A Simple Parameter Estimation Approach to modeling of Photovoltaic Modules Based on Datasheet Values

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This work presents a simple parameter estimation approach for a photovoltaic (PV) module using a single-diode five-parameters electrical model. The proposed approach only uses the information from manufacturer datasheet without requiring a specific experimental procedure or a curve extractor. The number of parameters to be determined is first reduced from five to two by gaining insight to electrical equations of the model at the standard test conditions (STC). A nonlinear least square objective function is then constructed and minimized by a complete scan for all possible values of the two parameters within some specific ranges based on their physical meaning. Consequently, the single-diode five-parameters electrical model at the STC is determined based on two optimal parameter values. Besides, a PV full characteristic model with consideration of both the irradiance and temperature dependencies is also constructed by using the data at the nominal operating cell temperature (NOCT) test conditions. The proposed approach is easy to implement and free of the convergence problem. The evaluations on several PV modules show that the proposed approach is capable of extracting accurate estimates of the model parameters.

Keyword: PV module, parameter estimation, equivalent circuit, modeling

1 Introduction

Both the study of the dynamic analysis of converters from solar energy to electric energy and the study of tracking the maximum power point (MPP) call for an electrical model of photovoltaic (PV) modules. However, nonlinear I-V characteristics of the PV modules hinder the construction of the model. In addition, these characteristics are further changed under various temperatures and irradiance conditions. There-

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fore, extensive efforts have been devoted to improve the accuracy and computational efficiency of modeling and simulation of PV modules.

Until now, current lumped electrical models can generally be classified into two types: the single-diode model and double-diode model [1]. Although the double-diode model has been shown to have a very high accuracy in multicrystalline silicon cells by incorporating a separate current component with its own exponential voltage dependence, it is computationally expensive. Instead, the single-diode model is the most studied in the literature due to its reasonable balance between simplicity and accuracy [2], which is governed by five parameters: dark saturation current (I_0), photoelectric current (I_{ph}), series resistance (R_s), parallel resistance (R_p), and ideality factor (A). For simplicity, this paper focuses on the single-diode model shown in Fig.1.

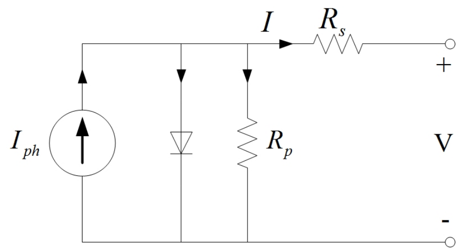

Fig.1. The equivalent circuit of the photovoltaic module

Manufacturers' datasheets generally bring information about the characteristics and performance of PV modules with respect to the standard test condition (STC), which means an irradiance of $1000W/m^2$ with an $AM1.5$ spectrum at 25^oC [2]. The information for the STC generally includes open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), MPP voltage (V_{mpp}), MPP current (I_{mpp}) and maximum power (P_{mpp}). Unfortunately, the parameters of the electrical model are not included in the datasheets. Therefore, the task of identifying the single-diode model is to extract the five unknown module parameters from the information presented in the datasheets.

There are numerous approaches to extracting parameters based on the datasheets or experimental data. It is not intended to be a comprehensive literature review on identifying the PV module model. Since value of R_p is generally high and the value of the R_s is generally low, the ideal single-diode model eliminating the series and parallel resistance was chosen in [2] due to its simplicity and an analytical solving procedure without parameters coupling. However, an accurate I-V characteristics at the MPP cannot be guaranteed. Thus, in [3], Xiao el al. provided a simplified PV-cell model and a parameter extracting approach guaranteeing that the I-V characteristic curves pass through the remarkable points given in the datasheets. Furthermore, in [4], Mahmoud proposed a simple and easy-to-model approach avoiding the use of a nonlinear solver. The primary problem for Xiao's approach and Mahmoud's approach is that they neglect the influence of R_s or R_p. Nonlinear least-square (NLS) approach based on trust-region algorithm was proposed in [5] to extract the unknown five parameters. In general, the approach is easy to get stuck in a local minimum. An improved coefficient calculator for the California Energy Commission PV module was presented in [6]. Some heuristic methods were also adopted to improve the success rate of the coefficient calculator. In [7], Dezso sera et al. presented the construction of a model for PV modules using the single-diode five-parameters model based exclusively on datasheet values. Some numerical methods such as Newton Raphson (NR) or bisection method, were used to estimate three unknown parameters R_s, R_p, and A in three different equations. The two other parameters were obtained analytically using the obtained three parameters. However, the numerical methods are highly sensitive to the initial values, which are not presented in the reference. Therefore, in [8], Can and Ickilli addressed the concerns about appropriate initial values for the convergent numerical solutions. However, a strict condition still limits the use of the NR method that the initial values should be very close to real values. In [9], a fast and accurate method for obtaining the five parameters was proposed by using the experimental I-V curve of the PV module. The five parameters are split in independent and dependent unknowns to reduce the dimensions of NLS problems. Furthermore, in [10], Silva et al. presented a comprehensive review of the aforementioned approaches and proposed an approach trying to overcome the limitations of some popular approaches in the technical literature. Because the parameters of the single-diode model have physical meaning and their values generally fall in some specific ranges, the approach scans all possible values of A and R_s and chooses the best of parameters based on the lowest value of the mean absolute error in power calculated between the curve generated by the electrical model and the curve extracted from the datasheet at the STC. Nevertheless, this approach relies on assumption that the photoelectric current I_{ph} is equivalent to the dark saturation current I_0 at the STC. Moreover, this approach requires many specific voltage points to estimate accurately the extracted power, which may not be numerically available to the datasheets. Therefore, this approach uses a curve extractor algorithm developed in MATLAB to extract datasheet curves, which is sometimes inconvenient. Besides, soft computing methods such as particle swarm optimization and bacterial foraging algorithm in [11] and [12], can also be employed if identifying the parameters of PV modules is viewed as a nonlinear constrained optimization problem. Recently, the lighting search algorithm, as a novel nature-inspired optimization method, has been developed to extract the parameters for a PV module in [13]. However, as pointed out by [14], the soft computing methods that nature is inherently probabilistic fail to provide adequate information regarding the consistency of the soft computing solutions. For a comprehensive survey on parameter extraction of PV module electrical model and its recent advances, please refer to [14],[15] and [16].

In this paper, a simple approach for PV modeling is proposed that minimizes a NLS objective function by a complete scan of two parameters instead of using any nonlinear numerical solvers. The objective function is based on three equations: the current equation at the MPP, the derivative equation of power with voltage at the MPP, and the derivation equation of current with voltage at the short circuit point. This approach relies on the electrical relationship of the single-diode model that the parameters I_0, I_{ph} and R_p can be expressed as the functions of the parameters of R_s and A. Because the optimal values are obtained using the simple scan of the parameters of R_s and A with reasonable step sizes, the convergence problem can be avoided. Moreover, only the values explicitly obtained from the datasheets are required for the proposed approach. Compared with the approach given in [10], the proposed approach is more convenient and easier to implement.

Recently, along with the rising of test standard conditions for the PV modules, many advanced PV module manufacturers also provide the electrical data with respect to nominal operating cell temperature (NOCT) test condition, which means an irradiance of $800W/m^2$, an ambient temperature of 20^oC, and a wind speed of $1m/s$. These data can reflect performance of PV modules at higher temperature and at somewhat lower insolation conditions. In this study, these data are utilized to construct a PV full characteristic model considering both the irradiance and temperature dependencies.

This paper is organized as follows. A parameter estimation approach using datasheet values at the STC is proposed in the next section. Then, a PV full characteristic model using datasheet values at NOCT test conditions is constructed. Afterwards, some numerical experiments will be provided. Finally, a conclusion will finish the paper.

2 Proposed Parameter Estimation Approach by Using Datasheet Values at STC

2.1 Equivalent Electrical Model of a PV Module.

The widely-used single-diode model of a PV module can be typically be represented by a current source in parallel with one diode, as shown in Fig.1. The current-voltage relationship is formulated by:

$$I = I_{ph} - I_0(e^{\frac{V+R_sI}{N_sV_tA}} - 1) - \frac{V+R_sI}{R_p} \tag{1}$$

In the above equation, V_t is the junction thermal voltage

$$V_t = \frac{k \cdot T_{STC}}{q} \tag{2}$$

where q is the electron charge ($1.60217646 \times 10^{-19}C$), k is the Boltzmann constant ($1.3806503 \times 10^{-23}J/K$), T_{STC} (in Kelvin) is the temperature of the $p-n$ junction at the STC, and N_s is the number of cells in the PV module connected in series. Since the dark saturation current I_0 whose magnitude scale is generally less than $10^{-5}(A)$ is much smaller than the photoelectric current I_{ph} ($> 1(A)$), the term '-1' in Eq.(1) is negligible.

Three remarkable current-voltage points at the STC are always provided in the datasheet: short circuit (I_{sc},0), MPP (I_{mpp},V_{mpp}), and open circuit (0,V_{oc}). As an example, Table 1 shows the datasheet values at the STC from the module TSM-PD05.05(250W), a 60 cell multi-crystalline PV module from Trinasolar.

TABLE 1. Summary of Electrical Measurements at the STC for the Module TSM-PD05.05(250W)

Electrical Measurements (STC)	Values
Peak Power Watts-P_{MAX}(W)	250
Maximum Power Voltage-V_{mpp}(V)	30.3
Maximum Power Current-I_{mpp}(A)	8.27
Open Circuit Voltage-V_{oc}(V)	38.0
Sort Circuit Current-I_{sc}(A)	8.79

For the above-mentioned values of the remarkable points, there are three electrical equations to describe the I-V characteristics for the single-diode model as following. At the short circuit points, $V=0$, $I=I_{sc}$, gives

$$I_{sc} = I_{ph} - I_0(e^{\frac{I_{sc}R_s}{N_sV_tA}}) - \frac{I_{sc}R_s}{R_p} \tag{3}$$

At the open circuit point, $V=V_{oc}$, $I=0$, gives

$$I_{oc} = 0 = I_{ph} - I_0(e^{\frac{V_{oc}}{N_sV_tA}}) - \frac{V_{oc}}{R_p} \tag{4}$$

At the MPP, $V=V_{mpp}$, $I=I_{mpp}$, we have

$$I_{mpp} = I_{ph} - I_0(e^{\frac{V_{mpp}+I_{mpp}R_s}{N_sV_tA}}) - \frac{V_{mpp}+I_{mpp}R_s}{R_p} \tag{5}$$

The primary goal of the study is to estimate five unknown parameters (I_{ph},I_0,R_s,R_p,A) from the given points and equations. Obviously, these parameters are mutually coupled due to the nonlinear I-V characteristics. For reducing the number of the unknown parameters, the photoelectric current I_{ph} can be expressed as a function of R_s,R_p and A by using the Eq.(4):

$$I_{ph} = I_0(e^{\frac{V_{oc}}{N_sV_tA}}) + \frac{V_{oc}}{R_p} \tag{6}$$

By inserting Eq.(6) into Eq.(3), we have

$$I_{sc} = I_0(e^{\frac{V_{oc}}{N_sV_tA}} - e^{\frac{I_{sc}R_s}{N_sV_tA}}) + \frac{V_{oc}-I_{sc}R_s}{R_p} \tag{7}$$

Since the second term in the parenthesis of Eq.(7) may be significantly smaller than the first term, Eq.(7) can be approximated as:

$$I_{sc} = I_0(e^{\frac{V_{oc}}{N_sV_tA}}) + \frac{V_{oc}-I_{sc}R_s}{R_p} \tag{8}$$

Therefore, the dark saturation current I_0 can also be expressed as a function of R_s,R_p and A by using Eq.(8):

$$I_0 = (I_{sc} - \frac{V_{oc}-I_{sc}R_s}{R_p})e^{-\frac{V_{oc}}{N_sV_tA}} \tag{9}$$

Eq.(6) and (9) can be inserted into Eq.(5), which will take the form:

$$I_{mpp} = I_{sc} - \frac{V_{mpp}+I_{mpp}R_s-I_{sc}R_s}{R_p} - (I_{sc} - \frac{V_{oc}-I_{sc}R_s}{R_p})e^{\frac{V_{mpp}+I_{mpp}R_s-V_{oc}}{N_sV_tA}} \tag{10}$$

Furthermore, the parallel resistance R_p can be expressed as a function of R_s and A by using Eq.(10):

$$R_p = \frac{V_{mpp}+I_{mpp}R_s-I_{sc}R_s-(V_{oc}-I_{sc}R_s)e^{\frac{V_{mpp}+I_{mpp}R_s-V_{oc}}{N_sV_tA}}}{I_{sc}-I_{mpp}-I_{sc}e^{\frac{V_{mpp}+I_{mpp}R_s-V_{oc}}{N_sV_tA}}} \tag{11}$$

To sum up, I_{ph}, I_0 and R_p can be expressed as the functions of R_s and A. Only two parameters R_s and A need to be found.

Remarks. By inserting Eq.(9) into Eq.(6), we have

$$I_{ph} = (1+\frac{R_s}{R_p})I_{sc} \tag{12}$$

Thus, Eq.(12) determines $I_{ph} \neq I_{sc}$ due to the introduction of the resistances R_s and R_p. As described in [2], the photoelectric current I_{ph} taking into account the influence of the series and parallel resistances can improve the model.

2.2 Parameter Estimation Procedure.

So far the above equations are obtained only using the circuit model. Two additional equations can be derived using mathematical characteristics of the I-V curve. The first equation is derived by the fact that the derivative of power with voltage at the MPP is zero:

$$\left.\frac{dP}{dV}\right|_{V=V_{mpp},I=I_{mpp}} = 0 \tag{13}$$

The second equation is derived by the fact that the derivative of current with voltage at the short circuit point is given as the negative of the reciprocal of R_p:

$$\left.\frac{dI}{dV}\right|_{I=I_{sc}} = -\frac{1}{R_p} \tag{14}$$

In addition, the parameters R_s, A and R_p have their physical meaning and their values lie in some reasonable ranges according to the experience or experiments. Consequently, an optimization problem is constructed to find the values of R_s and A as follow:

$$\begin{aligned}&\min_{R_s,A} f(R_s,A) = [f_1(R_s,A)]^2+[f_2(R_s,A)]^2+[f_3(R_s,A)]^2\\ &Subject\,to:\\ &R_{s,\min} \le R_s \le R_{s,\max}\\ &A_{\min} \le A \le A_{\max}\end{aligned} \tag{15}$$

where $f_1(R_s,A)$ can be derived by Eq.(10):

$$f_1(R_s,A) = I_{sc} - \frac{V_{mpp}+I_{mpp}R_s-I_{sc}R_s}{R_p} - (I_{sc} - \frac{V_{oc}-I_{sc}R_s}{R_p})e^{\frac{V_{mpp}+I_{mpp}R_s-V_{oc}}{N_sV_tA}} - I_{mpp} \tag{16}$$

$f_2(R_s,A)$ can be derived by Eq.(13):

$$f_2(R_s,A) = I_{mpp} + V_{mpp}\frac{-c\cdot e^{(V_{mpp}+I_{mpp}R_s-V_{oc})/(N_sV_tA)}-\frac{1}{R_p}}{1+(c\cdot R_s\cdot e^{(V_{mpp}+I_{mpp}R_s-V_{oc})/(N_sV_tA)})+\frac{R_s}{R_p}} \tag{17}$$

and

$$c = \frac{I_{sc}R_s - V_{oc} + I_{sc}R_p}{N_sV_tA} \tag{18}$$

$f_3(R_s,A)$ can be derived by Eq.(14):

$$f_3(R_s,A) = \frac{-c\cdot e^{(I_{sc}R_s-V_{oc})/(N_sV_tA)}-\frac{1}{R_p}}{1+(c\cdot R_s\cdot e^{((I_{sc}R_s-V_{oc})/(N_sV_tA)})+\frac{R_s}{R_p}} + \frac{1}{R_p} \tag{19}$$

When some nonlinear numerical solvers such as trust-region algorithm or Levenberg-Marquardt algorithm are applied to optimize the constrained NLS problem Eq.(15), it is sometimes troubled by the convergence problem that in some cases is an inappropriate choice of initial values that can lead to non-convergence. In order to overcome the shortcoming, we propose a simple optimization approach that performs a complete scan of all possible values of R_s (from $R_{s,min} = 0.1\Omega$ to $R_{s,max} = 1\Omega$ with a step size $\Delta R_s = 0.001\Omega$)and A (from $A_{min} = 1$ to $A_{max} = 2$ with a step size $\Delta A = 0.01$). The value of R_p derived by Eq.(11) should also fall in a reasonable range $[R_{p,min}, R_{p,max}]$. If the value of R_p is beyond the range, the calculation of the objective function in Eq.(15) can be ignored and we continue the next scan. In this study, we set $R_{p,min} = 100\Omega$ and $R_{p,max} = 4000\Omega$. The flowchart of the proposed approach is shown in Fig.2.

Remarks. The $R_{p,min}$ is given analytically in [3] as:

$$R_{p,\min} = \frac{V_{mpp}}{I_{sc}-I_{mpp}} - \frac{V_{oc}-V_{mpp}}{I_{mpp}} \tag{20}$$

The minimum value of R_p is estimated by calculating the slope of the line segment between the short circuit and the maximum power points. In the following experiments, we found that the values of $R_{p,min}$ for all experiments derived by Eq.(20) were about 100Ω. Thus, the setting of $R_{p,min}$ in the proposed approach is feasible.

3 Construction of the PV Full Characteristic Model Using the Datasheet Values at the NOCT

The datasheet values at the NOCT test conditions can be used to obtain the full PV full characteristics under varying irradiance and temperature conditions. Similarly, as an

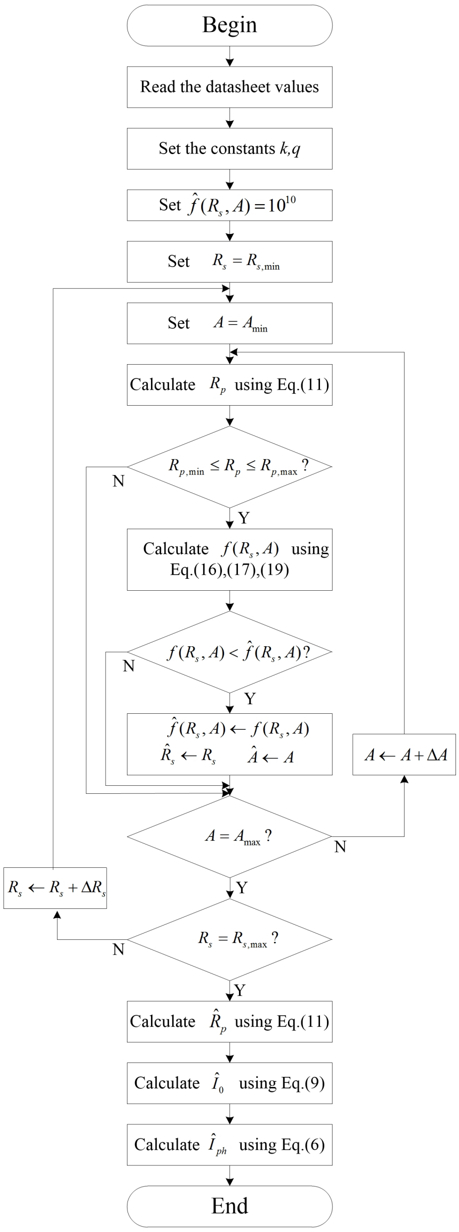

Fig.2. Proposed approach flowchart for determination of the PV module parameters at the STC.

example, Table 2 shows the datasheet values at the NOCT from the module TSM-PD05.05(250W).

TABLE 2. Summary of Electrical Measurements at the NOCT for the Module TSM-PD05.05(250W)

Electrical Measurements (NOCT)	Values
Peak Power Watts-P_{MAX}(W)	186
Maximum Power Voltage-V_{mpp}(V)	28.1
Maximum Power Current-I_{mpp}(A)	6.63
Open Circuit Voltage-V_{oc}(V)	35.3
Sort Circuit Current-I_{sc}(A)	7.10
NOCT (^oC)	44
Temperature Coefficient of P_{MAX} ($\%/^oC$)	-0.41
Temperature Coefficient of V_{oc} ($\%/^oC$)	-0.32
Temperature Coefficient of I_{sc} ($\%/^oC$)	0.05

3.1 Irradiance and Temperature Dependence for Short Circuit Current

The short circuit current of the PV module is considered to be dependent on both the irradiance G and temperature T:

$$I_{sc}(G,T) = I_{sc} \cdot \frac{G}{G_{STC}}(1 + \delta I_{sc}(T - T_{STC})) \tag{21}$$

where G_{STC} and T_{STC} are the irradiance and temperature at the STC, respectively. The temperature coefficient δI_{sc} of short circuit current can be obtained from the datasheet.

3.2 Irradiance and Temperature Dependence for Open Circuit Voltage

The open circuit voltage of the module is also considered to be dependent on both the irradiance G and temperature T according to modifications to ASTM E1036-96 in [17]:

$$V_{oc}(G,T) = V_{oc}(1 + \delta_{oc}^{G}(ln(G) - ln(G_{STC})))(1 + \delta V_{oc}^{T}(T - T_{STC})) \tag{22}$$

where the temperature coefficient δV_{oc}^{T} of open circuit voltage can also be obtained from the datasheet. The irradiance correction coefficient δV_{oc}^{G} can be derived by using the values of $V_{oc}(G,T)$ and δV_{oc}^{T} from the datasheet, given as:

$$\delta V_{oc}^{G} = \frac{\frac{V_{oc}(G,T)}{V_{oc}(1+\delta V_{oc}^{T}(T-T_{STC}))} - 1}{ln(G) - ln(G_{STC})} \tag{23}$$

As an example, the value of δV_{oc}^{G} for the Module TSM-PD05.05(250W) is 0.0489.

3.3 Temperature dependence for parameters R_s and A

Generally, the series resistance R_s increases and the ideality factor A decreases for the PV module, while temperature increases [18]. Therefore, the work proposes two expressions including the specific temperature effects, given by:

$$R_s(T) = R_s + \Delta R_s(T - T_{STC}) \tag{24}$$

$$A(T) = A + \Delta A(T - T_{STC}) \tag{25}$$

where ΔR_s and ΔA are the temperature coefficients of the series resistance and the ideality factor, respectively. The two parameters are unknown and solved by a simple approach in the following context.

3.4 Irradiance and Temperature Dependence for Dark Saturation Current and Photoelectric Current

Both are derived by directly using Eq.(9) and (12), given as:

$$\begin{aligned} &I_0(G,T) \\ &= (I_{sc}(G,T) - \frac{V_{oc}(G,T) - I_{sc}(G,T)R_s(T)}{R_p})e^{-\frac{V_{oc}(G,T)}{N_s V_t(T) A(T)}} \end{aligned} \tag{26}$$

$$I_{ph}(G,T) = I_{sc}(G,T)(1+\frac{R_s(T)}{R_p}) \quad (27)$$

where $V_t(T) = qT/k$. Obviously, both are functions of ΔR_s and ΔA.

Remarks. Generally, the irradiance and temperature dependencies for the open circuit voltage V_{oc} and the dark saturation current I_0 are derived from cell physics, which can be found in [19] and [20]. The dark saturation current I_0 in Eq.(26) exhibits a complex nonlinear relationship with both the irradiance and temperature by substituting Eq.(21)and (22) into Eq.(26), although V_{oc} is assumed to be linear with the log of effective irradiance or the temperature in Eq.(22) and I_{sc} is also assumed be linear with the effective irradiance or the temperature in Eq.(21). The choice is based on three factors. Firstly, the relationship in Eq.(21) and Eq.(22) is based on modifications to ASTM E1036-96. The correction coefficients for performance deviation are determined from linearity when module temperature and solar radiation flux vary [21]. For instance, Fig.3 shows the relationship between the irradiance and the open circuit voltage of PV module KC200GT [22]. It can be seen from the right figure of Fig.3 that the open circuit voltages vary linearly with the log of the irradiance. Secondly, it can fully use the temperature coefficients provided by the datasheet. Given the temperature coefficients of V_{oc} and I_{sc} from the datasheet, the irradiance correction coefficient can be simply derived from Eq.(23). Finally, the PV full characteristic model is fitted with the data at the NOCT test condition by regulating the coefficients ΔR_s and ΔA.

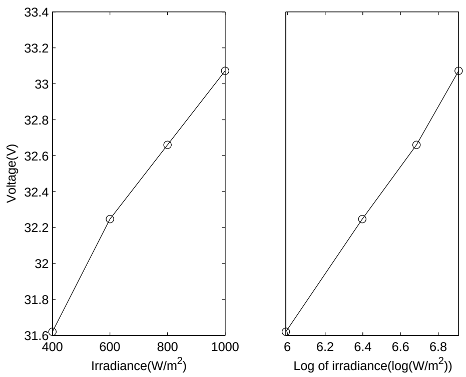

Fig.3. Relationship between the irradiance and the open circuit voltage of PV module KC200GT.

3.5 Solving Unknown Temperature Coefficients

Table 3 lists all data needed for solving unknown temperature coefficients ΔR_s and ΔA. Given the irradiance (G) and temperature (T) at the NOCT test conditions and the parameter estimation results at the STC, an optimization problem being similar to Eq.(15) can be constructed by replacing the parameters at the STC with variables at the NOCT test conditions. Correspondingly, the optimization variables are changed to ΔR_s and ΔA. A similar optimization procedure is adopted by a complete scan of all possible values of ΔR_s (from 0 to 0.01 with a step of 0.00001) and ΔA (from ΔA_{min} to 0 with a step of 0.00001). Because the value of $A(T)$ should lie in the range $[1,2]$ and ΔA should less than or equal to 0, the lower limit ΔA_{min} of the coefficient ΔA is given as:

$$\Delta A_{\min} = \begin{cases} (2-A)/(T-T_{STC}) \; if \; T-T_{STC}<0 \\ (1-A)/(T-T_{STC}) \; otherwise \end{cases} \quad (28)$$

TABLE 3. Data needed for solving unknown temperature coefficients ΔR_s and ΔA

Data source	Data
data at the STC from datasheet	G_{STC},T_{STC} V_{oc},I_{sc},V_{mpp},I_{mpp}
data at the NOCT from datasheet	G,T $V_{oc}(G,T)$,$I_{sc}(G,T)$ $V_{mpp}(G,T)$,$I_{mpp}(G,T)$
temperature coefficients from datasheet	δV_{oc}^T,δI_{sc}
irradiance coefficients from Eq.(23)	δV_{oc}^G
parameters obtained at the STC	R_s,R_p,A

4 Simulation Results

4.1 Validation and Analysis of the Proposed Approach at the STC

In this subsection, the proposed approach was first compared with the approach given in [8] by using the same modules at the STC. Only datasheet values at the STC were utilized to calculate the five parameter values, which are shown in Table 4. Because the approach in [10] requires plenty of specific data extracted by the curve extractor for guaranteeing the estimation accuracy, the comparison results with the approach in [10] are no longer provided.

TABLE 4. Datasheet values at STC for the Modules

Values	PV Modules			
	BP 5170S	BP MSX120	KC 200GT	MSX60
P_{MAX}	170	120	200	60
V_{mpp}	36	33.7	26.3	17.1
I_{mpp}	4.72	3.56	7.61	3.5
V_{oc}	44.2	42.1	32.9	21.1
I_{sc}	5	3.87	8.21	3.8
N_S	72	72	54	36

Table 5 shows the comparison results obtained using the approach in [8] and the proposed approach for the four modules. We set $f(R_s,A)$ as the performance index. It can be seen from Table 5 that the proposed approach presents better fitting results to match the remarkable points than the approach in [8] for all four modules. The comparison clearly highlights the ability of the approach to obtain very low fitting error. In particular, the proposed approach achieves significant performance improvement for the KC 200GT module. The improvement should owe to the accurate estimation of parallel resistance. However, the proposed approach is free of the convergence problem. Moreover, the approach is

TABLE 5. Comparison Results (the proposed approach/the approach in [8]) for the Modules

Values	Module			
	BP 5170S	BP MSX120	KC 200GT	MSX60
R_s	0.5580/0.5625	0.5060/0.4729	0.2010/0.2198	0.1570/0.1702
R_p	3923.1/2319.8	1064.4/1366.7	3338.3/991.5159	779.3135/641.7938
A	1.03/1.0284	1.36/1.3975	1.39/1.3370	1.43/1.4038
$f(R_s,A)$	$4.58\times10^{-6}/9.44\times10^{-4}$	$3.72\times10^{-7}/2.47\times10^{-5}$	$1.79\times10^{-7}/1.6\times10^{-3}$	$4.05\times10^{-8}/6.6\times10^{-5}$

particularly simple as it only uses a complete scan of the few parameters falling in the reasonable ranges.

The proposed approach also gives the optimal solution $R_s = 0.3740\Omega$, $R_p = 771.7812\Omega$ and $A = 1.03$ for the TSM-PD05.05(250W) module at the STC. Fig.4 depicts I-V characteristics and output power characteristics of the module. The MPP of the model curve estimated by the proposed approach is exactly match with that obtained by the manufacturer' datasheet.

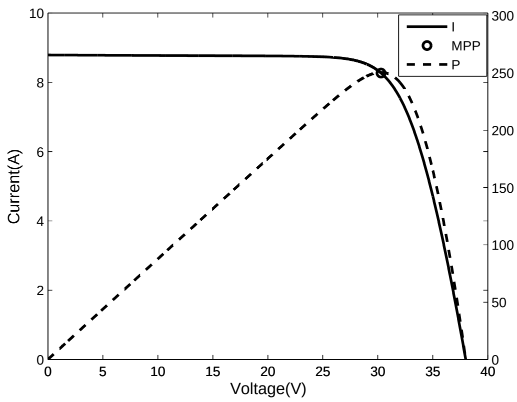

Fig.4. The I-V characteristics and out power characteristics of TSM-PD05.05(250W) module.

Next, we compare predicted I-V curves with publicly available experimental data provided in [9]. Table 6 shows the datasheet values of a 36 cell multi-crystalline PV module (Photowatt-PWP 201) for the test condition under 1 sun ($1000W/m^2$) at 45^0C. Given a set of N measured voltages V_n, with $n = 1,\dots N$, the predicted current values $\hat{I}_n$ in Eq.(1) were calculated by using NR method with maximum iterative step of 5. The root mean square error (RMSE) has been adopted to evaluate the predicted performance, given by:

$$RMSE = \sqrt{\sum_{n=1}^{N}\left(I_n - \hat{I}_n\right)^2} \tag{29}$$

where I_n are the measured current values. The obtained five parameters and the values of RMSE are reported in Table 7 for the proposed approach and its competition approaches including the solution 1.A and solution 1.B given in [9] and the approach in [8]. Although the RMSE value of the proposed approach is the worst value among all reported approaches, the results of the approaches in [9] were obtained by using all measured values, while the proposed approach only used the three remarkable points from the datasheet. Therefore, it is reasonable that the approaches using more data experimental points yield more accurate identification results than the proposed approach. When the RMSE, as a optimization objective, was added to the objective function in Eq.(15), the proposed approach yielded the best RMSE value 0.011. However, the availability of such experimental data is generally questionable. Moreover, it is important to emphasize that the results of the approach in [8] were obtained by making multiple intelligent guesses with the result of [8]. In fact, the optimization problems in [8] and [9] should have constraints that the parameters have to keep to be positive in the iterative process. However, the optimization problems are always viewed as the unconstrained problem for reducing the solving difficulties. Therefore, their main shortcoming lies in the non-convergence, while the proposed approach is free of convergence problem because it finds the optimal values by the scanning operation instead of the iteration calculation.

TABLE 6. Summary of Electrical Measurements for the Module (Photowatt-PWP 201)

Electrical Measurements (STC)	Values
Maximum Power Voltage-V_{mpp}(V)	12.6490
Maximum Power Current-I_{mpp}(A)	0.9120
Open Circuit Voltage-V_{oc}(V)	16.7785
Sort Circuit Current-I_{sc}(A)	1.0317

Furthermore, the comparison was executed to experimental I-V data of a commercial mono-crystalline PV module called "AD285M6-Ab" from the Aide Solar company. Fig.5 shows the estimated I-V curve obtained by using the proposed approach and the experimental data at the STC. The curve obtained by using the approach in [8] is not drawn because the curve is almost identified with our curve from a visual point of view. However, in this experiment, the value of RMSE coming from the proposed approach is smaller than the one obtained by using the approach in [8]. Therefore, the performance comparison about the value of RMSE is probably a bit dependent on the measured data.

TABLE 7. Comparison Results for the Module (Photowatt-PWP 201)

Values	Approach			
	solution 1.A in [9]	solution 1.B in [9]	the approach in [8]	the proposed approach
R_s	1.218407	1.224053	1.313	1.160
R_p	783.516	689.321	582.3323	981.7575
A	1.336752	1.329426	1.2770	1.4
I_0	3.035367×10^{-6}	2.825571×10^{-6}	1.6710×10^{-6}	5.4383×10^{-6}
I_{ph}	1.032173	1.033537	1.034	1.0329
$RMSE$	0.0125	0.0128	0.0160	0.0175

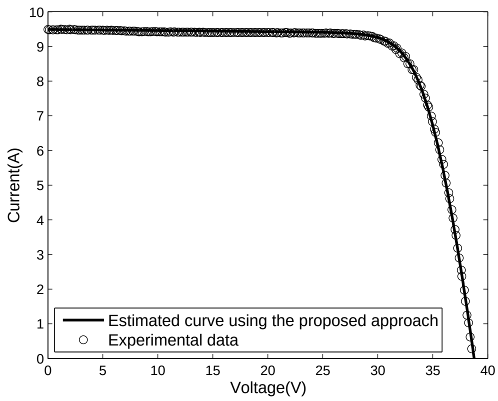

Fig.5. The I-V characteristics and experimental data of AD285M6-Ab module.

4.2 Validation and Analysis of the Proposed Approach in Different Temperature and Irradiance Conditions

Using the data of the TSM-PD05.05(250W) module at the NOCT test conditions, the proposed approach gives the optimal temperature coefficients $\Delta R_s = 0.0003/^oC$ and $\Delta A = -0.00041$. Fig.6 shows five I-V curves at different irradiance conditions for the module NOCT of 44^oC. Fig.7 shows five I-V curves at different temperature conditions for the module irradiance condition of $800W/m^2$.

Next, we consider the parameter estimation for the TSM-PD05.05(260W) module and compare the results of the proposed approach and the datasheet. The optimal solution at the STC is $R_s = 0.3610\Omega$, $R_p = 1217.70\Omega$ and $A = 1$. However, when the data at the NOCT test conditions are utilized, both the coefficients ΔR_s and ΔA are equal to 0 and the objective function value is 0.1312 . Obviously, the objective function is too large and the estimation is worse. This can be interpreted that the ranges of parameters R_s and/or A limit the optimal solution to be scanned for the optimization problem. Therefore, the lower limit of A is reduced to 0.9 and the algorithm is operated again. As a result, an optimal solution from the proposed approach is $\Delta R_s = 0$ and $\Delta A = -0.0016$. The corresponding objective function value is 3.6533×10^{-4}, which is significantly less than the previous value. The estimated MPP using the proposed approach exactly matches with that obtained by manufacturers' datasheet again. Therefore, although the value of ΔR_s violated the assumption that the value of the series resistance R_s should be linearly dependant with the module temperature conditions, the solution obtained from the proposed approach is still feasible from the view of fitting functions. Consequently, the estimated I-V curves of the module at a module temperature of 25^oC varying irradiance conditions are shown in Fig.8. As a comparison, the real curves shown in Fig.9 are directly copied from the manufacturer' datasheet. As can be seen from the Fig.8 and 9, the simulated curves are graphically well-matched with the real curves.

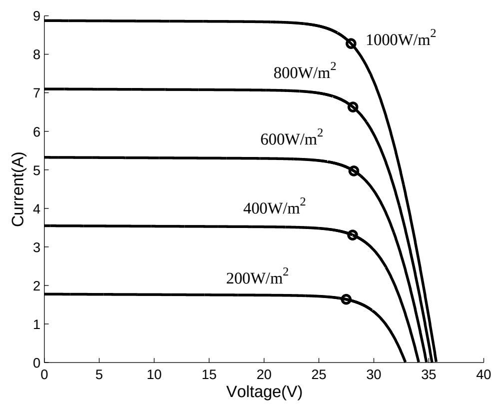

Fig.6. The I-V characteristics of TSM-PD05.05(250W) module at different irradiance conditions at the NOCT.

5 Conclusions

In this paper, a simple approach to estimating parameters of PV modules is presented. The data needed for the proposed approach are directly from the manufacturers' datasheets. The start point of the proposed approach is that extracting the parameters of the single-diode five-parameters

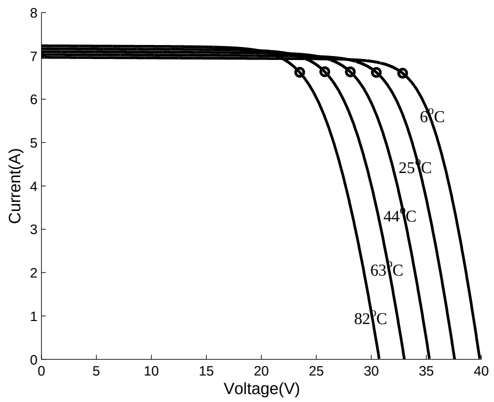

Fig.7. The I-V characteristics of TSM-PD05.05(250W) module at different temperatures at fixed irradiance ($G = 800W/m^2$).

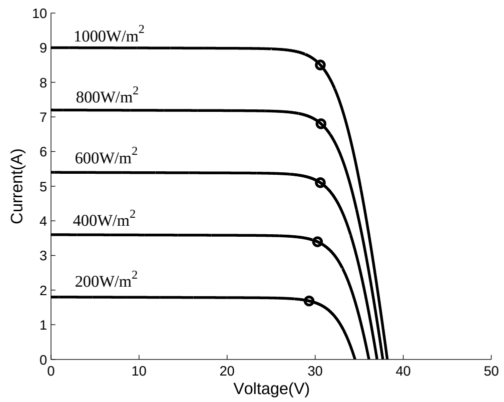

Fig.8. The estimated full I-V characteristics of TSM-PD05.05(260W) module at different irradiance conditions at the STC.

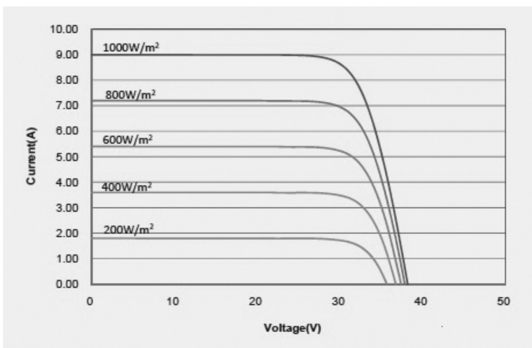

Fig.9. The full I-V characteristics of TSM-PD05.05(260W) module from the datasheet. (Copy from: http://www.trinasolar.com/us/product/PC05.html)

electrical model at the STC is derived by optimizing a nonlinear optimization technique. Instead of using the classical nonlinear numerical solvers, a simple lattice search of the parameters is performed within some reasonable ranges based on their physical meaning. Thus, the search space is firstly reduced by analyzing the inherit mathematical relations between the parameters. The optimization process is free of the convergence problem. Furthermore, by fully making use of the data at the NOCT test conditions, we also construct a full characteristic model with consideration of both the irradiance and temperature dependencies. The full characteristic model has a similar optimization procedure as that at the STC. The proposed approach is simple and easy to implement. The evaluations on several PV modules show the effectiveness of the proposed approach.

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