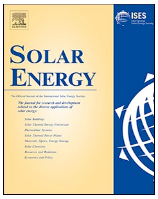
Solar Energy 174 (2018) 628–639

Contents lists available at ScienceDirect

Solar Energy

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



Impacts of temperature and irradiance on polycrystalline silicon solar cells parameters

D.M. Fébba*,[1], R.M. Rubinger[1], A.F. Oliveira[1], E.C. Bortoni[1]

Universidade Federal de Itajubá, Brazil

ARTICLE INFO

Keywords:
Solar cells
Solar cell parameters
Temperature dependence
Illumination intensity
Differential Evolution
Polycrystalline silicon

ABSTRACT

The accurate knowledge of the solar cells parameters dependence on irradiance and temperature is of vital importance for the performance assessment of photovoltaic modules and development of new devices, and many works have been published so far to understand the aforementioned dependence, but none employed a metaheuristic technique. To understand the temperature and irradiance impacts on the single-diode parameters, seven polycrystalline silicon solar cells were studied through a careful experimental characterization in the range of 600–1000 W/m^2 and 25–55 °C. To extract single-diode parameters, the Differential Evolution optimization technique was employed, resulting in very low fitting errors between experimental and simulated I-V curves. The results obtained showed that the shunt and series resistance were more affected by the increasing temperature, with an exponential decrease, than for increasing irradiance, with a linear increase and decrease for series and shunt resistance, respectively. The diode ideality factor showed no significant changes with increasing temperature and irradiance, while the diode saturation current showed an exponential dependence on increasing temperature, but no significant changes with increasing irradiance. Furthermore, it was seen that even with same nominal features, polycrystalline silicon solar cells may present very different values and behaviors for the single-diode parameters.

1. Introduction

The accurate modeling of solar cells is essential to understand and predict how photovoltaic devices operate under different temperature and irradiance conditions, considering that these devices generally operate in non-standard conditions (25 °C and 1000 W/m^2) (Durisch et al., 1996). The most important parameters for the performance evaluation of a solar cell are extracted from the current-voltage (I-V) characteristics and, among the mathematical models available to describe these I-V curves, the most widely used is the single-diode model, due to its simplicity and accurate results (Abbassi et al., 2018; Humada et al., 2016). The equation describing this model can be written as:

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

where I, V, q, k, T, I_{ph}, I_0, n, R_s and R_{sh} are the current (A) and voltage (V) on the solar cell terminals, the electronic charge ($1.602\,176\,62 \times 10^{-19}$ C), Boltzmann constant ($1.38064852 \times 10^{-23}\,J\,K^{-1}$), temperature (K), photocurrent (A), diode saturation current (A), diode ideality factor, series and shunt resistance (Ω), respectively.

Although this model is simpler when compared to others that take into account resistive losses and diode non-idealities, the extraction of the five electrical parameters of interest (I_{ph}, I_0, n, R_s, R_{sh}) for a given temperature and illumination is a challenging task, since Eq. (1) is a transcendental and non-linear equation.

The problem of extracting the five single-diode parameters from the I-V characteristics may be classified into three main categories, according to the approach employed: analytical, numerical and soft computing algorithms (Lin et al., 2017). Analytical techniques require the knowledge of some key points of the I-V characteristics and slopes at short-circuit and open circuit regions (Ishaque et al., 2012). In this way, these methods rely on the choice of some regions of the I-V characteristics to perform curve fittings, and if these regions are not properly selected, significant errors may occur (Bühler et al., 2014).

Numerical techniques can provide better results than the analytical ones since all I-V points are utilized, but its accuracy depend on the type of the fitting algorithm and on the chosen initial points (Chellaswamy and Ramesh, 2016; Ishaque et al., 2012). The metaheuristic techniques,

---

* Corresponding author.

E-mail addresses: davifebba@uol.com.br (D.M. Fébba), rero@unifei.edu.br (R.M. Rubinger), adhimarflavio@unifei.edu.br (A.F. Oliveira), bortoni@unifei.edu.br (E.C. Bortoni).

[1] Address: Av. BPS, 1303, Pinheirinho, Itajubá, MG 37500-903, Brazil.

https://doi.org/10.1016/j.solener.2018.09.051
Received 21 June 2018; Received in revised form 5 September 2018; Accepted 17 September 2018

or soft computing algorithms, are considered as stochastic optimization approaches, and have been successfully employed in the extraction of the single-diode parameters, providing betters results among all mentioned techniques (Lin et al., 2017).

A great deal of research effort, employing analytical or numerical techniques, has been carried out in order to understand the behavior of these parameters under different temperature and irradiance conditions (Arora et al., 1986; Banerjee and Anderson, 1986; Chegaar et al., 2013; Cuce et al., 2013; del Cueto, 1999; Deshmukh and Nagaraju, 2005; Ding et al., 2005; Eikelboom and Reinders, 1997; Ghani et al., 2015; Khan et al., 2010b, 2013, 2014, 2016; Lim et al., 2015; Priyanka et al., 2007; Rajkanan and Shewchun, 1979; Ruschel et al., 2016; Singh et al., 2008; Singh and Ravindra, 2012).

Differently from all related works, the aim of this paper is to investigate the behavior of the single-diode parameters with different temperature and illumination conditions employing a metaheuristic technique known as Differential Evolution (DE) and, as far as the authors know, no similar work employing this technique has been done before. For this purpose the I-V characteristics of seven polycrystalline silicon solar cells were experimentally obtained for seven different temperatures and five different illumination conditions in the range of 25–55 °C and 600–1000 W/m^2, followed by a robust computational effort to provide the best possible extracted parameters.

The remaining of this work is organized as follows: Section 2 provides a review of the aforementioned related works, Section 3 will discuss the experimental setup and provide details on how the DE algorithm was employed to extract the best single-diode parameters from the I-V curves; Section 4 will present and discuss the results, and Section 5 will conclude this work.

2. Review of related works

Arora et al. (1986) investigated the dependence of series resistance on temperature and irradiance using dark and illuminated I-V curves and found an increasing series resistance for both single-crystal and polycrystalline silicon solar cells over a wide temperature range (−173 °C to 227 °C), and a decreasing series resistance with irradiance up to 2 suns.

The method used to obtain these results was developed by Mathur et al. (1982) after solving the illuminated and dark I-V equations for the same 'current flow through junction' conditions, assuming that the short circuit current equals the photocurrent for practical solar cells, for which $R_{sh} \gg R_s$ is generally true (Mathur et al., 1982). By plotting the dark and illuminated I-V characteristics on the same origin, R_s can be determined from the slope of the line joining the points (V_d, I_s) and (V_{oc}, 0). This model employs the two-diode model, assuming that the diode ideality factors are equal to 1 and 2. However, this is not always the case, since these parameters may change as the temperature and irradiance changes (Khan et al., 2010b; Singh et al., 2008). Furthermore, this method only provides the value of series resistance.

Bouzidi et al. (2007) developed a method based on the single-diode model, using the slope of the illuminated I-V characteristics in the linear region to write the current as function of voltage, $V = f(I)$, determining the single-diode parameters through the solution of a system of 3 non-linear equations. However, there is no standard about defining a suitable range for which the approximations assumed in this model are valid. When dealing with noisy data, different intervals may provide different results.

Employing this method, Chegaar et al. (2013) studied the single-diode parameters dependence on irradiance in the range of 160–1000 W/m^2 for a polycrystalline silicon solar cell under room temperature and found a linear increase in ideality factor, exponential increase in the diode saturation current, invariant series resistance and linearly decreasing shunt resistance with increasing irradiance.

Priyanka et al. (2007) developed a method for determining the series and shunt resistances based on the single-diode model, considering the I-V characteristics in the third and fourth quadrants and the V_{oc}−I_{sc} characteristics of the cell along with the slope at the short-circuit region. This method was then applied to only one silicon solar cell and it was found that the series resistance decreased with increasing irradiance in the range of 100–1000 W/m^2 at a fixed temperature of 25 °C, while R_{sh} was found to be independent of intensity.

This method gives different R_s values at different points on the I-V curve, i.e., the series resistance varies with the applied voltage across the solar cell. Therefore, this method fails to determine an accurate single value of R_s for a given illumination intensity and temperature (Khan et al., 2013).

Using the method developed by Priyanka et al. (2007) in the range of 22–47 °C and for a irradiance of 1000 W/m^2 for crystalline silicon solar cells, Singh et al. (2008) found an almost constant diode ideality factor, and a linear decrease for series and shunt resistance with temperature.

Singh and Ravindra (2012) studied the temperature dependence of the diode saturation current for silicon solar cells between 0 °C and 250 °C based on a fit to experimentally achieved open-circuit voltage, and found an exponential dependence for this parameter with increasing temperature.

Banerjee and Anderson (1986) considered that in the low bias region the diode current is primarily dominated by shunt resistance, especially at low temperatures, and applying a low level bias voltage ($<$ 150 mV) and measuring the corresponding current, investigated the temperature dependence of shunt resistance for three silicon solar cells between −223 °C and 127 °C. It was found that this parameter showed distinct decreasing trends for each cell, and these differences were attributed to the solar cells manufacturing process.

Eikelboom and Reinders (1997) used the Orthogonal Distance Regression (ODR) (Burgers et al., 1996) as the fitting algorithm to adjust the two diode model to the I-V characteristics of silicon solar cells, assuming that the ideality factors are equal to 1 and 2 and independent from temperature, and found an increasing series resistance, a decreasing shunt resistance and increasing diode saturation currents with increasing irradiance in the range of 200–1000 W/m^2, under 25 °C.

Ghani et al. (2015) employed a numerical method to examine the temperature influence on crystalline silicon solar cells characterization parameters based on solving the single-diode equation using the Lambert-W function at five experimental points. This implies solving a system of five non-linear equations, which can be done by the Newton-Raphson method. However, the location of the five points from the experimental I-V data is very important, and should be extracted from short-circuit, open circuit and maximum power point (Ghani et al., 2014). Additionally, the Newton-Raphson method requires the specification of suitable initial values, which can be estimated by analytical methods, such as the method developed by Phang et al. (1984).

Following this approach, Ghani et al. (2015) found a linearly decreasing diode ideality factor and shunt resistance, polynomial increase of saturation current and linearly increasing series resistance with the temperature increasing between 25 °C and 75 °C under a irradiance of 1000 W/m^2 for a crystalline silicon solar cell.

Cuce et al. (2013), employing the method of Bouzidi et al. (2007) in the range of 15–60 °C and of 200–500 W/m^2 for mono and polycrystalline silicon photovoltaic modules, found a linear decrease of diode ideality factor for both increasing temperature and irradiance, and a linear decrease of series and shunt resistance for increasing temperature; the shunt resistance was found to have neglecting differences with irradiance.

Khan et al. (2010a) developed an analytical method to determine R_s, R_{sh}, n and I_0 from the variation of slopes of the I-V characteristics of the cell near short circuit and open circuit conditions with the intensity of illumination in a small range of intensity. However, when compared with other methods available in literature, discrepancies were found among the results.

Khan et al. (2010b) employed the method developed in (Khan et al.,