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A Novel Method to Extract Single-Diode PV Parameters Based on Datasheet Values

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Very few manufacturers that are providing a wide range of graphical data necessary to use high-performance predictive tools for PV systems. On the other hand, reliable graphical data require precise laboratory measurements that increase manufacturing costs. Furthermore, most of the methods used to determine photovoltaic performance require iterative techniques, additional mandatory information and users with a certain level of knowledge. For this reason, PV system designers have to choose between the use of cheap PV modules, lacking in technical data, and the reliable energy predictions that are possible only if the current–voltage characteristics are provided by the PV module manufacturers. This paper presents a novel method to extract the single diode five parameters model for different manufacturer's modules using the minimum set of technical data that are usually provided by all manufacturers. The proposed procedure uses an accurate and easy method that does not require iterative techniques, other obligatory information or users with special knowledge but only datasheet values from a technical catalog of photovoltaic modules to simulate photovoltaic performance. The method uses an empirical relationship that enables to calculate the initial values of series and shunt resistances and extracts the parameters of the model from datasheet values provided by manufacturers only. The capability of the proposed model to calculate the current–voltage characteristics was tested by comparing the results with data measured by different manufacturers' panel models (mono-crystalline and poly-crystalline) silicon modules. The method was also compared with other similar methods. The results of the new model application confirm the reliability of the procedure.

Key words: *PV systems, method of determination of photovoltaic modules characteristics, one-diode photocell model, current-voltage characteristics, photocell model testing, datasheet*

Nowadays a photovoltaic market is growing at a very fast rate and it is possible to buy any PV module for every user. Photovoltaic users could be grouped as researchers, designers of PV systems and smaller users [1]. The demands of these users show a wide spectrum. For example, researchers need accurate results, PV designers ask for short- term optimization of the PV system, while small- scale users want a feasible and simple method to achieve PV performance [2]. Although all existing methods are precise and suitable for obtaining and evaluating model parameters and thus PV performance, to use them, users with specific knowledge are needed. The main outcomes of the existing methods could be summarized below in an unexhaustive manner. It is impossible to measure the I-V curve for every user, especially small ones [3]. The model parameters are calculated by using difficult mathematical calculations [4] or iterative techniques [5] in some methods. Furthermore, some of these methods require programming software like MATLAB, Mathematica, or special equation solvers [6]. The sales price of software is quite high for PV designers and small users. Consequently, not only PV designers and small users but also researchers are unable to use existing methods. Therefore, methods based solely on datasheet values are more attractive for small- scale users and PV designers, and even for researchers, because they are easy to calculate PV performance. There are numerous methods to extract panel parameters. Among various mathematical models of the PV module proposed in the literature, there is a very simple method to determine photovoltaic performance using data sheet values [7]. Since parasite resistances have been neglected, the simulation accuracy of this method in different operating conditions is very low. Another method based on datasheet values is suggested in [8]. Instead of using a premeasured or digitized I-V curve, a simplified method was proposed. Two nonlinear equations are solved to obtain the parameters of a PV system. A new procedure was reported based on datasheet values [9]. The diode ideality factor (A) is taken as a constant to reduce the number of equations.

In this paper, a model for a PV panel is constructed using a single- diode five- parameters model based solely on datasheet parameters. The proposed method is precise and easy to use requires no iterative techniques, no additional mandatory information, and no users with special knowledge, but only data sheet values in the technical catalog of photovoltaic modules to simulate photovoltaic performance. Also, the method enables to calculate the PV system parameters without using the experimental I-V curve.

Single diode model of PV cell. Mathematical descriptions of the I-V characteristics of PV cells are available for many years and are derived from the physics of the p-n semiconductor junction. A crystalline solar cell is a large-area silicon diode. In the dark state, the I-V characteristic curve of this diode corresponds to the one of a normal p-n junction diode and it produces neither a voltage nor a current. Illumination of the PV cell creates free charge carriers which let current flow through a connected load. The so-called photocurrent I_{ph} is proportional to irradiance [8].

If the circuit is open the photocurrent is shunted internally by the *p-n* junction diode. The simplest equivalent circuit of a PV cell as shown in Fig.1, is a current source which intensity is proportional to the incident radiation, in parallel with a diode *D* and a shunt resistance R_{sh}. This resistance is the leakage current to the ground. The internal losses due to current flow and the connection between cells are modeled as a small series resistance R_s [8].

A PV panel based on the single diode model has a general current voltage characteristic:

$$I = I_{ph} - I_0\left(e^{\frac{V+IR_s}{n_s V_t}} - 1\right) - \frac{V + IR_s}{R_{sh}}. \tag{1}$$

In the above equation, V_t is the thermal junction voltage:

$$V_t = \frac{AKT}{q}. \tag{2}$$

The equation (1) can be written for three V-I key points: short circuit point, the maximum power point and the open circuit point.

$$I_{sc} = I_{ph} - I_0 e^{\frac{I_{sc}R_s}{n_s V_t}} - \frac{I_{sc}R_s}{R_{sh}}; \tag{3}$$

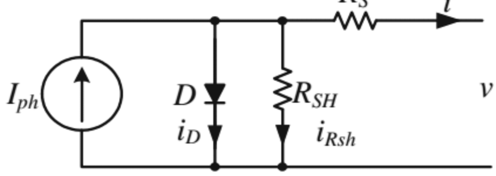

Fig. 1. Equivalent circuit of a PV cell using the single diode model

$$I_{mpp} = I_{ph} - I_0 e^{\frac{V_{mpp}+I_{mpp}R_s}{n_s V_t}} - \frac{V_{mpp} + I_{mpp}R_s}{R_{sh}}; \tag{4}$$

$$I_{oc} = 0 = I_{ph} - I_0 e^{\frac{V_{oc}}{n_s V_t}} - \frac{V_{oc}}{R_{sh}}. \tag{5}$$

The photo- generated current I_{ph} and the dark saturation current I_0 can be expressed from the formula of the open circuit and short circuit conditions:

$$I_{ph} = I_0 e^{\frac{V_{oc}}{n_s V_t}} + \frac{V_{oc}}{R_{sh}}. \tag{6}$$

By inserting Eq. (6) into Eq. (3), it takes the form:

$$I_{sc} = I_0\left(e^{\frac{V_{oc}}{n_s V_t}} - e^{\frac{I_{sc}R_s}{n_s V_t}}\right) + \frac{V_{oc} - I_{sc}R_s}{R_{sh}}. \tag{7}$$

The second term in the parenthesis of the above equation can be omitted, because it is small compared to the first term. Then Eq. (7) becomes:

$$I_{sc} = I_0 e^{\frac{V_{oc}}{n_s V_t}} + \frac{V_{oc} - I_{sc}R_s}{R_{sh}}. \tag{8}$$

The solution of the above equation for I_0, results in:

$$I_0 = \left(I_{sc} - \frac{V_{oc} - I_{sc}R_s}{R_{sh}}\right) e^{-\frac{V_{oc}}{n_s V_t}}. \tag{9}$$

From the equation (4):

$$R_{sh} = \frac{V_{mpp} + I_{mpp}R_s}{I_{mpp} - I_{ph} + I_0 e^{\frac{V_{mpp}+I_{mpp}R_s}{n_s V_t}}}. \tag{10}$$

Supposing that the derivative of the maximum power is zero [8]:

$$\frac{dp}{dV} = 0 = I + \frac{\partial t}{\partial V}V; \tag{11}$$

$$A=\frac{q(2V_{mpp}-V_{oc})}{n_s KT\left(\frac{I_{sc}}{I_{sc}-I_{mpp}}+\ln\left(1-\frac{I_{mpp}}{I_{sc}}\right)\right)}. \qquad (12)$$

The last parameter to be determined is the series resistance R_s [9]:

$$R_s=R_{sc}=-\frac{1}{\frac{q}{AKT}I_0 e^{\frac{V_{oc}}{n_s V_t}}}. \qquad (13)$$

A. Initial Estimation of PV Parameters

From the equations (6)–(12) it is clear that exact determination of the initial value of reference series (R_{s0}) is essential to calculate the reference single diode model parameters; R_s, R_{sh}, and I_0. Therefore, the more precise determination of the R_{sc} is, the more precise parameters of the model are. On the other hand, the initial value of reference shunt resistance (R_{sh0}) which is to initiate the calculation of model parameters in the equations (6,9) with assumptions of $R_{sh}=R_{sh0}$ and $R_s=R_{sc}$. The expression to estimate the R_{sh0} value is given below [9].

$$R_{sh0}=\frac{V_{mpp}}{I_{sc}-I_{mpp}}. \qquad (14)$$

The R_{sc} could be correlated directly with the few datasheet values of V_{oc}, V_{mpp} and I_{mpp} as:

$$R_{sc}=\frac{V_{oc}-V_{mpp}}{2I_{mpp}}. \qquad (15)$$

B. Extraction of PV parameters under variable radiation and temperature conditions

The previous section deals with the parameter determination of solar panels at the standard test condition ($G_{ref}=1000$ W/m^2, $T_{ref}=25$ °C, spectrum AM1.5). Therefore, the following equation is used to extract the variation of all the parameters of the single-diode model with respect to the change in radiation and temperature.

$$I_{sc}(G,T)=I_{sc.ref}\frac{G}{G_{ref}}+K_i(T-T_{ref}); \qquad (16)$$

$$V_{oc}(G,T)=I_{sc.ref}\frac{V_{oc.ref}}{1+\alpha\ln\left(\frac{G_{ref}}{G}\right)}+K_p(T-T_{ref}). \qquad (17)$$

The parameter (α) can be determined as follows [10]:

$$\alpha=\frac{1}{\ln\left(\frac{G_{ref}}{G}\right)}\left(\frac{\sum_{n=1}^{n}Vc(G_{ref})_n}{\sum_{n=1}^{n}Vc(G)_n}-1\right); \qquad (18)$$

$$R_{sh}(G)=R_{sh.ref}\frac{G_{ref}}{G}; \qquad (19)$$

$$A(G,T)=A_{ref}\frac{T}{T_{ref}}; \qquad (20)$$

$$I_{ph}(G,T)=\left(\frac{R_s(G,T)+R_{sh}(G)}{R_{sh}(G)}\right)I_{sc}(G,T); \qquad (21)$$

$$I_0(G,T)=\frac{\left(I_{sc}(G,T)-\frac{V_{oc}(G,T)-I_{sc}(G,T)R_s(G,T)}{R_{sh}(G)}\right)}{e^{\frac{qV_{oc}(G,T)}{n_s AK}}}; \qquad (22)$$

$$R_s(G,T)=R_{s.ref}\frac{T}{T_{ref}}\left(1-0{,}217\ln\left(\frac{G_{ref}}{G}\right)\right). \qquad (23)$$

Results and discussion. The previous section describes the construction of a PV panel model. This model has been implemented in MATLAB, to be verified in different temperature and irradiance conditions. It can be seen that calculated (I-V) curves at different conditions are in good agreement with the experimental data for different models SP75 (monocrystalline) solar module and KC200GT (poly-crystalline) solar module, their datasheet values are listed in Table 1.

Table 1

Shows the data obtained from the datasheet for KC200GT solar module sand SP75 solar module at 25 °C, AM1.5, and 1000 W/m^2

Parameter	KC200GT solar module	SP75 solar module
Max. Power (Pmpp)	200 W	75 W
Max. Power Voltage (Vmpp)	26.3 V	17 V
Max. Power Current (Impp)	7.61 A	4.4 A
Open Circuit Voltage (Voc)	32.9 V	21.7 V
Short Circuit Current (Isc)	8.21 A	4.8 A
Temperature Coeff. of Voc(Kv)	- 0.123V/C	- 76 mV/C
Temperature Coeff. of Isc(Ki)	+ 3.18 mA/C	+ 2 mA/C
Number of cells (ns)	54	36

The results have been compared to the characteristics and values provided by the product data sheet. The temperature dependencies of the model's V-I curve have been verified by plotting the characteristics for three different temperatures.

The Fig. 2, 3 show that the short-circuit current and the open-circuit voltage are in very good agreement with the data-sheet values for SP75 (monocrystalline silicon) solar module and KC200GT (multi-crystal silicon) solar module. The change in the open-circuit voltage and short-circuit current are in accordance with the temperature coefficients given in the datasheet.

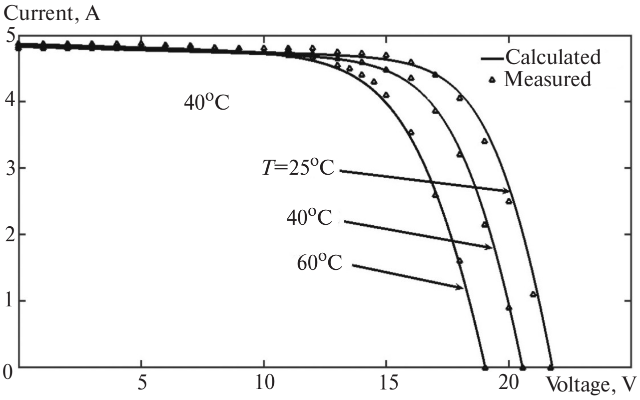

Fig. 2. Voltage-Current characteristics of the shell SP75 model (monocrystalline silicon) at three different temperatures and standard irradiation

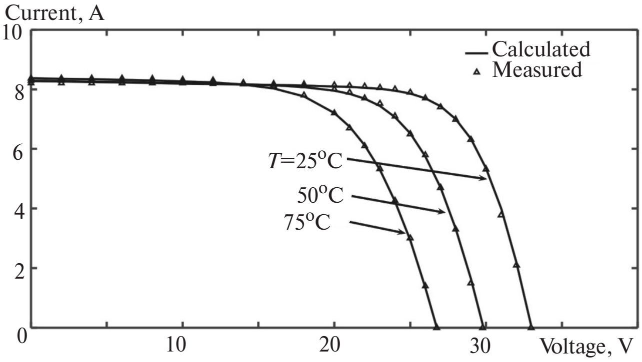

Fig. 3. Voltage-Current characteristics of the KC200GT model (multi-crystal) at three different temperatures and standard irradiation

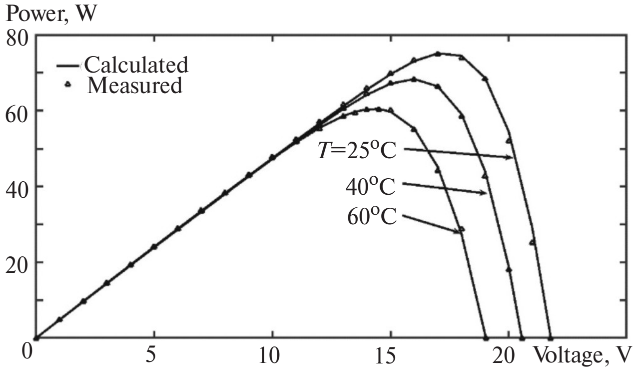

Fig. 4. Voltage-Power characteristics of the shell SP75 model (monocrystalline silicon) at three different temperatures and standard irradiation

The calculated and experimental variations of power with voltage for the shell SP75 model and the KC200GT model, at three different temperatures and standard irradiation, are illustrated in Fig. 4, 5.

Fig. 4, 5 provide a clear view of how the curves vary with temperature. There is a significant reduction in the power output of the photovoltaic system as cell temperature increases. Also, the calculated (*P-V*) curves at different temperatures are in good agreement with the experimental data for different models (SP75 and KC200GT).

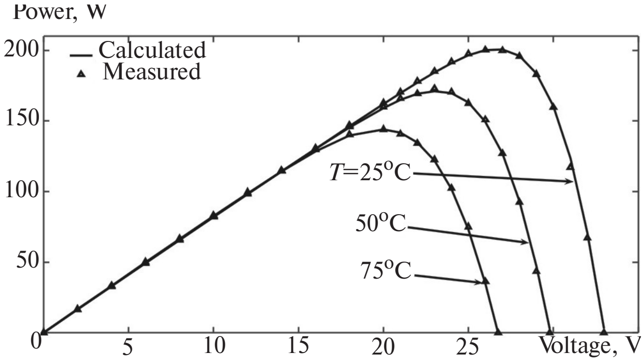

Fig. 5. Voltage-Power characteristics of the KC200GT model (multi-crystal silicon) at three different temperatures and standard irradiation

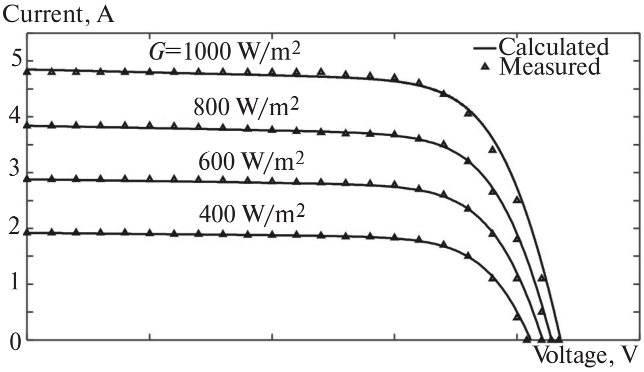

Fig. 6. Voltage-Current characteristics of the shell SP75 model (monocrystalline silicon) at different irradiation and standard temperature

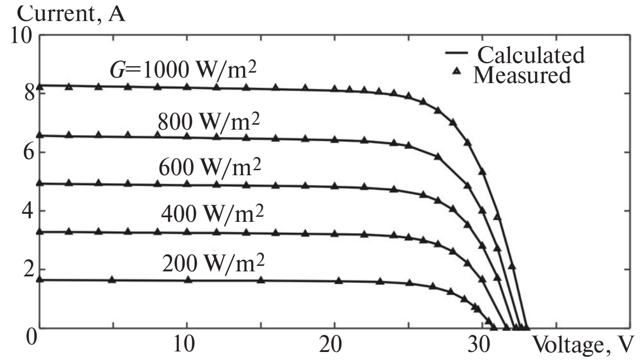

Fig. 7. Voltage-Current characteristics of the KC200GT model (multi-crystal) at different irradiation and standard temperature

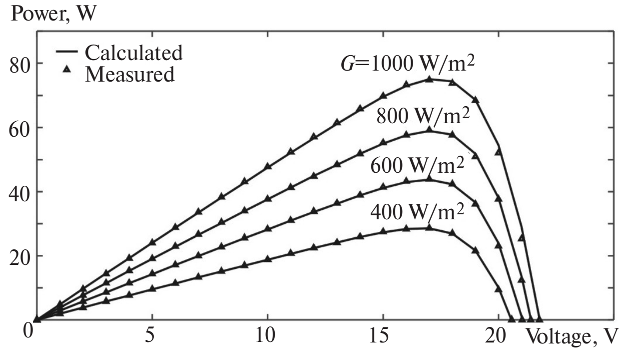

Fig. 8. Voltage-Power characteristics of the shell SP75 model (monocrystalline silicon) at different irradiation and standard temperature

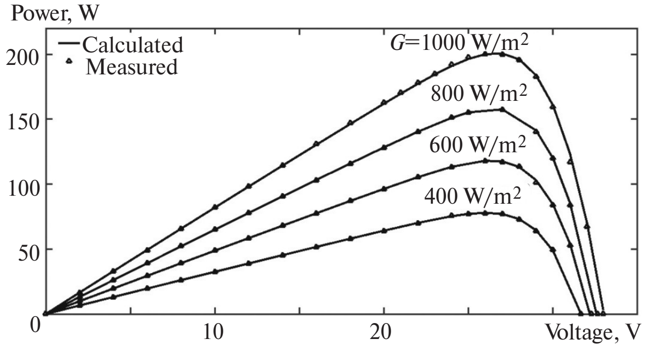

Fig. 9. Voltage-Power characteristics of the KC200GT model (multi-crystal) at different irradiation and standard temperature

To show the effect of irradiance on the performance of a module the temperature is kept fixed at 25 °C, and the values of irradiance are changed. The variation of the current-voltage characteristics with irradiance is shown in Fig. 6, 7.

From the Fig. 6, 7 it can be noted that, according to the theory, the short circuit current shows a linear dependence with the irradiation, unlike the open-circuit voltage, which increases logarithmically with the irradiation. Fig. 6, 7 show that the calculated (I-V) curves at different irradiation are in good agreement with the experimental data for different models (SP75 and KC200GT). In the same way, Fig. 8, 9 show the comparison between the calculated P-V characteristic and the experimental characteristic. Also, the calculated (*P-V*) curves at different irradiation are in good agreement with the experimental data for different models (SP75 and KC200GT).

To evaluate the accuracy of the proposed model, the corresponding normalized root mean square error percentage [*NRMSE* (%)] is calculated at different conditions. the corresponding normalized root mean square error percentage [*NRMSE* (%)] is calculated by:

$$NRMSE(\%)=\frac{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(E_i-M_i)}}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}M_i^2}}, \qquad (24)$$

where N is the number of measurements; E_i is the calculated value; M_i is the measured data.

Table 2 shows the corresponding percentage of normalized root mean square error [*NRMSE* (%)] for the parametrization method proposed in this study, the method in [4] and the curve- fitting method calculated by [6].

Table 2

Evaluated *NRMSE* for KC200GT at different environmental conditions

G, W/m^2	T, °C	This method *NRMSE*, %	Method in [4] *NRMSE*, %	Method in [6] *NRMSE*, %
1000	25	0,68	7,00	0,86
1000	50	0,73	3,74	1,59
1000	75	0,64	2,09	1,51
800	25	0,65	5,43	0,68
600	25	0,88	9,80	1,23
400	25	0,42	9,59	2,17
200	25	0,65	24,50	2,41

Conclusion. A photovoltaic panel model has been developed and implemented exclusively using datasheet values. The method is easy to apply, i.e. it doesn't require iterative techniques, additional mandatory information or users with a specific level of knowledge are required. Furthermore, the calculated (I-V) curves based on the proposed model are in good agreement with the experimental data for various environmental effects (temperature and irradiance). The main contribution of the method is to allow to simulate the PV performance by using only datasheet values in a simpler and more accurate manner. Thus, it can be utilized as a useful estimating tool especially for PV designers and small-scale users, even researchers, under different outdoor conditions because it has significant advantages in the simulation of PV performance.

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Новый метод определения параметров однодиодной модели фотоэлемента на основе табличных данных

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Немногие производители фотоэлектрических модулей предоставляют достаточный набор графических зависимостей, необходимый при прогнозировании и оптимизации работы фотоэлектрических систем. Получение вольт-амперных характеристик требует точных лабораторных измерений, что ведет к увеличению производственных затрат. Кроме того, большинство методов определения характеристик фотоэлектрических модулей требует итерационных подходов, нуждается в дополнительной информации и может эффективно использоваться лишь специалистами высокого уровня. По этой причине разработчикам фотоэлектрических систем приходится выбирать между использованием дешевых фотоэлектрических модулей без достаточного набора технических данных и надежным прогнозированием режимов работы модулей, возможным в случае предоставления их производителями вольт-амперных характеристик. В статье рассмотрен новый метод определения характеристик (параметров) 5-параметрической однодиодной модели фотоэлемента для модулей различных производителей. Параметры определяются минимальным набором технических данных, обычно предоставляемых всеми производителями. Предлагаемая процедура использует точный и простой метод, не требует итерационных подходов, дополнительной информации и высокой квалификации пользователей. Метод использует эмпирическую зависимость, позволяющую рассчитывать начальные значения последовательного и шунтирующего сопротивлений и определяет параметры однодиодной модели, используя информацию, предоставленную производителями. Способность разработанной модели воспроизводить вольт-амперные характеристики фотоэлементов была проверена путем сравнения результатов предложенного метода с данными измерений на фотопанелях с кремниевыми модулями (монокристаллическими и поликристаллическими) различных производителей. Метод также сравнивался с другими аналогичными методами. Результаты исследований подтверждают надежность предложенного подхода.

Ключевые слова: *фотоэлектрические системы, метод определения характеристик фотоэлектрических модулей, однодиодная модели фотоэлемента, вольт-амперные характеристики, тестирование моделей фотоэлементов, табличные данные*