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An explicit approximate *I–V* characteristic model of a solar cell based on padé approximants

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Abstract

This paper proposes a new explicit current–voltage (*I–V*) modeling approach for the single-diode model of solar cells. An accurate *I–V* model of solar cells is inherently implicit and nonlinear, which calls for iterative calculations to obtain an analytical expression of current as function of voltage. In this paper, padé approximants method is proposed to express the exponential function of *I–V* characteristic equation and then an explicit analytical description of current is obtained. Furthermore, two modified five-parameter models based on padé approximants method, named the basic padé approximants model and the modified padé approximants model, respectively, are developed. To validate the effectiveness of the two models proposed in the paper, the two different photovoltaic (PV) modules are tested at different irradiance and temperature conditions. A comparison between the proposed models and the traditional five-parameter model is made. Experiment results show the proposed models are simple, accurate and effective explicit models for solar cells.
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Keywords: Solar cells; *I–V* characteristics; Analytical model; Explicit *I–V* model; Photovoltaic power generation

1. Introduction

Since fossil energy is reducing, to develop and utilize the renewable energy becomes very imperative. Solar photovoltaic (PV) power generation is the most practical, the cleanest, the most promising power generation. The photovoltaic power generation systems are studied and utilized extensively (Wang et al., 2013; Blaabjerg et al., 2006; Li and He, 2011; Bialasiewicz, 2008). A PV generation system usually consists of solar PV arrays and electric converters. A PV array is formed by series/parallel combination of PV modules and a PV module usually consists of 36 solar cells which are connected in series (Ding et al., 2012; Karatepe et al., 2007). There are usually two kinds of model descriptions of a solar cell. One is the model of a solar cell with one diode, named a single-diode model or single exponential model, the other is the model of a solar cell with two diode, named a two-diode model or double exponential model (Cheknane et al., 2008). However, the mathematical descriptions of the two kinds of models are both implicit and nonlinear about voltage and current characteristics. Implicit *I–V* characteristic equation needs turning into a explicit analytical representation as a function of the terminal voltage *V*, which has to resort to numerical methods. However, these numerical algorithms are sensitive to the initial values and often fail to converge even with good initial guess values. Therefore, an explicit analytical approximate representation is convenient and necessary in several practical applications. This type of approximation would

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Nomenclature

a	ideality factor parameter defined as $a = nN_skT/q$ (eV)	I	output current of solar cells (A)
I_L	photo current density (A)	V	output voltage of solar cells (V)
R_s	series resistance (Ω)	I_o	diode reverse saturation current (A)
n	ideality factor	R_{sh}	shunt resistance (Ω)
k	Boltzmann's constant (1.381×10^{-23} J/K)	q	electron charge (1.602×10^{-19} C)
T	cell temperature (K)	N_s	solar cell number in series
V_{oc}	open-circuit voltage (V)	I_{sc}	short-circuit current (A)
I_{mp}	current at maximum power point (A)	V_{mp}	voltage at maximum power point (V)
$Q_n(x)$	polynomial of degree n	$P_m(x)$	polynomial of degree m
$[m/n](x)$	padé approximants	$f(x)$	function defined by the series
Q_{1-n}	coefficients of polynomial $Q_n(x)$	P_{0-m}	coefficients of polynomial $P_m(x)$
z	variable defined as $z = IR_s/a$	f_{0-m+n}	coefficients of function $f(x)$
b	coefficients in Eq. (10)	a_1	coefficients in Eq. (10)
d	coefficients in Eq. (10)	c	coefficients in Eq. (10)
B	parameter in Eq. (11)	A	parameter in Eq. (11)
Y_1	parameter in Eq. (11)	C	parameter in Eq. (11)
I_P	approximation of current I (A)	Y_2	parameter in Eq. (11)
α_{Isc}	temperature coefficient of short-circuit current (A/K)	$\beta_{V_{oc}}$	temperature coefficient of open-circuit voltage (V/K)
$I_{o,ref}$	diode reverse saturation current at SRC (A)	$I_{L,ref}$	photo current density at SRC (A)
$R_{sh,ref}$	shunt resistance at SRC (Ω)	$R_{s,ref}$	series resistance at SRC (Ω)
S	total absorbed irradiance (W/m^2)	a_{ref}	ideality factor parameter at SRC (eV)
S_{ref}	total absorbed irradiance at SRC (K)	T_{ref}	cell temperature at SRC (K)
$I_{mp,ref}$	current at maximum power point at SRC (A)	$V_{mp,ref}$	voltage at maximum power point at SRC (V)
$I_{sc,ref}$	short-circuit current at SRC (A)	$V_{oc,ref}$	open-circuit voltage at SRC (V)
a_{T_c}	ideality factor parameter at T_c (eV)	V_{oc,T_c}	open-circuit voltage at T_c (V)
I_{o,T_c}	diode reverse saturation current at T_c (A)	I_{L,T_c}	photo current density at T_c (A)
E_g	material band gap (eV)	T_c	cell temperature defined as $T_c = T_{ref} + 10$ (K)
P_{mp}	maximum power (W)	$E_{g,ref}$	material band gap at reference temperature (1.121 eV for silicon cells) (eV)
P	predicted power (W)		

be computationally advantageous in device models that are to be used repeatedly in circuit simulator programs, in problems of device parameter extraction (Jain and Kapoor, 2004; Ortiz-Conde and Garcia Sanchez, 1992). Especially, when I–V output characteristics of solar cells are not identical due to soiling, non-uniform irradiation and temperature variations, cell damaging, partially shading etc., series connected modules need studying voltage separately and parallel connected modules need studying current separately in order to obtain more accurate I–V characteristics of PV array. However, implicit I–V characteristic equation cannot be used to research current and voltage separately, which makes the I–V characteristic analysis of series and parallel connected module more difficult.

Some efforts have been made to transform I–V characteristic implicit representation into an explicit form Abuelma'atti (1992), Fjeldly et al. (1991), Das (2011), Das (2012), Karmalkar and Saleem (2008), Karmalkar and Saleem (2011), Jain and Kapoor (2011), Wang and Zhao (2012), Saloux et al. (2011). In Abuelma'atti (1992) and Fjeldly et al. (1991), a trial function in conjunction with a Taylor series expansion is used to obtain a approximate analytical solution of generalized diode equation with a series resistance. So the models are not suitable to represent the solar cell with shunt resistances. In Das (2011), a explicit I–V characteristic model is proposed to estimate the maximum power point and fill factor according to open-circuit voltage V_{oc}, short-circuit current I_{sc} and any two voltage values between 0 and V_{oc}. This model is useful for design, characterization and simple fill factor calculation and its applicability was demonstrated with the measured data of a wide variety of solar cells. However, this model is intuitive and lacks the analytical support. Therefore, a new analytical explicit I–V model is presented in Das (2012), which is derived from the physics based on implicit I–V equation. In Karmalkar and Saleem (2008), the explicit power law model of a solar cell is proposed, which allows an easy closed-form estimation of the entire I–V curve, fill factor and peak power point of an illuminated solar cell from a few measurements as well as physical parameters. However, the validity of the model is established for a limited class of cells, having moderately

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