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Comparison of four methods for parameter estimation of mono- and multi-junction photovoltaic devices using experimental data

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ABSTRACT

The present work analyses four methods used to estimate the physical properties of photovoltaic devices for a single diode model. Two of the most efficient photovoltaic technologies—mono- and multi-junction devices—are used under different temperature and solar radiation conditions for comparing the applicability of each method. Three of the four parameter estimation methods are analytic and the remaining one uses an algorithm for the optimization of non-linear problems, i.e., the generalized reduced gradient. The different methods are summarized and a comparative analysis is performed using experimental data obtained from the literature, highlighting the advantages and disadvantages of each method. Criteria such as the mean absolute percentage error, the coefficient of determination, the absolute error in current calculated at the maximum power point, and computational cost are used. Accordingly, it is concluded that, for all the methods considered in this study, the best accuracy is obtained from simulations using the method proposed by Blas et al. [34] applied to mono-junction modules, and the method proposed by Xiao et al. [39] to multi-junction devices.

1. Introduction

In response to the recent energy crises that have affected most of the developed countries and the world development in the last century, the scientific community has contributed more efforts to the research of different sources of energy, generally known as alternative or renewable energy. Accordingly, photovoltaic solar energy is an alternative source of energy and it has gained more space in the scientific community and commercial production.

Photovoltaic (PV) solar cells can be defined as diodes of large area that have been optimized to absorb light and convert it to electric energy with the highest possible efficiency [1]. There are different materials that can be used for manufacturing photovoltaic solar cells. Silicon is the most abundant and easy to find material in nature, whereas Cadmium telluride (CdTe), copper indium selenide (CIS), Gallium arsenide (GaAs), organic materials, and polymers originate from chemical processes in laboratories [2]. Depending on the type of material used in manufacturing solar cells, the efficiency and properties of the cells change; however, there is a characteristic common to all types of photovoltaic cells. This is related to the environmental conditions, such as ambient temperature and incident radiation properties (magnitude, spectrum, etc.), which affect its performance. These factors change constantly with time, owing to climatic variation, season loading, and daytime [3]. Moreover, the information related to the characteristics of the working operation of a PV system is provided for standard test conditions (STC), in which the incident irradiation, air mass, and temperature are adopted as 1000 W/m^2, 1.5 e, and 25 °C, respectively. Therefore, these values cannot be used to predict the production of energy from the system and in some circumstances there is also difficulty in measuring the values of irradiance and temperature of the cell as shown in [4]. Hence, the PV energy system requires mathematical models with high accuracy and reliability [5].

These models can be used to simulate the electrical and dynamic characteristics of photovoltaic systems under different meteorological conditions or to determine the best operation points of a photovoltaic energy generation plant at a specific location [6–8]. Additionally, these models assist engineers and other professionals in designing, optimizing, and sizing the photovoltaic solar energy plant [9]. Therefore, a simulation of the real operating conditions of photovoltaic systems is an important tool from a technological and economic perspective. Modelling of photovoltaic devices and simulating their behaviors represents a significant portion of recent research related to solar energy [10]. The models that use an equivalent circuit are significant since they allow joint simulation of a photoelectric device with a power electronics interface.

Currently, there are different models designed to determine the main characteristics of photovoltaic systems under different environmental conditions [11]. In a recent work [12], the authors summarized

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Nomenclature

FF	Fill factor
I_d	Diode current (A)
I_0	Saturation current (A)
I_{ph}	Photo generate current (A)
I_{sc}	Short circuit current (A)
k	Boltzmann number (J/K)
n	Diode ideality factor (dimensionless)
P	Power (W)
q	Electron charge (C)
R_s	Series resistor (Ω)
R_{sh}	Shunt resistor (Ω)
T	Temperature (°C)
V_{oc}	Open circuit Voltage (V)
V_{th}	Thermal voltage (V)
X	Solar concentration coefficient

Greek Symbols

η	Efficiency (%)
ε	error

Subscripts

c	cell
e	Equivalent
i	subcell
mp	Max power
o	Initial value
r	Reference
sh	shunt
T	Total

the main models applied to PV cells under high concentration. Most of these approaches are based on single and double diode models that represent the physical phenomena inside the cells [13].

The single diode model is described by the modified Shockley diode equation, where the diode ideality factor (n) incorporates the effects of diffusion and recombination of minority carriers in the depletion zone of the photovoltaic cell. Furthermore, the double diode model incorporates the effects mentioned above in a separate manner. Therefore, it is possible to obtain results with higher accuracy, although the equations to be implemented are highly complex and require the use of computational tools [14–17]. Thus, the single diode model is commonly used mainly owing to its accuracy and simplicity [18–23]. However, regardless of the model selected (single or double diode), it is interesting to highlight that the manufacturers, generally, do not provide this data. The parameters required depend on the model and the consideration; thus, the use of a single diode has a significant advantage since its implementation requires fewer parameters compared to the double diode model, and these parameters can be calculated from the information provided in the datasheet. There are many papers focusing on the comparison between these two models, such as [1,24–30].

The single diode model is shown in Fig. 1, where all the factors were analysed and the five parameter model was obtained. I_{ph} represents the photogenerated current of the PV cell, I_0 represents the reverse saturation current, and n represents the ideality factor. The series resistance (R_s) model is related to the voltage drop owing to the resistance of the material in the cell. Finally, representing the leakage current, a shunt resistor (R_{sh}) is added and Eq. (1) relates all these parameters.

$$I = I_{ph} - I_0\left[\exp\left(\frac{V + IR_s}{nVth}\right) - 1\right] - \frac{V + IR_s}{R_{sh}} \tag{1}$$

In Eq. (1), V_{th} is the thermal voltage owing to temperature, and this term can be calculated from Eq. (2), where k is the Boltzmann constant, q is the electron charge, and T_c is the temperature of the PV cell.

$$Vth = \frac{kT_c}{q} \tag{2}$$

There is another approach in which it is assumed that the value of R_{sh} is very high and therefore this parameter is not considered in the model; thus, this approach is commonly known as the four parameter model, shown in Eq. (3). However, in some conditions like low radiation level [31] the assumption of this scenario is unrealistic and does not reflect the real behavior of a photovoltaic cell.

$$I = I_{ph} - I_0\left[\exp\left(\frac{V + IR_s}{nVth}\right) - 1\right] \tag{3}$$

When PV cells are connected in series or parallel in order to raise the level of output voltage and current, and using the five parameters model the output current is expressed by Eq. (4), where N_p and N_s are the number of cells in parallel and series, respectively [32].

$$I = N_pI_{ph} - N_pI_0\left[\exp\left(\frac{1}{nVth}\left(\frac{V}{N_s} + \frac{IR_s}{N_p}\right)\right) - 1\right] - \frac{1}{R_{sh}}\left(\frac{N_p}{N_s}V + IR_s\right) \tag{4}$$

These models are valid only for mono-junction PV cells. However, the latest or multi-junction PV cells have been modelled by the circuit described in Fig. 2, in which each of the junctions of the cell is represented as an independent PV cell in a series array.

Accordingly, similar to mono-junction PV cells, Eq. (5) describe the behavior of each of the sub-cells. Since the connection is in series, the total current of the multi-junction cell is limited to the sub-cell that generates the minimum current as indicated in Eq. (6). However, the total voltage is the sum of the voltages of each sub-cell as shown in Eq. (7).

$$I^i = I^i_{ph} - I^i_0\left[exp\left(\frac{V^i + I^iR^i_s}{n^iVth}\right) - 1\right] - \frac{V^i + I^iR^i_s}{R^i_{sh}} \tag{5}$$

$$I = \min(I^i) \tag{6}$$

$$V = \sum V^i \tag{7}$$

It is evident that by implementing this type of model for multi-junction cells, the number of parameters to be estimated increases considerably. However, this problem can be addressed by considering a single junction with the characteristics described in Eqs. (6) and (7).

The single diode model shows that the characteristic I–V curve of a PV cell, shown in Fig. 3, depends on the values of the five parameters (I_{ph}, I_0, R_s, n, and R_{sh}).

The problems in modelling photovoltaic devices increase owing to the nonlinear behavior of the I–V curve. Hence, it is important to obtain these parameters accurately. Therefore, in the literature, there

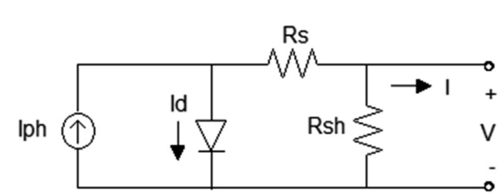

Fig. 1. Equivalent circuit of the single diode model.