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PV system behavior based on datasheet

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Abstract-- This article proposes an easy and accurate alternative approach to predict the I-V characteristics of a photovoltaic PV system using the single diode five parameters model. This approach is based exclusively on datasheet; it can be used to obtain the parameters of a PV system using information from the datasheet parameters (I_{sc}, V_{oc}, I_{mp}, V_{mp}). The five parameters I_{ph}, I_0, a, R_s, and R_p of a PV system are calculated with the aid of five equations that can be solved simultaneously. A new fifth equation $dP/dI=0$ at the maximum power point is introduced. This new equation replaces the equation, usually used in literature, determined from the slope of the I-V curve at the short circuit current, namely, $dI/dV=-1/R_p$. The benefit in using the new equation is that one doesn't rely on the experimental I-V curve to determine R_p. The PV system behavior at temperature and irradiance conditions other than Standard Test Conditions (SRC) is, also, predicted.

Keywords- solar cell, PV module, PV array, parameters determination

I. INTRODUCTION

A photovoltaic (PV) system generates electricity by direct conversion of Sun's light into electricity in a process that does not generate heat. PV power systems do not have any moving parts. They are reliable, require little maintenance and generate no pollutants or noise. The basic device of a PV system is the solar cell. Solar cells may be grouped to form modules, panels, and arrays.

The output of a PV system mainly depends on the light intensity, the cell temperature, the panel's (or array) orientation, and atmospheric conditions. The light intensity primarily affects the amount of current produced. On the other hand, the cell temperature controls the voltage produced. Upon increasing the cell temperature, the current produced remains (almost) the same while the voltage is reduced, reducing the output power. All of these factors need to be taken into consideration to accurately predict the PV system energy production.

The Sun's outer surface, photosphere, has an effective blackbody temperature of about 5800 K. Thus, as viewed from the Earth, the radiation emitted from the Sun appears to be essentially equivalent to that emitted from a blackbody at 5800 K [1]. The radiant flux, received from the Sun outside the Earth's atmosphere is remarkably constant. The so-called solar constant, 1367 W/m^2, defines the average amount of energy received in a unit of time on a unit area perpendicular to the path of the radiation outside the atmosphere at the average distance of the Earth's orbit around the Sun [1]. The radiation intensity outside the Earth's atmosphere is called the extraterrestrial radiation. On passing through the atmosphere, the extraterrestrial radiation experiences attenuation due to reflection, scattering, and absorption. The solar radiation is reflected and scattered primarily by clouds (moisture and ice particles), particulate matter (dust, smoke, haze and smog), and various gases. Reflection of incident solar radiation back into space by clouds varies according to their thickness and albedo (ratio of reflected to incident light) [2]. For any given location on Earth, the solar radiation reaching the surface decreases with increasing cloud covers.

Under clear-sky conditions selective scattering of sunlight accounts for the blue color of sky when the degree of scattering is sufficiently high. This is determined by the length of the atmospheric path traversed by sunlight [2], which is referred to as Air Mass (AM). Air Mass (AM) represents the strength or the mass of the atmosphere. It can be approximated by Eq. (1) when the Sun is at an angle ϕ to overhead as shown in Fig. 1 [3].

$$\text{Air Mass} = \frac{1}{\cos\varphi} \qquad (1)$$

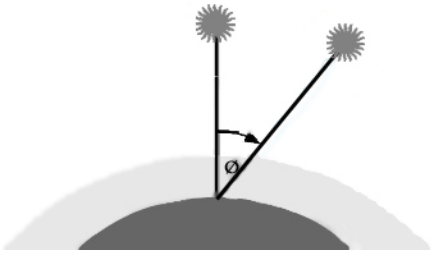

Fig. 1. Simple geometrical considerations of solar radiation path for ideal homogeneous atmosphere.

When the Sun is directly overhead, radiation passes through the earth's atmosphere to the ground in a shortest radial path. This radiation is called "Air Mass 1" or "AM 1.0". On the other hand, solar radiation must pass through additional Air Mass when it is at an angle other than high noon. When the Sun is at a zenith angle of 48.2 degrees, the incident radiation passes through 1.5 times as much Air Mass as at high noon. This radiation is termed AM 1.5.

Uniform Standard Test Conditions (STC) is usually specified so that a performance comparison can be made between different PV systems (cells, modules, etc.). The parameters obtained from such testing are usually provided on the manufacturer's datasheet. Measurements are performed under these STC and the electrical characteristics obtained characterize the PV system accurately under these conditions. At STC reference vertical irradiance with a typical value of 1000W/m^2, reference cell temperature for performance rating, T_0 with a typical value of 25˚C and a tolerance of ±2˚C, and a specified light spectral distribution with an Air Mass, AM1.5, are used.

In addition to supplying performance parameters at the STC, manufacturers also provide performance data under the Nominal Operating Cell Temperature (NOCT) [4]. It is defined as the temperature reached by the open circuited cells in a module under conditions in which irradiance on cell surface is 800W/m^2, ambient temperature is 20˚C, and average windspeed of 1 m/s, with the cell or module in an electrically open circuit state, the wind oriented parallel to the plane of the array, and all sides of the array are fully exposed to the wind.

The determination of PV system cell parameters from measured I-V characteristics is of vital importance for the quality control and the evaluation of its performance. Several authors [5-11] have suggested methods to extract the parameters that describe the non-linear model of PV systems. These parameters are the photo-generated current, the dark saturation current, the series resistance, the parallel resistance, and the diode quality factor. Wolf and Rauschenbach [5] have suggested a method involve fixed and variable illumination in addition to dark I-V characteristics. Some authors have suggested a method that analyzes the practical I-V measurements [6]. Others developed a method based on determining the photocurrent by calculating the total number of photons in the solar spectrum of AM1.5 [7].

Werner [8] has proposed and examined a method for the determination of the cell parameters based on the current and the conductance of both Schottky diodes and solar cells.

Chegaar *et al*. [9] have presented a comparative study of four methods for extracting solar cell parameters of the five parameters model. The methods are based on a vertical optimization method, and an analytical five point method, in addition to two other methods based on the current voltage characteristics and the subsequently calculated conductance.

M. Gradella *et al.* [10,11] have proposed a method of modeling and simulation of photovoltaic arrays based on adjusting the I-V curve at three points: open circuit, maximum power, and short circuit.

II. FIVE PARAMETERS MODEL

The PV cell or module is usually represented by a single exponential model (usually called the five parameters model) [12] or a double exponential model. The single exponential model equivalent circuit is shown in Fig. 2. In this model the current is expressed in terms of voltage and other parameters as shown in Eq.(2)

$$I = I_{ph} - I_0 \left\{ \exp\left[\frac{(V + IR_s)}{V_t a} \right] - 1 \right\} - \frac{V + IR_s}{R_p}, \qquad (2)$$

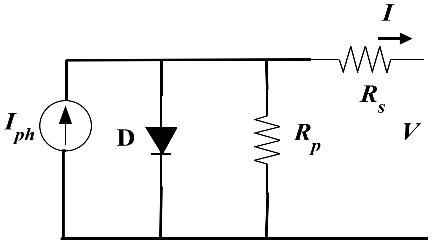

Fig. 2. The five parameters model equivalent circuit of a practical PV device.

where I_{ph} and I_0 are the photo-generated current and the dark saturation current of the PV system, respectively, and $V_t = N_s kT/q$ is the thermal voltage of the PV system with N_s cells connected in series, R_s and R_p are the cell series resistance and the cell shunt resistance, respectively, a is the diode quality factor, q is the electronic charge 1.6 x 10^{-19}C, k is the Boltzmann's constant 1.38 x 10^{-23} *J/K*, and T is the ambient temperature, in Kelvin. Although this model is widely used and accepted in the simulation and the testing of PV systems the double exponential model is more accurate and more difficult to solve [12]. The double exponential model is given by Eq. (3)

$$\begin{aligned} I = I_{ph} &- I_{01} \left\{ \exp\left[\frac{(V + IR_s)}{V_t} \right] - 1 \right\} \\ &- I_{02} \left\{ \exp\left[\frac{(V + IR_s)}{V_t a} \right] - 1 \right\} - \frac{V + IR_s}{R_p} \end{aligned}, \qquad (3)$$

where, I_{01} and I_{02} are the saturation current due to diffusion and the saturation current due to recombination in the space charge layer, respectively.

Models that use constant parameters have been proposed [13,14], but these models are inaccurate as they do not account for temperature variation.

The five parameters model as seen in Eq. (2) assumes that the dark current of a PV system can be described by a single exponential dependence modified by a diode quality factor a. The values of the five parameters in the equation must be determined to reproduce the I-V curve of a PV system. This requires five equations containing five unknowns that should be solved simultaneously to obtain the values of the parameters [15,9]. Some authors have further simplified this model by removing the shunt resistance R_p to obtain a model of moderate complexity [16] referred to as the four parameters model. This model reliably predicts the performance of single crystal and polycrystalline PV systems. The four parameters model assumes that the slope of the I-V curve is flat at the short-circuit condition

$$\left(\frac{dI}{dV}\right)_{v=0} = 0\,. \tag{4}$$

However, this assumption is not generally valid for amorphous PV systems. The short circuit I-V slope is finite and negative, so the four parameters model cannot reproduce the I-V characteristics of amorphous silicon, for example.

To determine the five reference parameters in the five parameters model (a, I_o, I_{ph}, R_s, and R_p), five pieces of information are needed at reference conditions (SRC). These pieces of information are the short circuit current (I_{sc}), open circuit voltage (V_{oc}), current and voltage at the maximum power point (I_{mp} and V_{mp}), respectively. The fourth piece of information required for the calculation of the five parameters can be obtained by realizing that the slope of the power at the maximum power point (dP/dV_{mp}) is equal to zero. The fifth piece of information is usually determined from the slope of the I-V curve at the short circuit current point [15,9] as shown in Eq. (5)

$$\left(\frac{dI}{dV}\right)_{I=Isc} = -\frac{1}{R_p}\,. \tag{5}$$

In the case that the slope of the I-V curve at the short circuit current point is not directly provided, it can be determined if the manufacturer provides an I-V curve at the reference conditions. If this is not provided, either the 4-Parameter model can be used which is not recommended for amorphous cell types, or the slope can be approximated by plotting the points provided by the manufacturer's datasheet (V_{oc}, V_{mp}, I_{mp}, I_{sc}) and determining the slope between the short circuit current point and the maximum power point. This value should be divided by two in order to obtain a reasonable slope value. This piece of information has a drawback since it relies on calculating the slope of the I-V curve at the short circuit condition.

In this article a new fifth piece of information is proposed. Figure 3 depicts the Power-Current variations for a typical solar cell. From this figure we conclude that the slope of the power at the maximum power point is equal to zero. Thus, from the Power-Current relation of a typical solar cell one obtains:

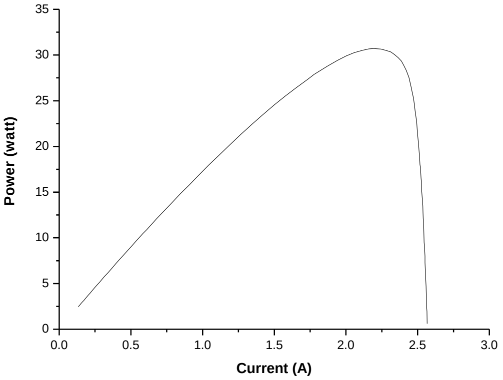

Fig. 3. Power-Current variations of a typical solar cell. A new fifth equation is obtained from this figure.

$$\left(\frac{dP}{dI}\right)_{\substack{V_{mp}\\ I_{mp}}} = 0\,. \tag{6}$$

The advantage of using this equation is that one doesn't rely on the experimental I-V graph to determine the value of R_p.

III. MODELING OF PV DEVICES

For the five parameters model, at the open-circuit point on the I-V curve, $V = V_{oc}$ and $I = 0$, substituting these values into Eq. (2), the first needed equation is given by

$$0 = I_{ph} - I_0\left\{\exp\left[\frac{V_{oc}}{V_t a}\right] - 1\right\} - \frac{V_{oc}}{R_p}\,. \tag{7}$$

At the short-circuit point on the I-V curve, $I = I_{sc}$ and $V = 0$, after substituting these values in Eq. (2), the second needed equation is given by:

$$I_{sc} = I_{ph} - I_0\left\{\exp\left[\frac{I_{sc}R_s}{V_t a}\right] - 1\right\} - \frac{I_{sc}R_s}{R_p}\,. \tag{8}$$

At the maximum-power point on the I-V curve one has $I = I_{mp}$ and $V = V_{mp}$. By substituting these values into Eq. (2), a third equation is obtained

$$I_{mp} = I_{ph} - I_0\left\{\exp\left[\frac{(V_{mp} + I_{mp}R_s)}{V_t a}\right] - 1\right\} - \frac{V_{mp} + I_{mp}R_s}{R_p} \tag{9}$$

An additional equation can be derived using the fact that on the P-V characteristics of a PV system at the maximum power point, the derivative of power with voltage is zero.

$$\left(\frac{dP}{dV}\right)_{\substack{V=V_{mp}\\ I=I_{mp}}} = \frac{d(IV)}{dV} = I + \frac{dI}{dV}V = 0\,. \tag{10}$$

Also, a fifth equation can be derived using the fact that on the P-I characteristics of a PV system at the maximum power point, the derivative of power with respect to current is zero

$$\left(\frac{dP}{dI}\right)_{\substack{V=V_{mp}\\ I=I_{mp}}} = \frac{d(IV)}{dI} = V + \frac{dV}{dI}I = 0. \qquad (11)$$

The five reference parameters (a, I_o, I_{ph}, R_s, and R_p) can be obtained by simultaneously solving Eq. (7) through Eq. (11) using the Mathcad solve block (Given …. Find) and by implementing the method of Conjugate Gradients.

The necessary guess values are easily determined as follows:

The value I_{ph} is approximately equal to the value of I_{sc} which can be used as a good guess value. Usually, the diode quality factor $1 \leq a \leq 1.5$ is reported in literature [11]. The reverse saturation current I_0 guess value can be obtained using the following equation [11]:

$$I_0 = \frac{I_{sc}}{\exp\left(V_{oc}/aV_t\right) - 1}$$

A guess value for R_p can be obtained by evaluating Eq. 2 at open circuit condition. Also, a guess value for R_s can be obtained by evaluating Eq. 2 at short circuit condition and assuming $R_p \rightarrow \infty$.

Table 1 shows the data obtained from the datasheet for KC200GT solar array and MSX60 solar module at 25 °C, AM1.5, and 1000 W/m^2. Table 2 illustrates that the model parameters obtained by this method are in good agreement with the parameters obtained by M. Villalva *et al* [10,11] for KC200GT solar array. Figure 4 depicts the I-V curve for KC200GT solar array at 25 °C, AM1.5, and 1000 W/m^2. It is clear that the generated I-V data obtained by this method are in good agreement with the I-V data obtained by M. Villalva *et al* [10,11].

Table 1. Parameters of the KC200GT solar array and MSX60 solar module at 25 °C, AM1.5, and 1000 W/m^2 from datasheet.

Parameter	KC200GT solar array	MSX60 solar module
I_{mp}	7.61 A	3.5 A
V_{mp}	26.3 V	17.1 V
P_{max}	200.143 W	59.85 W
I_{sc}	8.21 A	3.8 A
V_{oc}	32.9 V	21.1 V
N_s	54	36

Table 2. A comparison between the calculated values and the published values of the parameters for KC200GT solar array

Parameter	Calculated values	Published values
I_o	4.812 x 10^{-8} A	9.825 x 10^{-8} A
I_{ph}	8.215 A	8.214 A
a	1.235	1.3
R_s	0.247 Ω	0.221 Ω
R_p	414.89 Ω	415.405 Ω

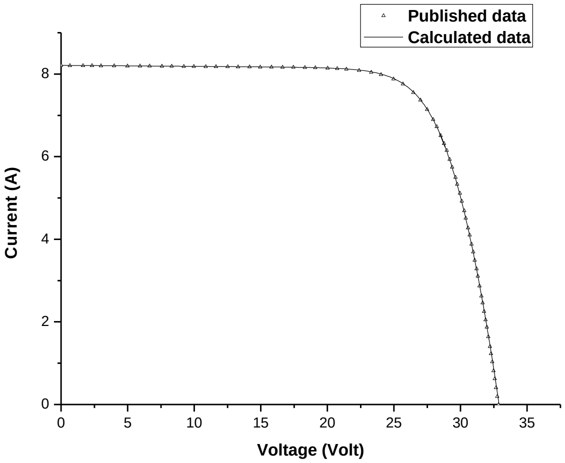

Fig. 4. I-V Characteristics for KC200GT solar array at 25°C, AM1.5, and 1000 W/m^2. Points are published data, line is calculated data.

Table 3 shows the calculated parameters obtained for MSX60 solar Module. Figure 5 illustrates the I-V curve for MSX60 solar module at 25°C, AM1.5, and 1000 W/m^2. It is obvious that the calculated data are in good agreement with the experimental data.

Table 3. The calculated values of the parameters for MSX60 solar module at 25°C, AM1.5, and 1000 W/m^2.

Parameter	Calculated values
I_0	1.866 x 10^{-7} A
I_{ph}	3.812 A
a	1.358
R_s	0.178 Ω
R_p	358.569 Ω

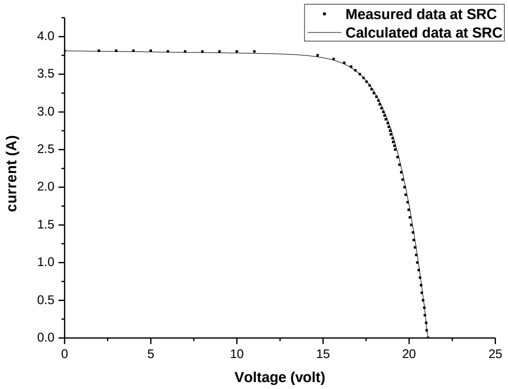

Fig. 5. I-V Characteristics for MSX60 solar module at 25°C, AM1.5, and 1000 W/m^2. Points are measured data. Line is calculated data.

To predict a PV module or solar cell I-V characteristics curve at temperature values where data or I-V curves are not available, parameter temperature coefficients are necessary. Temperature coefficients are the rate of change of different photovoltaic parameters with respect to temperature. These coefficients can be determined for I_{sc} (α_{Isc}), V_{oc} (β_{Voc}), I_{mp} (α_{Imp}), and V_{mp} (β_{Vmp}). It has been published that these four temperature coefficients are necessary to accurately model the effect of temperature on the I-V characteristics of a module [17]. The equations necessary to calculate the short circuit current and the maximum power point current at temperature values other than SRC are [17]

$$I_{sc}(T) = I_{sc}(T_r)[1-\alpha_{Isc}(T_r - T)]\,, \tag{12}$$

$$I_{mp}(T) = I_{mp}(T_r)[1-\alpha_{I_{mp}}(T_r - T)]\,. \tag{13}$$

The open circuit V$_{oc}$ voltage shows a linear dependence with the temperature [18,19] as shown in Eq. (14)

$$V_{oc}(T) = V_{oc}(T_r) - \beta_{Voc}(T_r - T)\,. \tag{14}$$

Also, the maximum power voltage is given by the following equation [19]

$$V_{mp}(T) = V_{mp}(T_r) - \beta_{Vmp}(T_r - T)\,. \tag{15}$$

Figure 6 shows the mathematical I-V curves for MSX60 solar module plotted with the experimental data at four different temperature conditions. It can be seen from this figure that the calculated I-V curves are in good agreement with the experimental data. Some points are not exactly matched which may be attributed to a non perfect translation equations. The mathematical and experimental variations of power with voltage for MSX60 solar module are illustrated in Fig. 7.

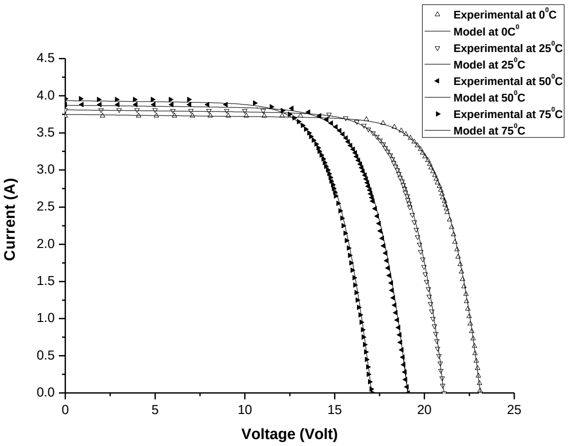

Fig. 6: I-V characteristics at various temperatures. Points are measured data. Lines are calculated data.

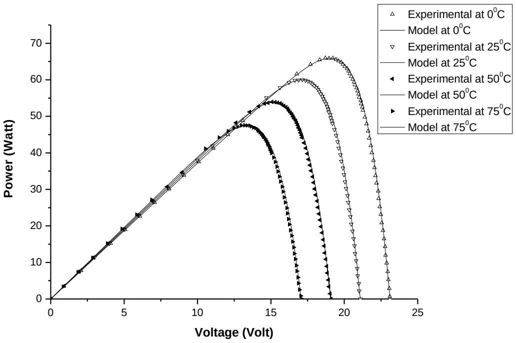

Fig. 7: Power vs. voltage at various temperatures. Points are measured data. Lines are calculated data.

Figure 8 shows the I-V curves at various irradiance levels, 25°C for MSX60 solar module. These curves were obtained using a set of translation equations for current and voltage. Such equations allow one to translate the entire current versus voltage curve from temperature T_1 to T_2 and irradiance E_1 to E_2. These equations are [20]

$$I_2 = I_1 + I_{sc1}\left(\frac{E_2}{E_1} - 1\right) + \alpha(T_2 - T_1)\,, \tag{16}$$

$$V_2 = V_1 - R_s(I_2 - I_1) - I_2 K(T_2 - T_1) + \beta(T_2 - T_1)\,, \tag{17}$$

where K is a curve-shape correction factor.

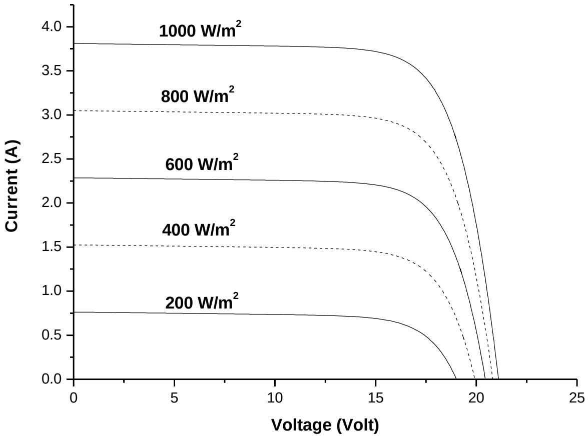

Fig. 8: I-V characteristics calculated at various irradiance levels, 25°C.

IV.CONCLUSION

An alternative approach to predict the I-V characteristics of a photovoltaic PV system using the single diode five parameters model is presented in this article. This approach is based exclusively on datasheet parameters. The five parameters I_{ph}, I_0, a, R_s, and R_p of a PV system are calculated with the aid of five equations that can be solved simultaneously. In this work, a new equation $dP/dI=0$ at the maximum power point replaces the equation, usually used in literature, determined from the slope of the I-V characteristics at the short circuit current, $dI/dV=-1/R_p$. This new equation allows one to calculate the five parameters without relying on the experimental I-V curve to determine R_p as usually reported in literature [15,9]. The PV system behavior at temperature and irradiance conditions other than Standard Test Conditions (SRC) is predicted.

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