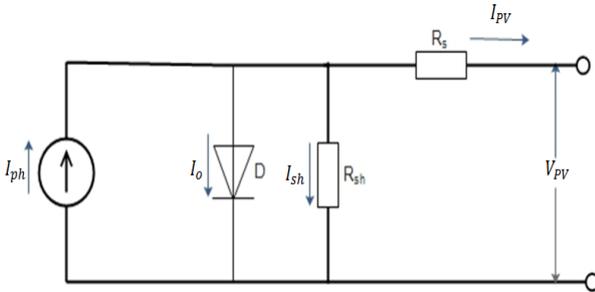

Fig.1. Equivalent circuit representing the model of the PV device.

$$I_{PV} = I_{ph} - I_o \left[\exp\left(\frac{q(V_{PV} + I_{PV} R_s)}{(n N_s K T)} \right) - 1 \right] - \frac{V_{PV} + I_{PV} R_s}{R_{sh}} \tag{1}$$

Equation (1) describes the single-diode model presented in Fig. 1. Some authors have proposed more sophisticated models that present better accuracy and serve for different purposes. For example, in [4] an extra diode is used to represent the effect of the recombination of carriers. A three-diode model is proposed in [5] to include the influence of effects that are not considered by the previous models. For simplicity, the single-diode model of Fig. 1 is considered in this paper.
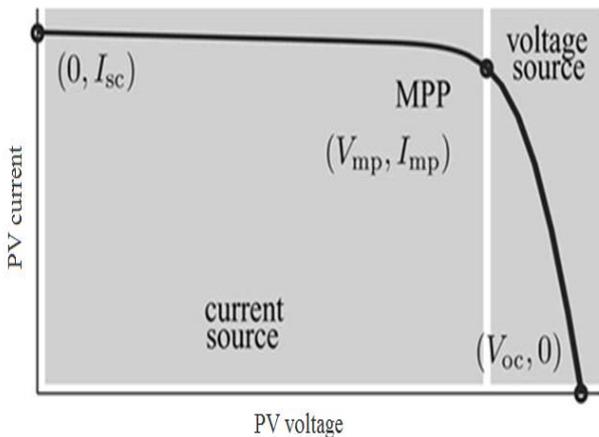

Fig.2. I–V Characteristic curve of a PV device.

Manufacturers of PV modules, instead of providing the I−V equation, provide only a few experimental data about electrical and thermal characteristics. Unfortunately, some of the parameters required for adjusting PV module models can not be found in the manufacturer's datasheets, such as the light-generated current, the series and shunt resistances, the diode ideality factor, the diode reverse saturation current, and the band gap energy of the semiconductor. All PV module datasheets bring basically the following information: the standard open-circuit voltage (V_{ocs}), the standard short-circuit current (I_{scs}), the standard voltage at the MPP (V_{mps}), the standard current at the MPP (I_{mps}), the open-circuit voltage/temperature coefficient (K_V), the short-circuit current/temperature

coefficient (K_I), and the maximum experimental peak output power (P_{maxs}). This information is always provided with reference to the nominal condition or standard test conditions (STCs) of temperature and solar irradiation (i.e., 25 ^{o}C and 1000 W/m^2). Some manufacturers provide the I–V curves for several irradiation and temperature conditions. These curves make the adjustment and the validation of the desired mathematical I–V equation easier. Basically, this is all the information one can get from datasheets of PV modules.
Table 1 shows the available data for the considered PV module at STC.

Table 1 Electrical characteristics of the LORENTZ LC80-12M PV module at STC.

Parameter	Value
Maximum power (P_{maxs})	80 W
Voltage at P_{max} (V_{mps})	17.2 V
Current at P_{max} (I_{mps})	4.6 A
Short-circuit current (I_{scs})	5.0 A
Open-circuit voltage (V_{ocs})	21.6 V
Temperature coefficient of I_{sc} (K_I)	0.0045 A/°C
Temperature coefficient of V_{oc} (K_V)	-0.0756 V/°C
Number of cells in series (N_s)	36

2.1 Reference Parameters Estimation
The I–V characteristic of the PV device shown in Fig. 2 depends on the internal characteristics of the device (R_s, R_{sh}) and on external influences such as irradiation level and temperature. The amount of incident light directly affects the generation of charge carriers, and consequently, the current generated by the device. The light-generated current (I_{ph}) of the elementary cells, without the influence of the series and parallel resistances, is difficult to determine. Datasheets only inform the standard short-circuit current (I_{scs}), which is the maximum current available at the terminals of the practical device. The assumption $I_{phs} \approx I_{scs}$ is generally used in the modeling of PV devices because in practical devices the series resistance is low and the parallel resistance is high. The light-generated current of the PV cell depends linearly on the solar irradiation and is also influenced by the temperature according to the following equation [1, 6].

$$I_{ph} = \left(I_{phs} + K_I (T - T_{ref}) \right) \frac{G}{G_{ref}} \tag{2}$$

Where I_{phs} is the light-generated current at STC and equals 5A for the considered PV module (table 1). T and T_{ref} are the actual and reference temperatures [in Kelvin], respectively. G is the incident irradiation on the device surface, and G_{ref} is the reference irradiation.

The diode reverse saturation current I_o and its dependence on the temperature may be expressed as [1, 2]:

$$I_o = I_{os} \left(\frac{T_{ref}}{T} \right)^3 e^{\frac{q E_g}{nK}\left(\frac{1}{T_{ref}} - \frac{1}{T} \right)} \tag{3}$$

Where E_g is the band gap energy for the considered PV module type. The value of E_g is a function of temperature and is related to its value at STC (i.e., E_{gs}) by [3]:

$$\frac{E_g}{E_{gs}} = 1 - 0.0002677\left(T - T_{ref}\right) \tag{4}$$

Noting that for the considered type of PV module, which is a polycrystalline silicon, $E_{gs} = 1.121\ ev$.

The value of the standard reverse saturation current is given by [1, 2]:

$$I_{os} = \frac{I_{scs}}{\left[exp\left(\frac{qV_{ocs}}{nKT_{ref}}\right) - 1\right]} \tag{5}$$

The saturation current I_o of the PV cells that compose the device depends on the saturation current density of the semiconductor (J_0, generally given in [A/cm^2]) and on the effective area of the cells. The current density J_0 depends on the intrinsic characteristics of the PV cell, which depend on several physical parameters such as the coefficient of diffusion of electrons in the semiconductor, the lifetime of minority carriers, the intrinsic carrier density, etc. This kind of information is not usually available for commercial PV modules. In this paper, the standard reverse saturation current I_{os} of the considered PV module is estimated, using Eq. (5) and the available module's data of table 1, to be 1.762×10^{-8} A. Noting, here, that Eq. (5) can be derived directly from Eq. (1) at standard open-circuit condition (i.e, $V_{PV} = V_{ocs}$, $I_{PV} = 0$, and $I_{ph} \approx I_{scs}$). Also, it is necessary to note, here, that the only unknown parameter in Eqs. (3) & (5), to be evaluated, is the value of the ideality factor (n), which will be estimated in the following section.

2.2 Ideality Factor Estimation

The value of the diode ideality factor (n) may be arbitrarily chosen. Many authors discuss ways to estimate the correct value of this constant. Usually, $1 \leq n \leq 2$ and the chosen value depends on other parameters of the I–V model. As it's given in [1], there are different opinions about the best way to choose n. Because n expresses the degree of ideality of the diode and it is totally empirical, any initial value of n can be chosen (e.g., $n_{initial} = 1$ in this work) in order to adjust the model. The value of n can be later modified by using the proposed iterative method, in order to improve the model fitting. This constant affects the curvature of the I–V curve and varying n can slightly improve the model accuracy. The effect of varying the diode ideality factor on the I-V characteristic of the considered PV module is shown in Fig.3. Thus, it is shown, from this figure, that increasing the value of n will decrease P_{max} and the fill factor of the device.
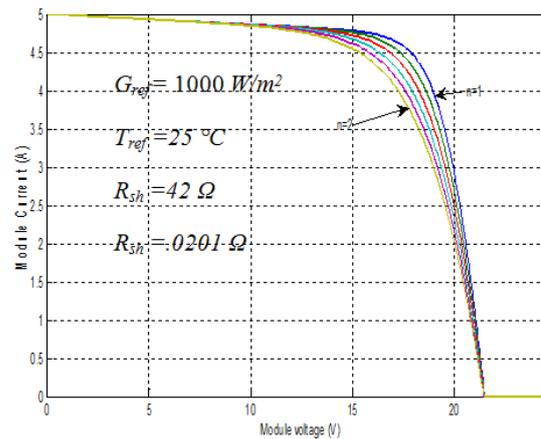

Fig.3. Effect of variation of diode ideality factor.

2.3 Series and Shunt Resistance Estimation

In the standard approaches R_s has been calculated using Eq. (6). But Eq. (6) is applicable only if the output characteristic curves are provided by the manufacturer. Only then the value of dV_{PV}/dI_{PV} at open circuit can be extracted. However, there are some datasheets that do not give any output curves. Thus, Eq. (6) can not be applied for these modules. Alternatively, the value of R_s can be estimated, for these modules, from Eq. (7) instead.

$$R_s = -\frac{nKN_sT_{ref}}{qI_o} e^{\frac{-qV_{ocs}}{nN_sKT_{ref}}} - \frac{dV_{PV}}{dI_{PV}}\bigg|_{V_{oc}} \tag{6}$$

$$R_s = \frac{nKT_{ref}N_s}{qI_{mps}} \ln\left(\frac{I_{scs} - I_{mps} + I_o}{I_o}\right) - \frac{V_{mps}}{I_{mps}} \tag{7}$$

Noting, here, that Eq. (7) can be derived from Eq. (1), by applying the MPP condition and rearranging the resulted terms.

In this work, an average initial value for R_s (i.e., $R_{s,initial}$) can be estimated, by using each of Eq. (6) & Eq. (7), for the considered PV module, which is $R_{s,initial} = .0201\ \Omega$.

The series resistance impacts the shape of the I-V curve near the MPP and speacially near the open-circuit condition. This effect is seen in Fig. 4, in which the I–V curves for the considered PV module at STC have been plotted for different series resistance values that are greater and lower than the determined average initial value.

Equation (8) determines the minimum value of R_{sh} (i. e., $R_{sh,min}$) [1], which is the slope of the line segment between the short-circuit and the maximum-power remarkable points. Although the actual value of R_{sh} is still unknown, it surely is greater than $R_{sh,min}$ and this is a good initial guess. Therefore, by using Eq. (8) the value of $R_{sh,min}$ can be estimated for the considered PV module to be $R_{sh,min} = 42\ \Omega$.

$$R_{sh,min} = \frac{V_{mp}}{I_{scs} - I_{mp}} - \frac{V_{ocs} - V_{mp}}{I_{mp}} \tag{8}$$

The shunt resistance R_{sh} controls the slope of the I–V curve at the short-circuit condition, such that large shunt resistances result in a horizontal slope. Figure 5 shows the

effect of halving and doubling the shunt resistance for considered PV module at STC.

Table 2 summarizes all the previously estimated and initial parameters of the considered PV module at STC.
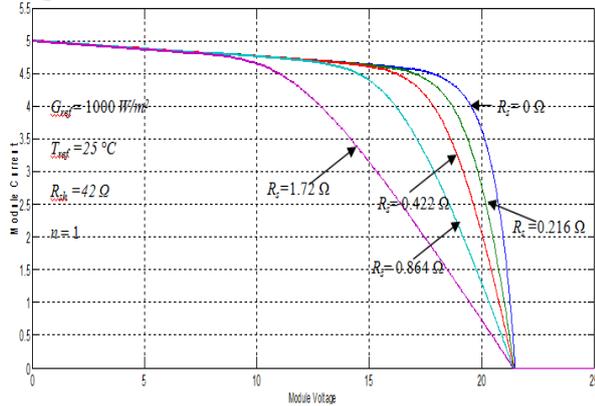

Fig.4. Effect of series resistance variation on the considered module's I-V characteristic at STC.
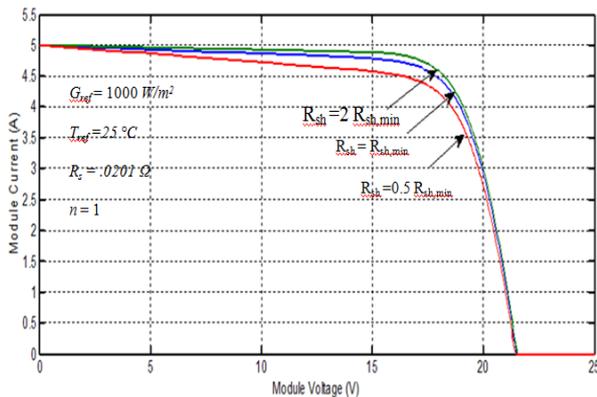

Fig.5. Effect of shunt resistance variation on the considered module's I-V characteristic at STC.

Table 2: Estimated and initial parameters of the LORENTZ LC80-12M PV module at STC.

Parameter	Value
I_{ph}	5A
I_o	1.762×10^{-8} A
$n_{initial}$	1
$R_{s,initial}$	0.0201 Ω
$R_{sh,min}$	42 Ω

III. THE PROPOSED ITERATIVE METHOD

The flowchart of the proposed iterative method that is designed to estimate the actual parameters of the considered PV module is illustrated in Fig. 6. In this work, this flow chart is implemented by writing the corresponding suitable Matlab code in an M-file.

This flowchart starts with reading the estimated and initial parameters of the considered PV module at STC. The main idea behind this flowchart is to use the iterative approach to determine the actual parameters (i.e., I_{os}, n, R_s ,and R_{sh}) of the considered PV module at the end of this

flowchart. In every iteration, the flowchart calculates the maximum power (P_{max}) and the fill-factor ($F.F$) of the considered module that correspond to the current values of the considered module's parameters. Noting, here, that P_{max} can be determined from Eq. (1) by rearranging its tearms to become in the form $V_{pv}= f(I_{pv})$. Also, the value of the PV power (P_{PV}) can be obtain from $P_{Pv} = I_{PV} \times f(I_{pv})$. Thus, the value of Imp can be obtained by solving the equation $dP_{PV}/dI_{PV} = 0$, using the Newton-Raphson method. Then, the value of V_{mp} can be obtained by substituting $I_{PV} = I_{mp}$ in Eq. (1). Consequently, the maximum power of the module is calculated from $P_{max} = I_{mp} \times V_{mp}$. In addition, the value of the module's fill-factor can be determined from $F.F = P_{max}/(V_{oc} \times I_{sc})$.
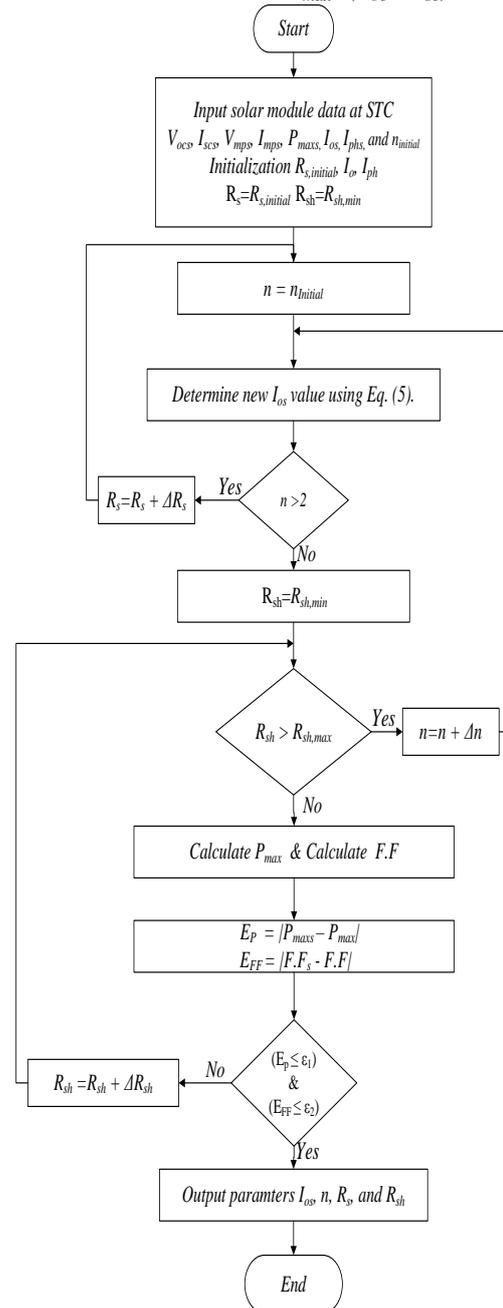

Fig.6. Flowchart of the PV parameters estimation.

Thus, starting from the estimated initial values of the considered PV module (i.e. I_{phs}, I_{os}, $n_{initial}$, $R_{s,initial}$, $R_{sh,min}$), the required actual values can be reached, through incriminting the module's required parameters successively, when the condition ($E_p \leq \varepsilon_1$) & ($E_{FF} \leq \varepsilon_2$) is satisfied. Where, E_p and E_{FF} are the absolute power and fill-factor errors, respectively. Also, ε_1 and ε_2 are the corresponding pre-adjusted error values.

IV. SIMULATION OF THE PV MODULE

The actual estimated parameters resulted from the proposed iterative method, that are shown in table 3, are used to modify the I-V equations of the considered PV module. Then, the actual developed model of the considered PV module is simulated by using Matlab/Simulink.

Figure 7 shows a plot of the simulated and datasheet I-V characteristics of the considered PV module at different insolation levels. Thus, it is indicated, from this figure, that developed PV module can accurately follow the actual I-V characteristics given in datasheet at different insolations.

The temperature dependencies of the model's I-V curve have been verified, also, by plotting the characteristics for three different temperatures, as shown in Fig. 8.

Table 3: Actual estimated parameters of the LORENTZ LC80-12M PV module at STC.

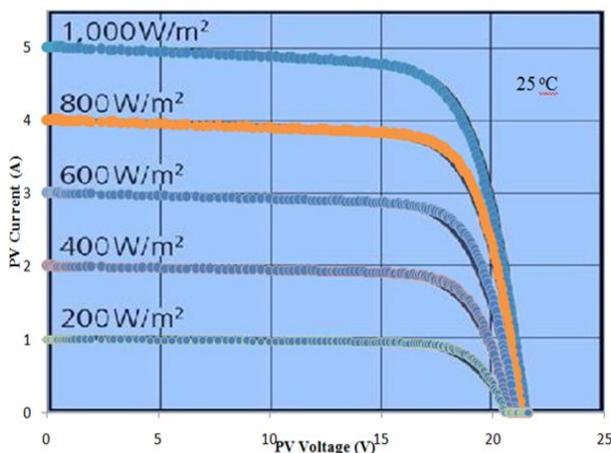| Parameter	Value
I_{phs}	5 A
I_{os}	3.838×10^{-8} A
n	1.25
R_s	0.216 Ω
R_{sh}	66.8 Ω

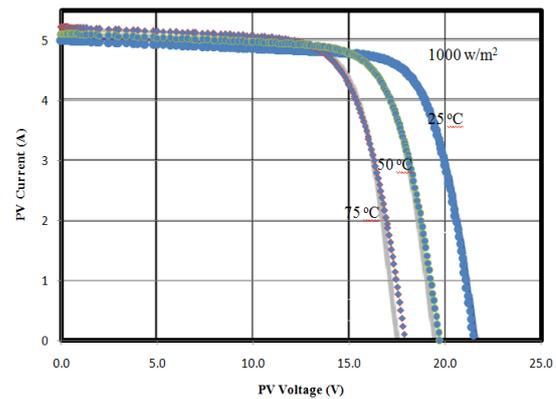Fig.7. Simulated and datasheet I-V characteristics at different insolation levels.

Fig.8. Simulated and datasheet I-V characteristics at different temperatures.

V. CONCLUSION

A proposed iterative method is developed to estimate the actual parameters for the considered PV module. This method uses the estimated and initial PV parameters developed from the manufacture's datasheet as inputs with the aim of arriving at the actual values of these parameters at end of the developed iterative method. The proposed iterative method is implemented in this work by writing the appropriate Matlab code in an M-file. The actual developed model of the considered PV module, using the resulted PV parameters, is simulated by using Matlab/Simulink. Simulation results show the high accuracy and validity of the simulated PV module compared to its datasheet characteristics at all insolation levels and cell temperatures.

REFERENCES

[1] Marcelo G. Villalva, Jonas R. Gazoli, and Ernesto R. Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays ", IEEE Transactions on Power Electronics, Vol. 24, No. 5, MAY 2009.

[2] Nalika N.B. Ulapane, Chamari H. Dhanapala, Shyama M. Wickramasinghe, Sunil G. beyratne, Nimal Rathnayake, and Prabath J. Binduhewa, "Extraction of Parameters for Simulating Photovoltaic Panels", 6th International Conference on Industrial and Information Systems, ICIIS, pp. 539-544, 2011.

[3] W. De Soto, S.A. Klein, W.A. Beckman, "Improvement and Validation of a Model for Photovoltaic Module Performance", Solar Energy, Vol. 80, pp. 78-88, 2006.

[4] Mohammad Hejri, Hossein Mokhtari, Mohammad R. Azizian, Mehrdad Ghandhari, and Lennart Soder, "On the Parameter Extraction of a Five-Parameter Double-Diode Model of Photovoltaic Cells and Modules", IEEE Journal of Photovoltaics, Vol. 4, No. 3, pp. 915-923, May 2014.

[5] K. Nishioka, N. Sakitani, Y. Uraoka, and T. Fuyuki, "Analysis of Multicrystalline Silicon Solar Cells by Modified 3-Diode Equivalent Circuit Model Taking Leakage Current Through Periphery into Consideration," Solar Energy Materials and Solar Cells, Vol. 91, No. 13, pp. 1222–1227, 2007.

[6] D. Sera, R. Teodorescu, and P. Rodriguez, "PV Panel Model Based on Datasheet Values," in IEEE International Symposium on Industrial Electronics, pp. 2392–2396, 2007.

[7] Yuncong Jiang, Jaber A. Abu Qahouq, and I. Batarseh, "Improved Solar PV Cell Matlab Simulation Model and Comparison", Circuits and Systems (ISCAS), Proceedings of 2010 IEEE International Symposium on, pp. 2770-2773, 2010.