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Review

Theoretical review of series resistance determination methods for solar cells

G.M.M.W. Bissels*, J.J. Schermer, M.A.H. Asselbergs, E.J. Haverkamp, P. Mulder, G.J. Bauhuis, E. Vlieg

Radboud University Nijmegen, Institute for Molecules and Materials, Heyendaalseweg 135, 6525 AJ Nijmegen, The Netherlands

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Using a systematic approach, a collection of expressions for the series resistance of a solar cell are derived from the diode model. Many published series resistance determination methods are among them, or are slight variations on them. Some expressions have not yet been described in the literature. Representation of the methods in a two-dimensional array allows for easy comparison and reveals that many of the previously published methods are more alike than might appear at first sight. From a discussion of the various methods, on the basis of the two-dimensional array arrangement, an overview of the required approximations and assumptions for each method is assembled. Taking the effect of these approximations and assumptions into account, it is expected that the method of Wolf & Rauschenbach will provide the most accurate value for the series resistance of a solar cell.

Contents

* Corresponding author. Tel.: +31 24 3653432.
E-mail address: G.Bissels@science.ru.nl (G.M.M.W. Bissels).

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1. Introduction

The importance of ohmic losses in a solar cell was already mentioned in the famous 1954 paper by Chapin, Fuller and Pearson from Bell Labs which marked the start of the modern era of photovoltaics [1]. Since the ohmic loss between the collector and the point in the solar cell where an electron–hole pair is generated depends on the location of that point [2–5], and electron–hole pairs are generated throughout an illuminated solar cell, the concept of R_s as a lumped effective series resistance of the solar cell is – by definition – a simplification. Nevertheless, as long as current crowding phenomena are small the series resistance of a solar cell can be well modeled by R_s [6], making R_s a useful concept and an important parameter in the analyses of a solar cell's performance. Unfortunately the value of R_s cannot be measured directly and is, in fact, rather a challenge to determine accurately. Studies concerning this started not long after the start of the modern era of photovoltaics and because of the emergence of new solar cell materials and designs the topic has been readdressed ever since. Recent developments in high-efficiency concentrator cells provide the latest challenge to determine R_s with an accuracy in the m Ω range for cells with surface areas in the mm^2 range. This is required in order to determine the optimal configuration of the grid contact as this has a major impact on the power output of a concentrator photovoltaic (CPV) system.

The many methods to determine R_s that have been described in the literature over the years have resulted in a large number of expressions for R_s in parameters that can be directly determined from a solar cell's *IV*-characteristic. The present study provides a systematic approach towards the derivation of these expressions for R_s for a large collection of methods [7–20], resulting in a framework in which these methods are arranged and compared with each other. This reveals that they are more alike than might appear at first sight. They all follow a derivation involving either an equation based on the diode model of a solar cell (labeled f here), its derivative (labeled f'), its integral (labeled F) or a combination of two of them. The systematic derivation of these equations and their arrangement in a two-dimensional array provides a convenient overview of all possible approaches to determine the series resistance of a solar cell from one or two of the above-mentioned equations. The two-dimensional array arrangement also reveals that there are several approaches to determine R_s which have not yet been described in the literature.

In a subsequent analysis of the methods we determine from a theoretical perspective which method is expected to give the best approximation for R_s. That is, which method uses the least unfavorable approximations and assumptions in the derivation towards its expression for R_s.

2. Theory

A general equivalent circuit of a single junction solar cell with a lumped effective series resistance R_s is displayed in Fig. 1. The associated expression for the current I generated by the cell as a function of voltage V is [21]:

$$I = I_L - \sum_{\alpha=a,b,c,\dots} (I_{D,\alpha}) - I_{sh}$$
$$= I_L - \sum_{\alpha=a,b,c,\dots} \left(I_{0,\alpha}\left[\exp\left(\frac{V+IR_s}{n_\alpha V_t}\right) - 1\right]\right) - \frac{V+IR_s}{R_{sh}}, \tag{1}$$

with I, V being the light induced current I_L (which is proportional to the irradiance E), the current $I_{D,\alpha}$ of diode α,[1] the series

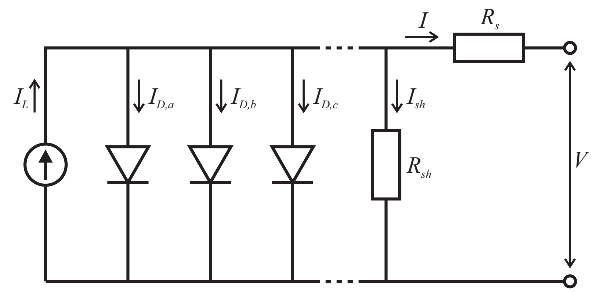

Fig. 1. General equivalent circuit of a solar cell with a lumped effective series resistance.

resistance R_s and the current I_{sh} flowing through shunt resistance R_{sh} all as defined in Fig. 1. $I_{0,\alpha}$ and n_α are the saturation current and ideality factor of diode α. Lastly, there is the thermal voltage V_t, defined as kT/q, with k being the Boltzmann constant, T being the absolute temperature of the solar cell and q being the elemental charge. A list of symbols is provided in Appendix A. With the sign convention used in Eq. (1) the direction in which the light generated current flows is defined as positive and the illuminated *IV*-curve lies in the first quadrant.

Unfortunately Eq. (1) has no general analytic solution. For this reason, the set of diodes is usually represented by a single diode with an associated n and I_0 value. This simplification causes these values to be functions of I and E. The diode ideality factor increases with I and decreases with E as illustrated in Fig. 2 and approaches 1 at high E and/or high V since recombination in the quasi-neutral region dominates under these conditions [22,23]. However, n and I_0 are generally approximated as constants. Another generally used approximation is that $R_{sh} \to \infty$, which is valid for a high quality solar cell. Using these simplifications Eq. (1) can be written as

$$I = I_L - I_0\left[\exp\left(\frac{V+IR_s}{nV_t}\right) - 1\right], \tag{2}$$

the so-called single-diode equation. And although this equation still has no general analytic solution, it can be rearranged into the explicit function

$$V = nV_t \ln\left(\frac{I_L + I_0 - I}{I_0}\right) - IR_s. \tag{3}$$

This equation could also be rewritten into an expression for R_s. However, the parameters I_L, I_0 and n are notoriously hard to determine. Therefore, the idea is to find an expression for R_s in terms of cell parameters which are easier to determine such as the short circuit current I_{sc}, the current and voltage at the maximum power point I_{mp} and V_{mp}, the open-circuit voltage V_{oc} and the area A under the *IV*-curve in the first quadrant. Since $I_0 \ll I_L$ in practice, a frequently applied way to avoid having to determine I_0 is to make sure it only appears in a sum together with I_L so that the approximation

$$I_c \equiv I_L + I_0 \approx I_L \tag{4}$$

can be applied. At short circuit conditions, Eq. (3) can be rewritten as

$$I_{sc} = I_L + I_0 - I_0 \exp\left(\frac{I_{sc}R_s}{nV_t}\right), \tag{5}$$

from which it follows that the short circuit current I_{sc} is a good approximation for the photo current I_L and/or I_c, as long as $I_{sc}R_s$ is

[1] Usually the number of constituent diodes is taken to be 2 or 3. Each diode represents a section of the solar cell where a specific recombination mechanism dominates. One diode represents the recombination in the quasi-neutral regions, another the recombination in the depletion region and at the cell surface. A third diode is sometimes included to represent Auger recombination in the solar cell, which can be important for in particular silicon cells and III–V cells under very high concentration ratios.