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Fitting of the Solar Cell *IV*-curve to the Two Diode Model

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Abstract

In this paper, the parameters for the solar cell two diode model are solved with respect to the cell series resistance, thus providing an efficient mean to extract the possible combinations for the model parameters. In the calculations, the diode ideality factors n_1 and n_2 have been left fixed. The usual way is to set $n_1 = 1$ and $n_2 = 2$ to represent the diffusion and recombination current terms, respectively. The procedure is tested with respect to some published cell parameter values with good results.

1. Introduction

The current versus voltage characteristics of a solar cell under illumination is commonly translated to an equivalent circuit containing a photocurrent source and a diode with a shunt resistor, and a series resistor in the load branch. To get a more accurate fit to a measurement data, a second parallel diode is sometimes added to the circuit. The two diode model allows one to separate the diffusion current term, in which the diode ideality factor n equals 1, and the recombination current term, in which the ideality factor equals 2. The other model parameters are the photocurrent, I_{ph}, the diode saturation currents I_{s1} and I_{s2}, the shunt resistance R_{sh}, and the cell series resistance R_s.

The task for extraction of the five model parameters from the cell current equation is not analytically solvable, and iterational methods must be used to fit the measured current versus voltage curve to the equation. The fit can be based on a set of five equations derived from the current equation in different ways. A common choice is to fit the parameters in the open circuit point $(0, V_{oc})$, short circuit point $(I_{sc}, 0)$ and maximum power point (I_m, V_m), with the remaining two equations derived from the curve slope at $(0, V_{oc})$ and $(I_{sc}, 0)$. One way to proceed to the solution is to solve as many parameters as possible with respect to a smaller set of parameters and iterate from this limited set of equations. With a proper choice of starting equations, four of the parameters can be presented as a function of the series resistance only, as presented in this paper. The series resistance R_s remains to be iterated. As the parameters I_{ph}, I_{s1}, I_{s2} and R_{sh} are represented as functions of R_s only, and should be positive in sign in the correct solution, one has a very effective mean to narrow out the R_s ranges inside which the solutions are to be found.

2. Equations used in the parameter extraction procedure

The current equation for the two diode model $F(I, V)$ is

$$F(I, V) = I - I_{ph} + I_{s1} \cdot (e^{(V + I \cdot R_s)/n_1 \cdot V_t} - 1) + I_{s2} \times (e^{(V + I \cdot R_s)/n_2 \cdot V_t} - 1) + \frac{V + I \cdot R_s}{R_{sh}} = 0,$$

where I is the cell output current, I_{ph} is the photocurrent, I_{s1}, I_{s2} are the saturation currents of diodes 1 and 2, R_s the series resistance, R_{sh} the shunt resistance, V is the output voltage of the cell, and $V_t = kT/q$ where k is the Boltzmann constant, T the cell temperature and q the electron charge. In this paper the diode ideality factors n_1 and n_2 are fixed to 1 and 2 to represent the diffusion and recombination current terms, respectively [3].

The five base equations are now derived in a somewhat similar manner as was done by Chan *et al.* [1] with the one diode model, and Enebish *et al.* [2] with the two diode model. Three of the five equations can be found putting the pairs $(0, V_{oc})$, $(I_{sc}, 0)$, (I_M, V_M) to $F(I, V)$. In the derivation of the remaining two formulas, one can use the relation [2]

$$\frac{dF}{dI} + \frac{dF}{dV}\frac{dV}{dI} = 1 + \left(R_s + \frac{dV}{dI}\right) \times \left(\frac{I_{s1}}{n_1 V_t} e^{(V + IR_s)/n_1 V_t} + \frac{I_{s2}}{n_2 V_t} e^{(V + IR_s)/n_2 V_t} + \frac{1}{R_{sh}}\right) = 0$$

and solve it in the short circuit $(I_{sc}, 0)$ and maximum power (I_M, V_M) points. To shorten the expressions, we now adopt the following notation:

$$A = e^{V_{oc}/n_1 \cdot V_t},\ B = e^{V_{oc}/n_2 \cdot V_t},\ C = e^{I_{sc} \cdot R_s/n_1 \cdot V_t}$$

$$D = e^{I_{sc} \cdot R_s/n_2 \cdot V_t},\ E = e^{(V_M + I_M \cdot R_s)/n_1 \cdot V_t},\ G = e^{(V_M + I_M \cdot R_s)/n_2 \cdot V_t}.$$

We also write

$$\alpha = C \cdot \left(1 + \frac{V_{oc} - I_{sc} \cdot R_s}{n_1 \cdot V_t}\right) - A,$$

$$\beta = D \cdot \left(1 + \frac{V_{oc} - I_{sc} \cdot R_s}{n_2 \cdot V_t}\right) - B$$

$$\gamma = E - A - C \cdot \frac{V_M + I_M \cdot R_s - V_{oc}}{n_1 \cdot V_t},$$

$$\delta = G - B - D \cdot \frac{V_M + I_M \cdot R_s - V_{oc}}{n_2 \cdot V_t}$$

Note that the expressions are functions of R_s only. Next, we define $dV/dI_{V=0} \equiv R_{sh0}$ to represent the diode shunt resistance as determined directly from the IV − curve slope in the short circuit $(I_{sc}, 0)$ point. After some mechanical calculations we can represent I_{s1}, I_{s2}, I_{ph}, and R_{sh} as a function of Rs only:

$$I_{s1} = \frac{\delta I_{sc} - 1/(R_{sh0} - R_s)\,(\beta(V_M + I_M R_s - V_{oc}) + \delta(V_{oc} - I_{sc} R_s)) - \beta I_M}{\gamma \cdot \beta - \alpha \cdot \delta}$$

$$I_{s2} = \frac{1}{\beta} \cdot \left(\frac{V_{oc} - I_{sc} \cdot R_s}{R_{sh0} - R_s} - I_{sc} - \alpha \cdot I_{s1} \right)$$

$$I_{ph} = I_{s1}\left(A - 1 - \frac{V_{oc}}{n_1 \cdot V_t} \cdot C \right) + I_{s2}$$

$$\times \left(B - 1 - \frac{V_{oc}}{n_2 \cdot V_t} \cdot D \right) + \frac{V_{oc}}{R_{sh0} - R_s}$$

$$\frac{1}{R_{sh}} = \frac{1}{R_{sh0} - R_s} - I_{s1} \cdot \frac{C}{n_1 \cdot V_t} - I_{s2} \cdot \frac{D}{n_2 \cdot V_t}.$$

The R_s can be iterated from the formula

$$1 + \left(R_s - \frac{V_M}{I_M} \right) \cdot \left(\frac{I_{s1}}{n_1 \cdot V_t} \cdot E + \frac{I_{s2}}{n_2 \cdot V_t} \cdot G + \frac{1}{R_{sh}} \right) = 0.$$

3. Results and discussion

A procedure to make the parameter extraction has been written in C. The input parameters defining the specific cell under study are the short circuit current I_{sc}, the open circuit voltage V_{oc}, the voltage V_M and current I_M in the maximum power point, the voltage versus current curve slope at short circuit R_{sh0}, and temperature T. The parameter extraction is initiated by checking the ranges of R_s inside where positive values of I_{ph}, I_{s1}, I_{s2} and R_{sh} can be found simultaneously. The possible solutions for R_s is then iterated inside these ranges.

The procedure was tested against published parameter values of a pn-junction solar cell. P. Sana, J. Salami and A. Rogathi [4] have fabricated high efficiency polycrystalline silicon solar cells and used NREL to make the standard measurements. Their NREL measurements at 25 °C on a 1.00 cm^2 17.7% efficient cell gave $V_{oc} = 0.6259$ V, $I_{sc} = 35.60$ mA, $V_M = 0.5284$ V, $I_M = 33.4$ mA. The shunt and series resistance measurements gave $R_{sh} = 299$ kohm and $R_s = 0.34$ ohm.

The group also analyzed the results with a two diode model using ideality factor of 3.6 with the second diode. Their calculations gave $I_{s1} = 1.33 \cdot 10^{-12}$ A and $I_{s2} = 9.37 \cdot 10^{-7}$ A for the diode saturation currents. The corresponding values from our procedure were $I_{s1} = 8.77 \cdot 10^{-13}$ A and $I_{s2} = 6.77 \cdot 10^{-7}$ A, which are very close to the reference, despite the fact that $n_1 = 1$ had to be assumed as in the reference paper its value was not mentioned. The R_s value obtained was 0.487 ohm, which is relatively far away from the 0.34 ohm measured reference value. In practical use, one of the most critical things with the procedure is the accurateness of the measured input parameters, e.g. T and R_{sh0}, as was pointed out in [1].

References

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