Parameter Extraction Algorithm for One-Diode Model of PV Panels based on Datasheet Values

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***Abstract*—A photovoltaic (PV) panel model is at the heart of an accurate performance model for a large PV farm. This paper presents an algorithm to calculate the parameters of the one-diode model of PV modules based solely on the manufacturer's datasheets. The important feature of this algorithm is that through reformulation of the characteristic equations at various points of the current-voltage ($\boldsymbol{I-V}$) curve, the unknown model parameters can be determined analytically. This is in contrast to many existing models which choose a value for one parameter and then calculate the other parameters through simultaneous solution of the system of equations. The calculated $\boldsymbol{I-V}$ curve is then compared with the manufacturer's curve to validate the proposed algorithm and quantify the modeling error.**

***Index Terms*—Parameter extraction, Photovoltaic panel, Polycrystalline, One-diode model**

I. Introduction

The steep increase in the interest and consequently, the installed photovoltaic power has necessitated accurate PV performance models. An accurate panel model goes a long way in the accuracy of forecast of the whole performance model of PV farm. The characteristics of a PV module can be approximated by one-diode model (ODM) shown in Fig. 1, two-diode model (TDM) with an additional diode shown in Fig. 2 or one-diode based four-parameter model (OFPM) obtained by neglecting the shunt resistance.

[1] and [2] presented an iterative algorithm to compute the five unknown parameters of the ODM presuming a value of the diode ideality factor. The results are highly dependent upon the chosen value of the diode ideality factor though. In [3], it is proposed to evaluate the $I-V$ characteristics at conditions other than the standard conditions and then to solve the system of non-linear equations simultaneously. This is difficult and relatively inaccurate owing to approximate nature of the temperature coefficients. Moreover, as outlined by [4], mere translation of parameters to another temperature does not provide additional independent equation. [4] calculated the ODM parameters through complicated formulation of model equations using the fill factor of the $I-V$ characteristics. This is based on an empirical relation for the fill factor of an ideal cell. [5] presented parameter extraction of ODM by solving a system of simultaneous non-linear equations. [6] determined the model parameters through neural fuzzy network approach which is very complicated and not very accurate. The curve-fitting techniques of [7] and [8] require actual $I-V$ measurements which is not quite convenient.

In order to reduce the order of the system, [9] [10] and [11] proposed to neglect the shunt resistance altogether, resulting in OFPM. This enables analytical calculation of parameters but at the cost of loss of accuracy.

The parameter extraction for TDM is also done after some simplifications and some loss of generalization. [12] assumed the saturation currents of both diodes to be equal whereas [13] set the values for the diode ideality factor. The method of [14] required semi-log plots of measured $I-V$ characteristic of the module which are generally not available.

In this work, an algorithm is developed to determine the five unknown parameters of the ODM without any simplification or presumption, based solely on the manufacturer's datasheets. The resulting $I-V$ characteristic and those obtained from TDM and OFPM are then compared to the characteristic curve provided by the manufacturer in the datasheet. The error is then quantified by root mean square error for the three models. A more accurate relation is derived for open circuit voltage and saturation current of ODM for non-standard environmental conditions. In section II, the three models are shortly presented with their equivalent circuit diagrams. Section III explains the proposed parameter extraction algorithm for ODM in detail. In section IV, the dependence of model parameters on environmental variables is presented. The proposed algorithm results are presented and compared in section V followed by conclusions in section VI.

II. Panel Models

A. One-Diode Model (ODM)

A real photovoltaic (PV) panel/module can be modeled using a current source with a parallel diode and a network of resistors, as shown in Fig. 1.

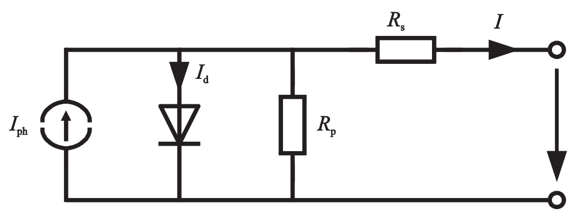

Fig. 1. One-diode equivalent circuit of a PV module

In this equivalent circuit, I_{ph} represents the current generated due to the irradiation incident upon the module called photocurrent. I_{d} is the p-n junction current according to Schockley equation. The intrinsic resistance of the semiconductor, the resistance of the metal grid connecting individual PV cells in a panel, the connection resistance and the connecting cable resistance are all lumped together into a series resistance R_{s}. The resistance R_{p} in Fig. 1 models the inherent shunts of the PV module. The terminal current-voltage $(I-V)$ characteristic is then given by:

$$I = I_{\mathrm{ph}} - I_{\mathrm{sat}}\left[\exp\left(\frac{V+IR_{\mathrm{s}}}{V_{\mathrm{th}}m}\right)-1\right]-\frac{V+IR_{\mathrm{s}}}{R_{\mathrm{p}}} \tag{1}$$

where I_{sat} is the reverse saturation current of the diode and m is the diode ideality factor. It signifies how closely the characteristic of a PV cell/module matches with that of an ideal diode. For an ideal diode, the diode ideality factor is unity. The second term of (1) represents the current I_{d} through the diode. V_{th} is the thermal voltage of the p-n junction diode. It depends upon the absolute panel temperature T and the number of series-connected PV cells N_{c} in the panel and is given by,

$$V_{\mathrm{th}} = \frac{N_{\mathrm{c}}kT}{e} \tag{2}$$

where k is the Boltzmann constant ($1.38065 \times 10^{-23}\ \mathrm{m^2kgs^{-2}K^{-1}}$) and e is the unit electronic charge (1.602176×10^{-19} C).

There are five unknown parameters in (1). These are the photocurrent (I_{ph}), the reverse saturation current (I_{d}), the diode ideality factor (m), the series resistance (R_{s}) and the shunt resistance (R_{p}). The algorithm to calculate these parameters is given in Section III.

B. Two – Diode Model (TDM)

The two-diode model (TDM) is obtained from ODM by adding another diode in parallel to the already existing diode. This second diode models the recombination losses in the depletion region [13]. The equivalent circuit of TDM is shown in Fig. 2.

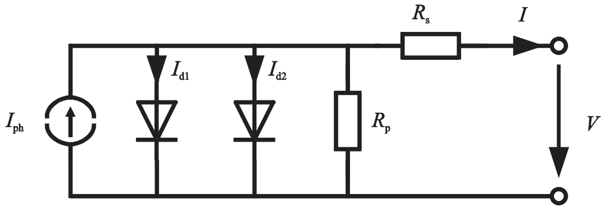

Fig. 2. Two-diode equivalent circuit of a PV module

The terminal $I-V$ characteristic for the equivalent circuit of Fig. 2 is given by:

$$I = I_{\mathrm{ph}} - I_{\mathrm{sat1}}\left[\exp\left(\frac{V+IR_s}{V_{\mathrm{th}}m_1}\right)-1\right]$$
$$-I_{\mathrm{sat2}}\left[\exp\left(\frac{V+IR_{\mathrm{s}}}{V_{\mathrm{th}}m_2}\right)-1\right]-\frac{V+IR_{\mathrm{s}}}{R_{\mathrm{p}}} \tag{3}$$

where, I_{sat1} is the saturation current representing conduction phenomenon in the quasi-neutral region of the p-n junction whereas I_{sat2} models the saturation current due to carrier recombination in the space charge region [12]; m_1 and m_2 are corresponding diode ideality factors.

There are seven unknown variables in (3). It is not possible to calculate these using only the information provided by the manufacturer. It is quite common to assume $m_1 = 1$ and $m_2 = 2$ or assume the two saturation currents to be roughly equal [12-14]. The resulting equation is then evaluated at different points of the $I-V$ curve and a system of simultaneous non-linear equations is solved to determine the remaining parameters.

C. One-Diode based Four-Parameter Model (OFPM)

The third model that is used for comparison in this work is the four-parameter model based on the ODM. In this model, it is assumed that the shunt resistance R_{p} is so high that it can be neglected without affecting the characteristics of the model significantly [9-11]. The equivalent circuit of OFPM is shown in Fig. 3.

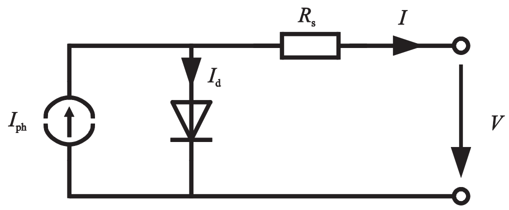

Fig. 3. One-diode based four parameter model of a PV module

The terminal $I-V$ characteristic of OFPM is given by:

$$I = I_{\mathrm{ph}} - I_{\mathrm{sat}}\left[\exp\left(\frac{V+IR_{\mathrm{s}}}{V_{\mathrm{th}}m}\right)-1\right] \tag{4}$$

The number of unknown variables in OFPM is four which is the same as the number of independent equations. Hence, a simultaneous solution of the system of equations yields the unknown variables.

III. PARAMETER EXTRACTION FOR ONE-DIODE MODEL

The five parameters of ODM to be determined are mentioned in Section II. There are three "conspicuous" points on the $I-V$ characteristic curve provided by the manufacturer of the PV panel. These are the open circuit point $(V_{\mathrm{ocn}}, 0)$, the short circuit point $(0, I_{\mathrm{scn}})$ and the maximum power point $(V_{\mathrm{mppn}}, I_{\mathrm{mppn}})$, as shown by the red circles in Fig. 4. Here, "n" in the subscripts indicates that these quantities are at 'nominal' or so-called Standard Test Conditions (STC). STC means a panel temperature of 25 °C, incident irradiation of 1000 W/m^2 in the plane of the panel and an air mass of 1.5. Air mass is the ratio of the mass of the atmosphere through which the direct component of light passes to the mass it would pass through if the sun were located at the zenith (directly overhead) [3].

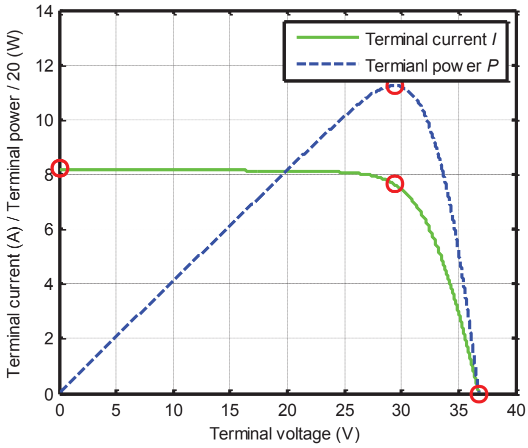

Fig. 4. $I-V$ and $P-V$ characteristics of TSM225PC05 module

In order to determine the five unknown parameters, (1) is evaluated at the three conspicuous points yielding three equations. Evaluating (1) at the short circuit point $(0, I_{\text{scn}})$ leads to,

$$I_{\text{scn}} = I_{\text{phn}} - I_{\text{satn}}\left[\exp\left(\frac{I_{\text{scn}}R_{\text{s}}}{V_{\text{th}}m}\right) - 1\right] - \frac{I_{\text{scn}}R_{\text{s}}}{R_{\text{p}}} \tag{5}$$

Evaluating (1) at the open circuit point $(V_{\text{ocn}}, 0)$ yields,

$$0 = I_{\text{phn}} - I_{\text{satn}}\left[\exp\left(\frac{V_{\text{ocn}}}{V_{\text{th}}m}\right) - 1\right] - \frac{V_{\text{ocn}}}{R_{\text{p}}} \tag{6}$$

Substituting for I_{phn} from (5) in (6) and simplification yields following equation for the diode saturation current.

$$I_{\text{satn}} = \frac{\left(1+\frac{R_{\text{s}}}{R_{\text{p}}}\right)I_{\text{scn}} - \frac{V_{\text{ocn}}}{R_{\text{p}}}}{\exp\left(\frac{V_{\text{ocn}}}{V_{\text{th}}m}\right) - \exp\left(\frac{I_{\text{scn}}R_{\text{s}}}{V_{\text{th}}m}\right)} \tag{7}$$

Back substituting (7) in (5) and solving for the photocurrent gives the following equation.

$$I_{\text{phn}} = \frac{\left(1+\frac{R_{\text{s}}}{R_{\text{p}}}\right)I_{\text{scn}}\left[\exp\left(\frac{V_{\text{ocn}}}{V_{\text{th}}m}\right)-1\right] + \frac{V_{\text{ocn}}}{R_{\text{p}}}\left[1-\exp\left(\frac{I_{\text{scn}}R_{\text{s}}}{V_{\text{th}}m}\right)\right]}{\exp\left(\frac{V_{\text{ocn}}}{V_{\text{th}}m}\right) - \exp\left(\frac{I_{\text{scn}}R_{\text{s}}}{V_{\text{th}}m}\right)} \tag{8}$$

Eq. (7) and (8) express the saturation current and the photocurrent in terms of other unknown variables, namely, R_{s}, R_{p} and m. All other quantities are either provided in the datasheet or depend upon the operating conditions. Now, evaluating (1) at the maximum power point (MPP) and substituting for I_{satn} and I_{phn} from (7) and (8) respectively leads to the following equation.

$$I_{\text{mppn}} = \frac{\left[\left(1+\frac{R_{\text{s}}}{R_{\text{p}}}\right)I_{\text{scn}}(A-1) - \frac{V_{\text{ocn}}}{R_{\text{p}}}\right]B}{A} - \frac{V_{\text{mppn}} + I_{\text{mppn}}R_{\text{s}}}{R_{\text{p}}} \tag{9}$$

Where, $A = \exp\left(\frac{V_{\text{ocn}}}{V_{\text{th}}a}\right) - \exp\left(\frac{I_{\text{scn}}R_{\text{s}}}{V_{\text{th}}a}\right)$ (10)

$$B = \exp\left(\frac{V_{\text{mppn}} + I_{\text{mppn}}R_{\text{s}}}{V_{\text{th}}a}\right) - \exp\left(\frac{I_{\text{scn}}R_{\text{s}}}{V_{\text{th}}a}\right) \tag{11}$$

Eq. (9) can be solved for the shunt resistance R_{p} resulting in the following relation.

$$R_{\text{p}} = \frac{\left[R_{\text{s}}(I_{\text{scn}} - I_{\text{mppn}}) - V_{\text{mppn}} - (R_{\text{s}}I_{\text{scn}} - V_{\text{ocn}})\frac{B}{A}\right]}{I_{\text{mppn}} - I_{\text{scn}}\left[1-\frac{B}{A}\right]} \tag{12}$$

where, A and B are given by (10) and (11) respectively.

Another independent equation can be derived by observing that at MPP, the rate of change of power with respect to terminal voltage is zero. Mathematically,

$$\left.\frac{\mathrm{d}p}{\mathrm{d}v}\right|_{\text{MPP}} = \frac{\mathrm{d}(v \cdot i)}{\mathrm{d}v} = 0 \Rightarrow \left.\frac{\mathrm{d}i}{\mathrm{d}v}\right|_{\text{MPP}} = -\frac{I_{\text{mppn}}}{V_{\text{mppn}}} \tag{13}$$

In order to calculate $\frac{\mathrm{d}i}{\mathrm{d}v}$, (1) is first written in the $f(i, v) = 0$ form and then the derivative is calculated using the chain rule resulting in the following relation.

$$\frac{\mathrm{d}i}{\mathrm{d}v} = \frac{\frac{-1}{V_{\text{th}}m}\left(\frac{\left(1+\frac{R_{\text{s}}}{R_{\text{p}}}\right)I_{\text{scn}} - \frac{V_{\text{ocn}}}{R_{\text{p}}}}{\mathrm{A}}\right)\exp\left(\frac{v+iR_{\text{s}}}{V_{\text{th}}m}\right) - \frac{1}{R_{\text{p}}}}{1+\frac{R_{\text{s}}}{V_{\text{th}}m}\left(\frac{\left(1+\frac{R_{\text{s}}}{R_{\text{p}}}\right)I_{\text{scn}} - \frac{V_{\text{ocn}}}{R_{\text{p}}}}{\mathrm{A}}\right)\exp\left(\frac{v+iR_{\text{s}}}{V_{\text{th}}m}\right) + \frac{R_{\text{s}}}{R_{\text{p}}}} \tag{14}$$

Evaluating (14) at $(V_{\text{mppn}}, I_{\text{mppn}})$ and substituting in (13) yields the following equation.

$$I_{\text{mppn}} - \frac{V_{\text{mppn}}\left[\frac{\left(\left(1+\frac{R_{\text{s}}}{R_{\text{p}}}\right)I_{\text{scn}} - \frac{V_{\text{ocn}}}{R_{\text{p}}}\right)C}{\mathrm{A}} + \frac{1}{R_{\text{p}}}\right]}{1+\frac{R_{\text{s}}\left(\left(1+\frac{R_{\text{s}}}{R_{\text{p}}}\right)I_{\text{scn}} - \frac{V_{\text{ocn}}}{R_{\text{p}}}\right)C}{\mathrm{A}} + \frac{R_{\text{s}}}{R_{\text{p}}}} = 0 \tag{15}$$

where,

$$C = \frac{\exp\left(\frac{V_{\text{mppn}} + I_{\text{mppn}}R_{\text{s}}}{V_{\text{th}}m}\right)}{V_{\text{th}}m} \tag{16}$$

Eq. (15) can be solved for the shunt resistance R_{p} as follows.

$$R_{\text{p}} = \frac{V_{\text{mppn}} - I_{\text{mppn}}R_{\text{s}} + C\left(\frac{R_{\text{s}}I_{\text{scn}} - V_{\text{ocn}}}{\mathrm{A}}\right)(V_{\text{mppn}} - I_{\text{mppn}}R_{\text{s}})}{I_{\text{mpp}} + \frac{I_{\text{scn}}C}{A}(I_{\text{mppn}}R_{\text{s}} - V_{\text{mpp}})} \tag{17}$$

Equating (12) and (17) eliminates the shunt resistance R_{p} resulting in the following equation.

$$\frac{\left[R_{\text{s}}(I_{\text{scn}} - I_{\text{mppn}}) - V_{\text{mppn}} - (R_{\text{s}}I_{\text{scn}} - V_{\text{ocn}})\frac{B}{A}\right]}{I_{\text{mppn}} - I_{\text{scn}}\left[1-\frac{B}{A}\right]} - \frac{(V_{\text{mppn}} - I_{\text{mppn}}R_{\text{s}})\left[1+C\left(\frac{R_{\text{s}}I_{\text{scn}} - V_{\text{ocn}}}{\mathrm{A}}\right)\right]}{I_{\text{mpp}} + \frac{I_{\text{scn}}C}{A}(I_{\text{mppn}}R_{\text{s}} - V_{\text{mpp}})} = 0 \tag{18}$$

Eq. (18) contains only two unknown variables, namely, the series resistance R_{s} and the diode ideality factor m. The value of m lies in the range $1 \le m \le 2$ for mono and polycrystalline modules. By iteratively solving (18) for different values of m in this range, different values of R_{s} can be calculated. However, not all of these values are valid. According to [1], the minimum and maximum values of R_{s} can be given as,

$$R_{\text{s,min}} = 0 \tag{19}$$

$$R_{\text{s,max}} = \frac{V_{\text{ocn}} - V_{\text{mppn}}}{I_{\text{mppn}}} \tag{20}$$

Thus, the values of R_{s} only in the range given by (19) and (20) are valid. Taking these values of R_{s} and the corresponding values of m, the shunt resistance R_{p} can be calculated using either (12) or (17). This value should not exceed the minimum value $R_{\text{p,min}}$ given by,

$$R_{\text{p,min}} = \frac{V_{\text{mppn}}}{I_{\text{scn}} - I_{\text{mppn}}} \tag{21}$$

The remaining two variables are then determined using (7) and (8). Given different sets of all the five parameters, the terminal current I is calculated for V in the range $[0 \;\; V_{\text{ocn}}]$ using (1) for each parameter set. Using these $I - V$ sets, the maximum power is calculated for each parameter set and the one resulting in minimum error from the rated maximum power is chosen for ODM. The flow chart for the proposed algorithm is shown in Fig. 5.

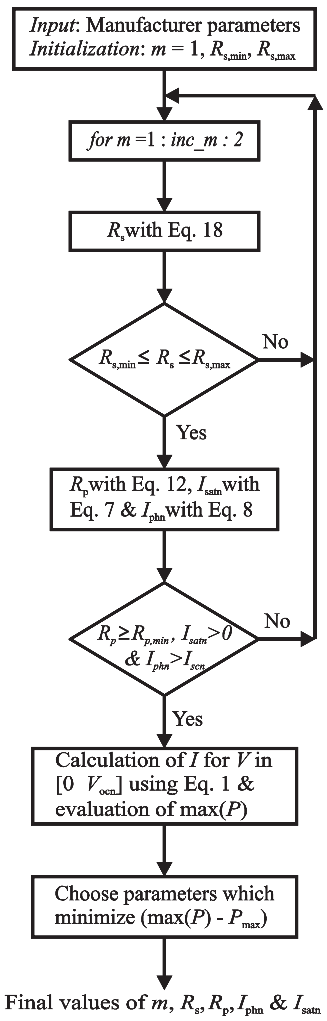

Fig. 5. Flow chart of the parameter calculation algorithm

It is worth mentioning here that sometimes the algorithm cannot find a solution because of a coarse step in the diode ideality factor. In such a case, the step size should be made smaller unless a solution is found. This would, however, increase the computational overhead.

The parameters extracted through this algorithm for ODM and the parameters for TDM and OFPM are presented and compared in Section V.

IV. Environmental Dependence of Parameters

The parameters provided by the manufacturer and those extracted in previous section are all at STC (panel temperature of 25 °C, insolation of 1000 W/m^2 and air mass of 1.5). These conditions, however, rarely exist in real world. In order to calculate performance of PV panels under real circumstances, the parameters have to be adapted to ambient temperature and irradiation. These dependencies are briefly mentioned in this section.

A. Photocurrent

The photocurrent is directly dependent upon the incident irradiation and the temperature difference, as given by the following relation.

$$I_{\text{ph}} = I_{\text{phn}}(1 + K_{\text{i}}\Delta T)\frac{G}{G_{\text{n}}} \tag{22}$$

where I_{ph} is the photocurrent at temperature T and irradiation G , K_{i} is the temperature coefficient of current (in units of 1/K). I_{phn} and G_{n} are the photocurrent and irradiation at nominal (STC) conditions.

Since short circuit current and the photocurrent are almost equal except for a small current in the shunt resistance and the leakage current of the diode, equation (22) is true for short circuit current as well. (22) is also valid for MPP current after replacing I_{phn} with I_{mppn}.

B. Saturation Current

A commonly used expression to depict the dependence of reverse saturation current of the diode in ODM on temperature is given below [1-5].

$$I_{\text{sat}} = I_{\text{satn}}\left(\frac{T}{T_n}\right)^3 \exp\left[\frac{eE_{\text{gn}}}{mk}\left(\frac{1}{T_n} - \frac{1}{T}\right)\right] \tag{23}$$

where I_{sat} is the saturation current at temperature T, E_{gn} is the band gap energy of the semiconductor material (1.12 eV for silicon at 25 °C [1]).

In this work, however, the authors propose to use (7) to calculate the saturation current at any condition of temperature and irradiation after adapting the short circuit current and open circuit voltage appropriately. The results of this approach and the conventional approach are given in the following subsection.

C. Open Circuit Voltage

The open circuit voltage V_{oc} at a temperature T of a PV panels is given by the following relationship [1-3].

$$V_{\text{oc}} = V_{\text{ocn}}(1 + K_{\text{v}}\Delta T) \tag{24}$$

where K_{v} is the temperature coefficient of the open circuit voltage (in 1/K).

This equation is devoid of any irradiation dependence. In reality, the PV panels exhibit dependence on irradiation as well. In [15], an empirical logarithmic relationship is presented. This, however, is found to be not accurate as it exaggerates the effect of irradiation. The authors came up with (25) to express the temperature and the irradiation dependence for open-circuit voltage.

$$V_{\rm oc} = V_{\rm ocn}(1 + K_{\rm v}\Delta T) + mV_{\rm th}\ln\left(\frac{G}{G_{\rm n}}\right) \qquad (25)$$

The derivation of (25) is given in the appendix. Fig. 6 shows a comparison of the calculated $I - V$ with the actual curves provided by the manufacturer at different irradiation levels for TSM225PC05 panels. The red curves represent the $I - V$ curves calculated using (25) in conjunction with (7) whereas the green curves are calculated using (23) and (24).

Fig. 6 shows the $I - V$ curves only in the vicinity of the MPP and the open-circuit point. It is evident that the open circuit voltage and the saturation current relations proposed in this work result in more accurate $I - V$ curves as compared to those obtained through conventional relations at different irradiation levels.

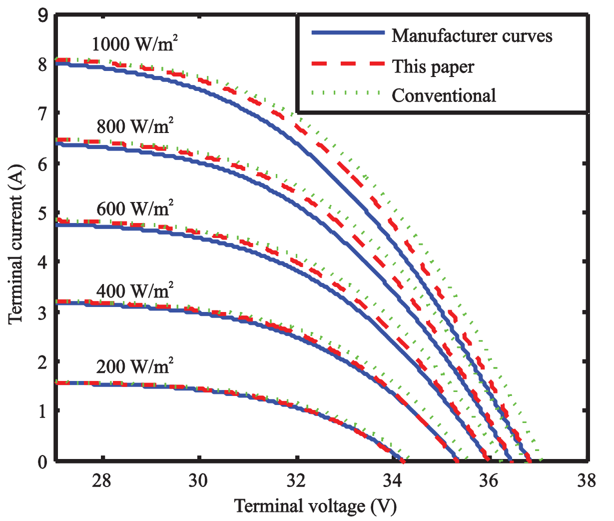

Fig. 6. Comparison of effect of conventional relations and the relations proposed in this paper for V_{oc} and I_{sat} on the $I - V$ curves at different irradiation levels

Fig. 7 shows the $I - V$ curves for KD135SXUPU panels at different temperatures. Again, the red curves are obtained (25) and (7) whereas the green ones are using (23) and (24).

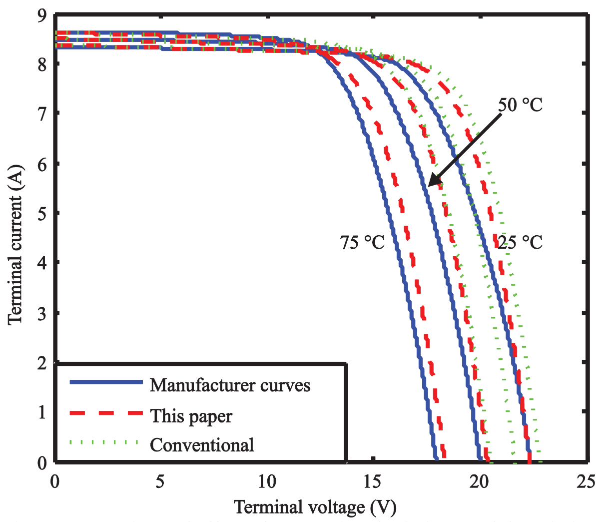

Fig. 7. Comparison of effect of conventional relations and the relations proposed in this paper for V_{oc} and I_{sat} on the $I - V$ curves at different temperatures

Fig. 7 also asserts that the relations proposed in this paper yield better results at non-standard conditions of temperatures and irradiation.

For the voltage at MPP, an expression similar to (25) can be used after replacing $V_{\rm ocn}$ with $V_{\rm mppn}$.

D. *MPP Power and Efficiency*

The available power at MPP depends upon the temperature and irradiation as follows.

$$P_{\rm mpp} = P_{\rm mppn}\left(1 + K_{\rm p}\Delta T\right)\frac{G}{G_{\rm n}} \qquad (26)$$

where $K_{\rm p}$ is the temperature coefficient of power (in 1/K) and $P_{\rm mpp}$ is the available power at the temperature T.

The efficiency of the panels, however, is independent of the incident irradiation and depends on the panel's temperature only. The efficiency η at temperature T is given by the following relation.

$$\eta = \eta_{\rm n}\left(1 + K_{\rm p}\Delta T\right) \qquad (27)$$

where $\eta_{\rm n}$ is the efficiency at nominal conditions of temperature and irradiation.

Other model parameters such as the shunt/series resistance as well as the diode ideality factor are assumed to be independent of temperature and/or irradiation.

V. Comparison Of Models

The proposed algorithm to calculate the parameters of ODM was used for a number of different polycrystalline PV modules. The $I - V$ curves resulting from these parameters were compared with those from OFPM and TDM. The $I - V$ curves provided in the datasheets were taken as the benchmark. The chosen figure of merit is the percentage root mean square error for the terminal current defined as,

$$RMSE\ (\%) = \frac{\sqrt{\frac{1}{N}\sum_{j=1}^{N}\left(I_{\rm j,c} - I_{\rm j,m}\right)^2}}{I_{\rm scn}} \times 100\% \qquad (28)$$

where N is the number of points in $[0 \quad V_{\rm ocn}]$, $I_{\rm j,c}$ is the calculated current and $I_{\rm j,m}$ is the current provided by the manufacturer.

Table 1 summarizes the results for six of the panels that were investigated. Out of the 13 different panels investigated, the ODM with proposed algorithm for parameter extraction gives quite good results for most of the cases. For some of panels, though, the RMSE for ODM is a little higher than TDM, as can also be seen in Table 1. However, a careful observation reveals that the difference is not much. Moreover, the values for the shunt resistance for TDM are unrealistically too high.

Fig. 8 shows example $I - V$ curves for TSM235PC05 panels for ODM, OFPM, TDM as well as the one provided by the manufacturer. Moreover, the current residuals (calculated values - given values) for different models are also given. It is quite clear that the residual is the least for ODM with the proposed algorithm in the whole operating range.

TABLE I

One-Diode Model Parameters & Comparison with TDM and OFPM Parameters

Panel	Model	Parameters						RMSE (%)
		m	I_{ph} (A)	I_{sat1} (A)	I_{sat2} (A)	R_s (Ω)	R_p (Ω)	
TSM225PC05	OFPM	1.239	8.200	3.34×10^{-8}	-	0.301	-	0.530
	ODM	1.05	8.208	1.03×10^{-9}	-	0.374	379.8	**0.176**
	TDM	-	8.200	2.95×10^{-10}	5.49×10^{-6}	0.367	18146	0.310
TSM235PC05	OFPM	1.17	8.310	9.66×10^{-9}	-	0.247	-	0.593
	ODM	1.06	8.314	1.14×10^{-9}	-	0.290	682	**0.227**
	TDM	-	8.310	2.72×10^{-10}	3.59×10^{-6}	0.296	35674	0.372
KD135SXUPU	OFPM	1.751	8.371	6.47×10^{-6}	-	0.042	-	1.392
	ODM	1.751	8.388	5.74×10^{-9}	-	0.168	85.2	**0.430**
	TDM	-	8.371	9.72×10^{-11}	1.53×10^{-5}	0.130	35564	0.988
EGP60C	OFPM	1.740	8.895	8.50×10^{-6}	-	0.106	-	1.653
	ODM	1.242	8.912	3.18×10^{-8}	-	0.272	145	**1.017**
	TDM	-	8.896	1.77×10^{-10}	2.08×10^{-5}	0.243	12891	1.534
BP-MSX60	OFPM	1.552	3.868	1.97×10^{-6}	-	0.033	-	1.572
	ODM	1.007	3.875	7.43×10^{-10}	-	0.297	168.75	1.011
	TDM	-	3.868	4.48×10^{-10}	1.38×10^{-5}	0.198	93453	**0.967**
LPC241	OFPM	1.435	8.566	3.83×10^{-7}	-	0.164	-	1.006
	ODM	1.129	8.575	3.86×10^{-9}	-	0.276	248	0.506
	TDM	-	8.566	1.95×10^{-10}	9.15×10^{-6}	0.271	13550	**0.400**

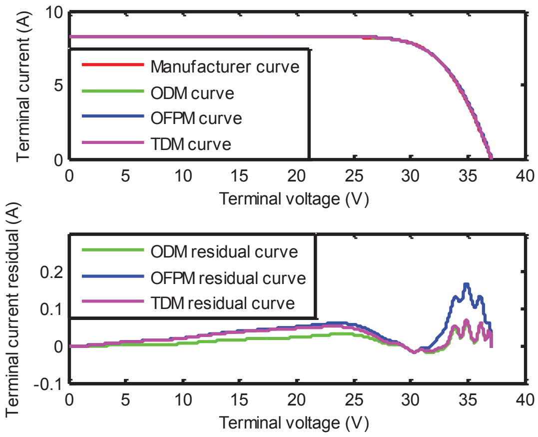

Fig. 8. $I-V$ curves and current residuals for ODM, OFPM and TDM of TSM235PC05 panels

VI. Conclusion

In this work, an algorithm is developed and presented to determine the five parameters of the one-diode model of PV panels. The proposed calculation method always yields plausible results unlike the simultaneous solution of an under-determined system of non-linear equations which sometimes yields non-physical results (e.g. negative series resistance or value of diode ideality factor beyond valid range). The RMSE of the proposed method is also quite low, as given in Table 1, which qualifies it as a useful algorithm. The results also indicate that the one-diode model is a good compromise between accuracy and complexity. Moreover, more accurate relations are derived for the open circuit voltage and diode saturation current that predict these quantities and hence, the $I-V$ characteristic, under all conditions of temperature and irradiation quite accurately.

Appendix

In this appendix, the dependence of open-circuit voltage on irradiation is derived. From (6), neglecting the -1 term as it is quite small as compared to the exponential term in the vicinity of open circuit point, following can easily be derived.

$$V_{ocn} = mV_{th}\ln\left(\frac{I_{phn}R_p - V_{ocn}}{I_{satn}R_p}\right) \quad (A1)$$

Usually, the shunt resistance R_p is quite high so that $I_{phn}R_p \gg V_{ocn}$. Thus, neglecting the second term in the logarithm of (A1), we get the following relation.

$$V_{ocn} = mV_{th}\ln\left(\frac{I_{phn}}{I_{satn}}\right) \quad (A2)$$

Similarly, evaluating (A2) at conditions other than the nominal conditions yields,

$$V_{oc} = mV_{th}\ln\left(\frac{I_{ph}}{I_{satn}}\right) \quad (A3)$$

Taking difference of (A3) and (A2),

$$V_{oc} - V_{ocn} = mV_{th}\ln\left(\frac{I_{ph}}{I_{sat}}\right) - mV_{th}\ln\left(\frac{I_{phn}}{I_{satn}}\right) \quad (A4)$$

After few mathematical manipulations, following relation can easily be arrived at.

$$V_{oc} - V_{ocn} = mV_{th}\ln\left(\frac{I_{ph}}{I_{phn}}\right) \quad (A5)$$

Since $I_{ph} \propto G$, the ratio of photocurrents can be replaced by the ratio of irradiations, as under.

$$V_{oc} - V_{ocn} = mV_{th}\ln\left(\frac{G}{G_n}\right) \quad (A6)$$

$$\Rightarrow \quad V_{oc} = V_{ocn} + mV_{th}\ln\left(\frac{G}{G_n}\right) \quad (A7)$$

Incorporating the temperature dependence as well results in (25).

REFERENCES

[1] M. G. Villalva, J. R. Gazoli, and E. R. Filho, “Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays”, IEEE Transaction on Power Electronics, vol. 24, 2009, pp. 1198-1208.

[2] M. G. Villalva, J. R. Gazoli, and E. R. Filho, “Modeling and circuit-based simulation of photovoltaic arrays”, Brazilian Power Electronics Conference, pp. 1244.

[3] W. De Soto, “Improvement and validation of a model for photovoltaic array performance”, Master thesis, University of Wisconsin-Madison, 2004.

[4] G. Farivar and B. Asaei, “Photovoltaic Module Single Diode Model Parameters Extraction Based on Manufacturer Datasheet Parameters”, in IEEE International Conference on Power and Energy, Nov. 2010, pp. 929-934.

[5] D. Sera, R. Teodorescu and P. Rodriguez, “PV panel model based on datasheet values”, in IEEE International Symposium on Industrial Electronics, Jun. 2007, pp. 2392-2396.

[6] A. Durgadevi, S. Arulselvi and S. P. Natarajan, “Photovoltaic modeling and its characteristics”, International Emerging Trends in Electrical and Computer Technology Conference, pp. 469-475, 2011.

[7] F. Nakanishi, T. Ikegami, K. Ebihara and S. Kuriyama, “Modeling and Operation of a 10 kW Photovoltaic Power Generator using Equivalent Electric Circuit Method”, Photovoltaic Specialists Conference, 2000.

[8] J. A. Gow and C. D. Manning, “Development of a photovoltaic array model for use in power-electronics simulation studies”, in IEEE Proceedings – Electric Power Applications, Mar. 1999, vol. 146, pp. 193-200.

[9] W. Xiao, W. G. Dunford, and A. Capel, “A novel modeling method for photovoltaic cells”, IEEE 35th Annual Power Electronics Specialists Conference, vol. 3, pp. 1950-1956, 2004.

[10] J. Crispim, M. Carreira and R. Castro, “Validation of Photovoltaic Electrical Models against Manufacturers Data and Experimental Results”, IEEE POWERENG, 2007.

[11] Z. Housheng and Z. Yanlei, “Research on Novel Digital Photovoltaic Array Simulator”, in International Conference on Intelligent Computation Technology and Automation, May 2010, vol. 2, pp. 1077-1080.

[12] Z. Ran, X. Hui-jun, Z. Zhi-ying and Z. Shun-hua, “A Simplified Double-Exponential Model of Photovoltaic Module in Matlab”, in International Conference on Energy and Environment Technology, Oct. 2009, vol. 3, pp. 157-160.

[13] K. Ishaque, Z. Salam and H. Taheri, “Simple, fast and accurate two-diode model for photovoltaic modules”, in Solar Energy Materials & Solar Cells, 2011, pp. 586-594.

[14] G. H. Yordanov, O. M. Midtgard and T. O. Saetre, “Two-diode Model Revisited: Parameter Extraction from Semi-log plots of I-V Data”, in 5th World Conference of Photovoltaic Energy Conversion, Sept. 2010.

[15] V. Quasching, “Regenerative Energiesysteme Technologie – Berechnung – Simulation”, 7th Edition, 2011.