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An explicit J–V model of a solar cell for simple fill factor calculation

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Abstract

The J–V equation of a solar cell is implicit and requires iterative calculation to determine the fill factor and the maximum power point. Here an explicit model for J–V characteristic is proposed which is applicable to a large variety of solar cell. This model allows an easy estimation of fill factor from four simple measurements of the bias points corresponding to V_{oc}, J_{sc}, and any two voltage values lying between 0 and V_{oc}, where V_{oc} is the open circuit voltage and J_{sc} is the short circuit current density.

Keywords: Solar cell; J–V model; Fill factor; Explicit model

1. Introduction

The electricity generated from solar cells is one of the best options for the sustainable future energy requirements of the world (Razykov et al., 2011). For an illuminated solar cell having parasitic series and shunt resistances, the simplest of the current density–voltage J–V equations called the Single Exponential Model (SEM), has an implicit form

$$J = J_{ph} - J_0\left\{\exp\left(\frac{V + JR_s}{\eta V_t}\right) - 1\right\} - \frac{V + JR_s}{R_{sh}}, \qquad (1)$$

where J_0 is the dark current density, J_{ph} is the photogenerated current density, V_t is the thermal voltage at temperature T, η is the ideality factor, R_s is the unit area parasitic series resistance, and R_{sh} is the unit area parasitic shunt resistance. The implicit form of (1) calls for iterative calculations to compute the maximum power point ($V_{mpp,}$, J_{mpp}) and the fill-factor (FF) in terms of physical parameters. But some stability & effectiveness of the parameters are required to get a fast convergence with automatic error correction in iterative computation (Zhu et al., 2011). For simplification of the calculation, efforts have been made to transform (1) to an explicit form (Karmalkar and Haneefa, 2008; Jain and Kapoor, 2004; Banwell and Jayakumar, 2000; Ortiz-Conde and Garcia Sanchez, 1992; Abuelma'atti, 1992; Fjeldly et al., 1991; Saloux et al., 2011). Some semiempirical approach is also used on solar panel (similar expression like (1)) to estimate the J–V (De Soto et al., 2006). Instead of deriving an explicit solar cell model some works (Green, 1981; Araujo and Sanchez, 1982) have focused on the derivation of approximate closed-form solution for (J_{mpp}, V_{mpp}) and FF alone. After the fabrication of solar cell it is most important to determine its (V_{mpp}, J_{mpp}) point and FF. Generally, these parameters are estimated from a detailed measurement of the J–V curve at numerous points (Chan et al., 1986).

In this paper a new approach is presented to address the problem of finding a closed form solution for (V_{mpp}, J_{mpp}) point and FF. This explicit model allows an easy estimation of these from four simple measurements of V_{oc}, J_{sc}, J for two values of V. The explicit model and the estimation of V_{mpp} and FF are presented in section 2 and the model is validated with wide variety of solar cells using the measured data available in the literature.

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2. Explicit model

Denoting the short circuit current density as J_{sc} and the open circuit voltage as V_{oc}, the normalized voltage, v and normalized current density j can be represented as $v = V/V_{oc}$ and $j = J/J_{sc}$ respectively. This normalization enables a compact representation of J–V values of wide variety of solar cell into $[0, 1] \times [0, 1]$ space. This representation shows that the simple analytical explicit function fits the wide variety of J–V measurement accurately,

$$v^m + j^n = 1 \tag{2}$$

The nature of the curve is shown in (Fig. 1) for different values of m and n. The (Fig. 2) represents a nice fit of the explicit model (2) with the implicit model (1) of a solar cell.

The closed form solution for (V_{mpp}, J_{mpp}) point and FF are derived from (2). The normalized maximum power voltage v_{mpp} is obtained from the equation $d(jv)/dv = 0$ at $v = v_{mpp}$, which yields $mv_{mpp}^m = nj_{mpp}^n$. Since $v_{mpp}^m + j_{mpp}^n = 1$ using (2), the normalized maximum power point can be represented as

$$v_{mpp} = \left(1 + \frac{m}{n}\right)^{-(1/m)} \tag{3}$$

And the FF is given by

$$FF = v_{mpp}j_{mpp} = \left(\frac{m}{n}\right)^{1/n}\left(1 + \frac{m}{n}\right)^{-\left(\frac{1}{m}+\frac{1}{n}\right)} \tag{4}$$

In this model, only four parameters are required to be extracted to fit the measured data and to estimate the maximum power point and FF. While J_{sc} and V_{oc} are measured directly, m and n are extracted using two additional simple measurement of j for two any values of v lies in [0, 1]. Since from (2), we can state that $\log n \log j = \log(1 - v^m) \approx -v^m$, measurement of j at $v = a$ and $v = b$ leads to,

$$m \approx \frac{\log(\log j_a / \log j_b)}{\log(a/b)} \tag{5}$$

And using the value of m, n can be approximated as

$$n \approx -a^m / \log j_a \tag{6}$$

Though Eqs. (5) and (6) holds for any set of values (a, b), $a = 0.8$ and $b = 0.9$ is a good choice of determining the fill factor satisfactorily.Using the aforesaid approach, m and n are extracted and then J–V curves, Vp, Jp, and FF for a number of cells whose measured data are available in the literature. The calculated and measured values are in good agreement, as shown in Table 1.

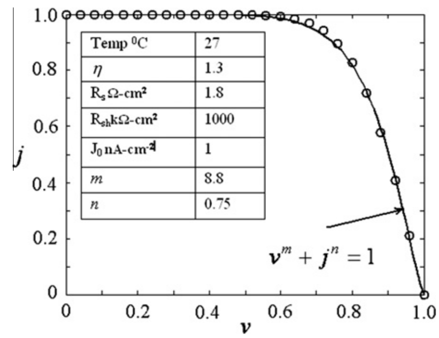

Fig. 2. Normalized J–V curve of silicon solar cell (Karmalkar and Haneefa, 2008) (parameters are shown in the table) and the explicit model using (2). Line shows the explicit model (2) whereas the points show the implicit model (1).

3. Discussion

The explicit description of normalized form (2) of simple exponential model (1) validates the data of wide variety of solar cells and gives a simple closed form Eq. (4) for the fill factor calculation. For $n = 1$, the explicit Eq. (2) can be transformed into $j = 1 - v^m$. This power law form can be viewed as the normalized characteristic of an ideal solar cell where R_{sh} is infinite and photo-current is not bias dependent (Das and Karmalkar, 2011). By setting $n = 1$ in (4), FF becomes $m(1 + m)^{-1-(1/m)}$ which has a close match with FF derived in Karmalkar and Haneefa (2008), Das and Karmalkar (2011). For low voltage while $v^m \ll 1$ the explicit Eq. (2) can be transformed into $j = 1 - (1/n)v^m$. Since v^m is very small, $(1/n)$ can be viewed as a constant linear factor for the linear region of the v–j curve. When v is close to 1, the value m dominates the region where v–j is non-linear. To find the values of m and n, it is required to fetch the quantitative information from the non-linear portion of the v–j curve and hence $a = 0.8$ and $b = 0.9$ are used for a satisfactory choices for the values a and b in Eq. (5).

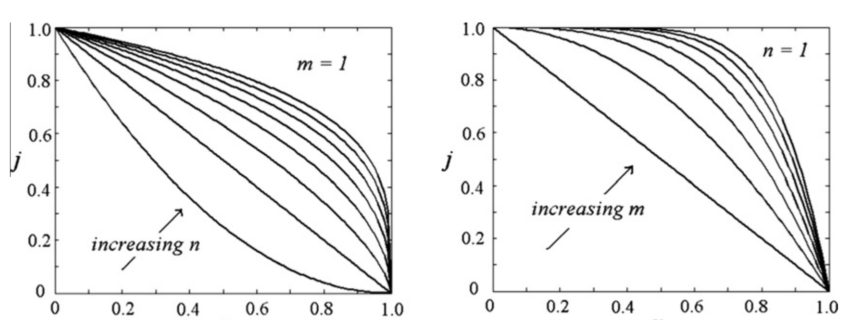

Fig. 1. Representative curves for the function $v^m + j^n = 1$ defined in Eq. (2) showing the behavior of the curves for different m and n.