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A procedure to calculate the *I–V* characteristics of thin-film photovoltaic modules using an explicit rational form

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HIGHLIGHTS

- A new model based on a simple rational function is presented.
- The model is able to describe the *I–V* curves of thin-film photovoltaic modules.
- The derivatives in the short circuit and open circuit points were considered.
- A comparison with the Ishaque et al. and the Gupta et al. models was made.

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ABSTRACT

Accurate models of the electrical behaviour of photovoltaic modules are effective tools for system design. One or two diode equivalent circuits have been widely used even though some mathematical difficulties were found dealing with implicit equations. In this paper, a new model based on a simple rational function, which does not contain any implicit exponential form, is presented. The model was conceived in order to be used with thin-film photovoltaic modules, whose current–voltage curves are characterised by very smooth shapes. The parameters of the model are evaluated by means of the derivatives of the issued characteristics in the short circuit and open circuit points at standard rating conditions, and assuming that the calculated current–voltage curve contains the rated maximum power point of the simulated panel.

The capability of the model to calculate the current–voltage characteristic for values of the solar irradiance and cell temperature far from the standard rating conditions was verified for various thin-film technologies, such as CIS, CIGS, amorphous silicon, tandem and triple-junctions photovoltaic modules. A comparison with the results obtained by another rational model and other two-diode models, which were used to simulate the electrical behaviour of thin-film photovoltaic modules, is also presented.

1. Introduction

During the last years the international market of thin-film photovoltaic (PV) modules has been increasing considerably mainly due to their simple and low-cost manufacturing process. The various thin-film technologies reduce the amount of light absorbing material that is necessary to produce a solar cell. Moreover, thin-film PV panels, which employ lightweight, flexible substrates, are more resistant than crystalline PV modules and very suited to advanced applications such as building-integrated photovoltaics, curtain walls, canopies, acoustic barriers, watercrafts, vehicles and portable electronics. Because thin-film cell materials generally show reduced energy efficiencies as compared to crystalline silicon cells, the accurate modelling of PV modules is of primary concern in order to allow the designer to optimise the system performance and maximise the cost effectiveness of the system.

The simulation of the behaviour of PV modules has been conveniently done by means of nonlinear lumped-parameter equivalent circuits (one and two diode models) whose parameters were determined from experimental current–voltage (*I–V*) characteristics by means of analytical or numerical extraction techniques. The two-diode model requires the determination of seven parameters, which variously affect the shape of the *I–V* characteristic. The solution of the seven-parameter equivalent circuit, which is a complex problem, was faced assuming some analytical simplifications. Many authors propose numerical and analytical procedures to calculate the five parameters of the one-diode model. Other authors study some simplified versions of the one-diode based on a set of four parameters. The problem of the identification of the

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Nomenclature

a_1, a_2	diode ideality factor
A, M, N	parameters of the proposed model
C_1, C_2, C_3	coefficients of the V_{oc} correlation
D_1, D_2	coefficients of the R_{so} correlation
G	solar irradiance (W/m^2)
G_{ref}	solar irradiance at SRC (1000 W/m^2)
i	normalised current generated by the panel
I	current generated by the panel (A)
I_L	photocurrent (A)
i_{mp}	normalised current in the maximum power point
$i_{mp,ref}$	normalised current in the maximum power point at SRC
I_{sc}	short circuit current of the panel (A)
$I_{sc,ref}$	short circuit current of the panel at SRC (A)
I_0, I_{01}, I_{02}	diode saturation current (A)
k	Boltzmann constant (J/K)
K_1, K_2, K_3	parameters of the Gupta et al. model
N_s	number of cells connected in series
p	parameter of the Ishaque et al. model
q	electron charge (C)
R_s	series resistance (Ω)
r_{so}	normalised reciprocal of the slope of the I–V characteristic for $V = V_{oc,ref}$ and $I = 0$ (Ω)
R_{so}	reciprocal of slope of the I–V characteristic for $V = V_{oc}$ and $I = 0$ (Ω)
$R_{so,ref}$	reciprocal of slope of the I–V characteristic for $V = V_{oc,ref}$ and $I = 0$ (Ω)
R_{sh}	shunt resistance (Ω)
r_{sho}	normalised reciprocal of the slope of the I–V characteristic for $V = 0$ and $I = I_{sc,ref}$ (Ω)
R_{sho}	reciprocal of the slope of the I–V characteristic for $V = 0$ and $I = I_{sc}$ (Ω)
$R_{sho,ref}$	reciprocal of the slope of the I–V characteristic for $V = 0$ and $I = I_{sc,ref}$ (Ω)
T	temperature of the PV cell (K)
T_{ref}	temperature of the PV panel at SRC (25 °C – 298.15 K)
v	normalised voltage generated by the PV panel
v_{mp}	normalised voltage in the maximum power point
$v_{mp,ref}$	normalised voltage in the maximum power point at SRC
V	voltage generated by the PV panel (V)
V_{oc}	open circuit voltage of the PV panel (V)
$V_{oc,ref}$	open circuit voltage of the PV panel at SRC (V)
$V_{oc,200}$	open circuit voltage of the I–V characteristic at $G = 200$ W/m^2 and $T = T_{ref}$ (V)
α_G	ratio between the current irradiance and the irradiance at SRC
m	diode ideality factor
α	thermal coefficient of the short circuit current (A/°C)
β	thermal coefficient of the open circuit voltage (V/°C)

parameters contained in the diode-based equivalent circuits is also tackled exploring the possibility of using alternative procedures such as the Lambert *W*-function, evolutionary algorithms, Padè approximants, genetic algorithms, cluster analysis, artificial neural networks, harmony search-based algorithms and small perturbations around the operating point. In addition to mathematical models, the numerical simulation offers advantages to the design, performance prediction and comprehension of the fundamental phenomena ruling the operation of devices, such as solar cells, and also permits to investigate the physics of their workings. In the literature of numerical simulators a choice is the wxAMPS software, which is an updated version of the one-dimensional simulation program Analysis of Microelectronic and Photonic Structures (AMPS-1D), which was initially developed by Zhu et al. [1]. wxAMPS is a powerful tool capable of representing the electrical transport and the optical behaviour of the solar cells, and also simulating the response of a solar cell.

In order to describe the electrical behaviour of thin-film PV cells and modules, different models, not based on equivalent circuits, are also proposed. Block et al. [2] developed a new modelling approach for the study of single and tandem pin-solar cells made from amorphous silicon. A one-dimension numerical solar cell simulation program was used by Lee et al. [3,4] to analyse the operation of CdTe and CIS solar cells. Gloeckler et al. [5] discussed the guidelines that should be considered assigning input parameters for numerical modelling of CIGS and CdTe solar cells. Solving a set of equations relative to electron and hole current densities, Das et al. [6] generated the I–V characteristics of a standard triple-junction amorphous silicon solar cell among different failures scenarios (variations in the thickness of different layers of the cell), comparing them with the normal condition. Numerical simulations were used by Zeman et al. [7] to analyse and optimise the optical and electrical properties of tandem micromorph and triple-junction silicon-based solar cells. Xiao et al. [8] modelled a thin film triple junction solar cell using the APSYS simulator, which is a general-purpose 2D/3D finite element analysis and modelling software for semiconductor devices.

One-diode and two-diode models, which were originally thought to describe the behaviour of mono-crystalline and poly-crystalline silicon PV panels, are also used to model thin-film PV modules. Marten et al. [9] presented an improved equivalent circuit for amorphous silicon solar cells and modules; the model was a single exponential model with a new term taking into account the recombination losses in the intrinsic layer of the device. An accurate and fast method to calculate the efficiency and the fill factor of CIGS and CdTe thin-film solar modules was described by Burgelman and Niemegeers [10]. Stutenbaeumer and Mesfin [11] found that a two-diode equivalent module, which includes the contribution of the diffusion and the recombination currents and the parasitic effects of series and shunt resistance, can simulate the dark I–V characteristics of crystalline, poly-crystalline and amorphous silicon solar cells. Using the one-diode model Brecl et al. [12] studied tandem solar cells consisting of two serially-connected thin-film solar cells under different weather and temperature, daily and seasonal conditions.

A four-parameter equivalent model was used by Xiao et al. [13] to simulate three PV panels made of different materials: CIS thin-film, poly-crystalline and mono-crystalline silicon. Burgelman et al. [14] presented a selection of currently available numerical simulation tools for thin-film solar cells and discussed their possibilities and limitations. The applicability of the one and two diode equivalent models for CIGS thin-film PV devices was analysed by Werner and Prorok [15] for a wide range of irradiance and module temperature values; the two-diode model seemed to give more reliable results than the most commonly used one-diode model. Werner and Zdanowicz [16] experimentally determined the values of the double diode model diffusion and recombination related components of the diode dark saturation current in a thin film CIGS solar cell Shell ST40. By means of linearized one-diode mathematical models, Ahmad et al. [17]