Renewable Energy 103 (2017) 468–477

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

A novel approximate explicit double-diode model of solar cells for use in simulation studies

Ahmad Dehghanzadeh [a, *], Gholamreza Farahani [a], Mohsen Maboodi [b]

[a] Department of Electrical Engineering and Information Technology, Iranian Research Organization for Science and Technology, Tehran, Iran
[b] Department of Electrical Engineering, Hashtgerd Branch, Islamic Azad University, Alborz, Iran

ARTICLE INFO

Article history:
Received 9 August 2016
Received in revised form
25 October 2016
Accepted 24 November 2016
Available online 25 November 2016

Keywords:
Photovoltaic cell
Double-diode model
Explicit model
Translation equation

ABSTRACT

In this paper a novel explicit model is proposed to represent I-V expression of conventional double-diode model for photovoltaic (PV) cells. This model is based on two rules in electronics: first, Thevenin's theorem to describe the linear components of equivalent circuit of PV cells, and second piecewise linear (PWL) model to approximate the behavior of remained nonlinear part. Defining a new parameter (a), an approximate explicit solution for I-V curve of PV model is extracted which surpasses conventional implicit model due to its high computational efficiency particularly in repetitive simulation of PV fields. Dispensing any need to change the concept and consequently the values of conventional double-diode parameters, only single new translation equation is developed for the parameter (a) in wide environmental conditions, which reduces the model complexity in comparison with other reported double-diode explicit solutions. The suitability of the proposed model would be thoroughly accredited by circuit analysis, experimental data and extensive simulation studies.

1. Introduction

Modeling of PV cells is inevitable for engineers in order to debug repeatedly the design and configuration of PV arrays within PV power plants in order to acquire the optimal operation. In fact, fast and accurate models empower the designers to conveniently simulate PV fields to predict the expected power under vast illumination and temperature degrees and also mismatch conditions like partial shading [1–3].

There are two widely used models for solar cells: the single-diode model and the double-diode model; both of which may be accompanied with series and parallel resistances corresponding to the power dissipation of the parasitic resistive non-idealities [4,5]. Fundamentally, these two models are implicit and nonlinear, which means they require numerical iterative methods for simulation studies, such as the Gaussian, Newton–Raphson or particle swarm optimization methods [6–9]. In practice, these iterative methods are often undesirable since they need initial values and probably fail to converge even with good initial guess values. As well, numerical iterations impose large volumes of computational load that destroys the calculation efficiency especially when the model is to be used repeatedly. Hence, if available, equivalent explicit models are the appropriate solution because of their easier and faster computation and also lack of need for initial values. Moreover, explicit models benefit from direct derivations to analytically obtain and track the maximum power point [10,11]. Also the existence of the explicit equations is favorable among researchers for their convenience in parameter extraction of solar cell [12–15].

Generally, there are two approaches to convert implicit models to explicit ones: exact and approximate approaches. Both are entirely investigated in multiple reports for single-diode models [16]. The exact explicit methods usually employ Lambert W-function to extract pure current or voltage terms encountering mathematical expressions like $W(x)\exp[W(x)]$ [17–21]. Alternatively, approximate explicit methods consider simple model such as cubic polynomias for a particular solar cell and estimate the model regulating parameters using curve fitting algorithms [22–25]. Moreover, there are lots of mathematical tools such as Taylor's series expansion, rational function, Pade approximation, Chebyshev polynomial and power law function to transform the inherently implicit single-diode model to explicit expression [26–30]. While these approximations have lost model accuracy to some extent,

* Corresponding author. Department of Electrical Engineering and Information Technology, Iranian Research Organization for Science and Technology, Sh. Ehsani Rad St., Enqelab St., Parsa Sq., Ahmadabad Mostoufi Rd., Azadegan Highway, P. O. Box 3353-5111, Tehran, Iran.
E-mail address: a.dehghanzadeh@irost.ir (A. Dehghanzadeh).

http://dx.doi.org/10.1016/j.renene.2016.11.051
0960-1481/

they do provide much simpler expressions and faster computation process.

Although some reports state that single-diode model exceeds double-diode one considering both of the antagonistic factors, accuracy and simplicity [31,32], it might fail to represent several conduction phenomena that significantly contribute to the total current of the cell p-n junction especially at low irradiance [33]. Despite numerous reports in literature which exactly and approximately introduce explicit expressions for single-diode models, explicit solutions for double-diode models have not been exactly investigated except for two exclusive cases: firstly, the case of double-diode model without parallel resistance in which the ideality factor of one of the diodes is twice of another; no explicit expression is found for cell current but terminal voltage is obtained explicitly without any need for Lambert W-function [34]. Secondly, the case of double-diode model with both series and parallel resistances in which the ideality factors of both diodes are equal, although this substantial constraint is not clearly mentioned in the source paper of [35].

In this paper, a novel approximate explicit model is presented for PV cell models consisting of two main types of exponential current transport mechanisms along with both series and parallel parasitic resistive losses. In Section 2, Thevenin's theorem is used for the linear elements of PV model circuit, and Thevenin equivalent resistance and voltage are computed. Then defining a regulating parameter (a) and using Lambert W-function, the methodology to obtain the explicit expression for I-V curve of PV model is explained. In Section 3, considering piecewise linear model of diodes, the capability of the regulating parameter (a) to convert conventional implicit model to approximate explicit one is proved by circuit analysis. In Section 4, the proposed model is verified with real data of a polycrystalline PV cell and a monocrystalline PV module at standard test condition (STC). Using synthetic data generated by a conventional model of a polycrystalline PV cell, an extensive simulation study is done in Section 5 for the proposed model assessment in wide range of temperature and irradiation, and eventually, a novel translation equation is developed in Section 6. The paper comes to a conclusion in Section 7.

2. Proposed model

The double-diode equivalent circuit of solar cells is represented in Fig. 1. Additional to two diodes reflecting the physical behavior of the p-n junction, this circuit consists of an ideal current source I_{ph} as photoelectric phenomena, series resistance R_s to replicate current circulation throughout the cell and parallel resistance R_p as current leakage of the p-n junction [4]. Also I is the current flowing

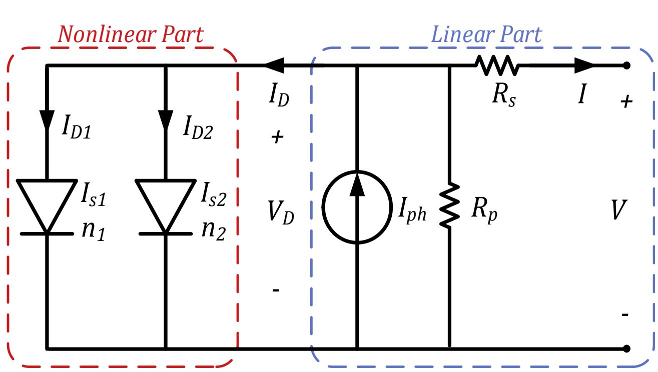

Fig. 1. Equivalent circuit for PV cell including two diodes, photo-generated current source, and also series and parallel resistive losses; Linear and nonlinear elements are distinctly obvious.

PV cell, V is the terminal voltage, I_{s1} and I_{s2} are the dark saturation currents of two diodes, V_T is the thermal voltage and eventually, n_1 and n_2 are the ideality factors corresponding to first and second diodes that choose the values between 1 and 2 in silicon based PV cells. The output current of this model is described as:

$$I = I_{ph} - G_p V_D - I_D \tag{1}$$

where G_p is parallel parasitic conductance used instead of $1/R_p$ for mathematical convenience. Also I_D is the total current of two diodes and V_D is the voltage across them. To express (1) explicitly in terms of PV cell parameters, the separation of linear and nonlinear components for PV cell model is demonstrated in Fig. 1. Then employing Thevenin's theorem, the equivalent circuit containing the nonlinear part and Thevenin equivalent of linear part can be represented as Fig. 2. This idea allows to deliberately make the five parameters of I, V, I_{ph}, R_s and R_p of linear part concise in two Thevenin equivalent parameters of V_{Th} and R_{Th}. These two parameters are described as:

$$R_{Th} = \frac{R_s}{1 + G_p R_s} \tag{2}$$

$$V_{Th} = \left(\frac{V}{R_s} + I_{ph}\right) R_{Th} \tag{3}$$

As [36] presented, if particular factors of R_{Th} are substituted at each branch in series with each diode, I_D can be approximately evaluated in explicit form. This hypothesis will be clarified with a circuit analysis in Section 3. In this paper, the factor (a) of R_{Th} and identical R_{Th} are considered respectively for first and second diode as shown in Fig. 3. The Shockley diode equation for first diode can then be described as:

$$I'_{D1} + I_{s1} = I_{s1} e^{\frac{V_{Th} - I'_{D1} a R_{Th}}{n_1 V_T}} \tag{4}$$

Multiplying the both sides of (4) by $\frac{aR_{Th}}{n_1 V_T} e^{\frac{aR_{Th}(I'_{D1} + I_{s1})}{n_1 V_T}}$, it can be rewritten as:

$$\frac{aR_{Th}(I'_{D1} + I_{s1})}{n_1 V_T} e^{\frac{aR_{Th}(I'_{D1} + I_{s1})}{n_1 V_T}} = \frac{I_{s1} aR_{Th}}{n_1 V_T} e^{\frac{V_{Th} + I_{s1} aR_{Th}}{n_1 V_T}} \tag{5}$$

On the other hand, it is well known that the Lambert W function of the variable x is the inverse function of [37]:

$$f(x) = xe^x \tag{6}$$

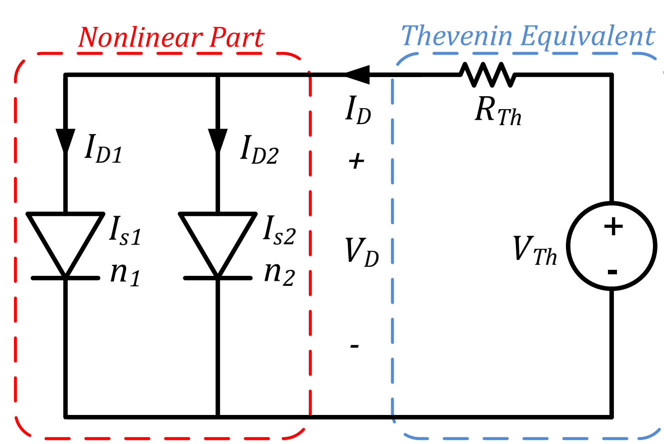

Fig. 2. Nonlinear part and Thevenin equivalent of the linear part of double-diode model for PV cell with the series and parallel resistive losses.