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Concerning a novel mathematical approach to the solar cell junction ideality factor estimation

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ABSTRACT

The problem of finding an analytical solution of the solar cell junction ideality factor n is studied in some detail, by the Special Trans Functions Theory (STFT). The advanced STFT iterative method just as the structure of the theoretical derivation is presented, while proofs and numerical results confirm the validity and base principle of the STFT. In addition, the obtained results are compared with the calculated values of other methods for alternative proving its significance. Undoubtedly, the proposed novel STFT exact analytical approach implies qualitative improvement of the conventional analytical and numerical methods.

1. Introduction

Model parameters of a p-n junction solar cell are of crucial importance for their design and evaluation. Among firstly published methods available in literature, attention was focused on measuring the series resistance of a solar cell [1–4], and shunt resistance [5]. Several methods are currently available to determine the values of series and shunt resistance of a solar cell. In Ghani and Duke [6] a new method is presented with the aim to numerically locate these values using the popular Newton–Raphson technique at maximum power point.

In general, different identification methods are used to identify the unknown parameters of the solar cell single diode models. In Askarzadeh and Rezazadeh [7], (HS)-based parameter method solves complex optimization problems unknown parameters of the models. Also, a novel parameter extraction method for the one-diode solar cell model is presented in Kim and Choi [8]. The proposed method deduces the characteristic curve of an ideal solar cell without resistance using the *I–U* characteristic curve measured and reported by solar cell manufacturers and calculates the difference between the deduced and actual measured curves.

Later on with the rapid development of accurate methods for extracting other neglected parameters, a special attention was given to determination of the ideality factor.

The ideality factor is a parameter of vital importance in the description of the solar cell's electrical behavior. Different authors have predicted different values for ideality factor n. For example, Shockley [9] gives the value of $n = 1$, while Shah

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et al. [10] predicted $n \leqslant 2$. The theories of Hall [11], Faulkner and Buckingham [12] gave the value of n between 1 and 2. This was verified by Nussbaum experiments [13].

A review of published papers presented new analytical methods for value determination of the ideality factor [14–19]. In Phang et al. [14] is described an analytical expression for ideality factor n using experimental data parameters mentioned in Charles et al. [15]. Quanxi et al. [16] presented the direct method to measure the ideality factor from illuminated output I–U curve, while Jain and Kapoor [17] presented the analytical method based on Lambert W-function. Also, Lambert W function can be used for finding an exact analytical solution of a two diode circuit model for organic solar cells [18]. Detailed review and tests of methods for the determination of solar cell junction ideality factor has been described in Bashahu and Nkundabakura [19].

The current–voltage relationship in a solar cell can be reduced to a transcendental equation. Perovich's Special tran functions theory (STFT), has been proved to be a very useful tool for solving transcendental equations and obtaining exact analytical closed-form solutions [20–35]. Examples of its application are shown in papers concerning the calculation of the closed-form solutions in: theory of neutron slowing down [30,34,35], linear transport theory [25,30–32], Plutonium temperature estimation (Perovich et al. [30,24]), temperature estimation for the combination of the linear and non-linear resistances [22], nonlinear circuit theory [30,33] and Hopfield neuron analysis (Perovich et al. [21,30]), as well as conductive fluid level estimation [29,30,36] etc.

According to the authors' knowledge, the use of the STFT for solar cells circuit analysis is available in Singh et al. [37]. In addition, in Singh et al. [37] calculated values are compared with the values determined by other methods (using Lambert W-function [17], iterative solution based on Newton–Raphson method and analytical solution [14]. Let us note that in Singh et al. [37] some variant of the STFT formulae for determination of the ideality factor n are numerically simulated using conventional method.

In this article transcendental equations for solar cell analysis are presented in some detail and analytical closed form solutions are gained for them, with the usage of Special Tran Function Theory – STFT.

Though, the biggest impact of this work is in the usage of new original STF Theory in formulae genesis for the ideality factor n. In that way, all investigations and analysis about solar cells in this paper have been consistently accomplished with the usage of new STFT theory. Since STFT ensures reaching extreme precisions in numerical results (arbitrary number of accurate digits in the numerical structure of the transcendental numbers), the highest precision in defining the ideality factor n has been achieved in this work until now. That, of course, implies that constants (Boltzmann constant and electron charge) have been used with greater number of exact digits than in conventional approaches (as in [17,37]).

In addition, obtained results will be compared with all the most important results in this area of research [14,17,37,38].

We believe that STFT, supported by program Mathematica, represents the theoretical approach in solar cell and p-n structure analysis as a novel theoretical standard.

2. The problems definition

The solar cell is the basic unit of a photovoltaic module and it is the element in charge of transforming the sun rays or photons directly into electric power. The solar cell used is the p-n union, whose electrical characteristics differ very little from a diode, represented by the equation of Shockley [9]:

$$I_D = I_0\left(e^{\frac{U_D}{nV_T}} - 1\right), \quad V_T = \frac{kT}{q}, \tag{1}$$

where I_D is the diode current (A), I_0 is the saturation current of the diode (A), U_D is a diode voltage (V), q is a charge of an electron, n is a diode ideality constant, k is the Boltzmann's constant and T is a cell temperature (K).

The ideal solar cell can, theoretically, be modeled as a current source in anti-parallel with a diode, as shown in Fig. 1a), (Eq. (2), where I_{ph} is the current generated by the incident light and Eq. (3)). Because in the real operation of the solar cell some losses exist, they have been added to the model as a resistance in series (R_s) and another in parallel (R_{sh}) to get a more real behavior and to pick up these losses. Eqs. (4) and (5) describe the single-diode model presented in Fig. 1b).

In other words, certain solar cells circuit presented in Fig. 1 can be described through equation for current (Eqs. (2) and (4)) and through equation for diode voltage (Eqs. (3) and (5)). Consequently, the subject of the theoretical analysis presented

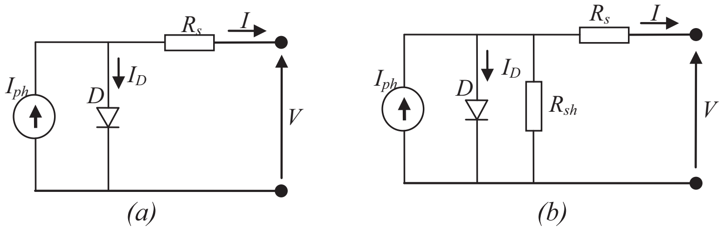

Fig. 1. Equivalent circuit of a practical PV device (a) without shunt resistances, (b) with shunt resistances.