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Comparative analysis of parameter extraction techniques for the electrical characterization of multi-junction CPV and m-Si technologies

Jesús Montes-Romero[a], Florencia Almonacid[a], Marios Theristis[b], Juan de la Casa[a], George E. Georghiou[b], Eduardo F. Fernández[a,*]

[a] Centre for Advanced Studies on Energy and Environment (CEAEMA), IDEA Solar Energy Research Group, Electronics and Automation Engineering Department, University of Jaén, Las Lagunillas Campus, Jaén 23071, Spain

[b] PV Technology Laboratory, FOSS Research Centre for Sustainable Energy, Department of Electrical and Computer Engineering, University of Cyprus, Nicosia 1678, Cyprus

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A B S T R A C T

Modelling the current-voltage (*I-V*) characteristics of photovoltaic (PV) modules under real operating conditions is crucial for the better understanding of each technology. The most commonly used model for the electrical characterization of PV is the single-diode model where the five parameters are extracted through a variety of techniques. Although numerous extraction methods were developed for conventional PV technologies, the studies concerning the concentrating photovoltaic (CPV) technology are still limited. In this work, three analytical parameter extraction methods (Phang et al., Blas et al. and Khan et al.) are applied and compared for a multi-junction (MJ) CPV and a monocrystalline (m-Si) module based on long-term outdoor measurements in Jaén, Spain. The sensitivity of the models against the dominant parameters that influence the behaviour of PV and CPV (i.e. irradiance, module temperature and air mass) is also investigated. Furthermore, the effect of irradiance on the extracted parameters is discussed including the derivation of the corresponding fitting equations and errors. The results indicate that the most robust method is the one proposed by Phang et al. for the CPV module (normalised root mean square error, *NRMSE*, of 1.55%) and the one proposed by Blas et al. for the m-Si module (*NRMSE* of 0.58%). The method of Khan et al. resulted the highest error values for every case (*NRMSE* of 4.5% and 1.74% for CPV and m-Si respectively) while the Phang et al. method exhibited a similar error for both technologies. The main outcome of this work contributes to the optimum selection of parameter extraction techniques depending on the technology and the desired associated errors while the analysis of the dependence of the parameters on irradiance provides a better understanding of each technology's behaviour in the field.

1. Introduction

Concentrating photovoltaics (CPV) are considered as one of the most promising photovoltaic (PV) technology (Talavera et al., 2017, 2016). This technology employs optics to concentrate the direct sunlight onto a smaller area, most often made of high efficiency multi-junction (MJ) solar cells. Due to the combination of different components and the requirement for solar tracking, such systems are characterised by a multiphysics behaviour that makes the performance assessment more complex and inherently different than conventional photovoltaic devices (Rodrigo et al., 2013). Therefore, the CPV behaviour under actual operating conditions is not as clear as in conventional PV, which are very well understood and predictable nowadays (Fernández et al., 2013b; Kurtz et al., 2015; Theristis et al., 2018). This fact triggered important efforts within the last decade to analyse the behaviour and to develop models tailored to the special features of CPV technology at cell (Domínguez et al., 2010; Fernández et al., 2013; Theristis and O'Donovan, 2015), module (Fernández et al., 2013a; Steiner et al., 2015; Theristis et al., 2017b) and system level (Fernández et al., 2015; Kim et al., 2013; Strobach et al., 2015). Knowledge of the current-voltage (*I-V*) output of CPV, as a function of the relevant input parameters, is crucial for the understanding of the CPV performance. This, in turn, can lead to a reduction in investment risk and increase in bankability and therefore contribute to the market expansion of the technology (Fernández et al., 2016a; Kurtz et al., 2015; Leloux et al., 2014).

The *I-V* curve provides valuable information about the operational characteristics of a PV cell, module or array (Almonacid et al., 2015). The *I-V* curve of such devices is defined by the equivalent circuit models. A frequently used equivalent circuit model is the single-diode

* Corresponding author.
E-mail address: fenandez@ujaen.es (E.F. Fernández).

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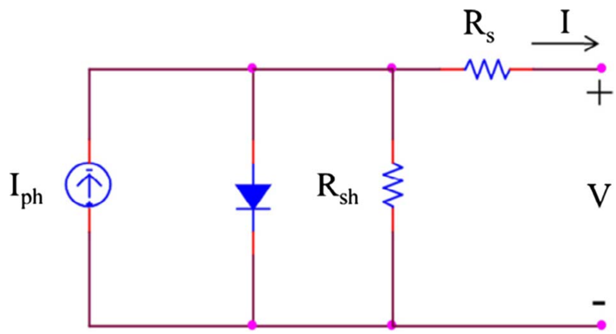

Fig. 1. Equivalent circuit of the single-diode model.

model (or single exponential model, SEM) illustrated in Fig. 1 for a single solar cell. The circuit is formulated using Kirchoff's current law where the current equals the photocurrent (I_{ph}) subtracted by the voltage-dependent current lost to recombination and the current lost due to shunt resistances:

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

where the current through the diode is modelled using the Shockley equation for an ideal diode, I_0 is the diode's saturation current, R_s is the series resistance, m is the diode's ideality factor, R_{sh} is the shunt resistance and V_T is the thermal voltage given by $V_T = kT/q$, where k is Boltzmann's constant (1.38E-23 J/K), T is the cell temperature and q is the elementary charge (1.6E-19C).

The estimation of the five characteristic parameters of the single-diode model (i.e. I_{ph}, I_0, R_s, m, R_{sh}) are of great importance for the modelling and evaluation of PV systems but also for degradation studies or other related scientific research in general (Celik and Acikgoz, 2007; Emery and Osterwald, 1987; Gasparin et al., 2016; Ishibashi et al., 2008; Kichou et al., 2016a,b; Sharma et al., 2014). Numerous studies in the literature developed and presented appropriate techniques capable of estimating and extracting the characteristic parameters of PV cells and modules (Ciulla et al., 2014; Cotfas et al., 2013; Humada et al., 2016; Li et al., 2013). The extraction methods presented in the literature can be divided into three main categories: a) the analytical methods (Chegaar et al., 2006; Tivanov et al., 2005; Wolf and Benda, 2013), b) the numerical methods such as the Lambert W functions (Ghani and Duke, 2011; Ortiz-Conde et al., 2006; Zhang et al., 2011) and Newton-Raphson method (Easwarakhanthan et al., 1986; Ghani et al., 2014) and c) the heuristic methods (Jamadi et al., 2016; Zagrouba et al., 2010; Ye et al., 2009; Yu et al., 2017). Numerical methods require suitable initial values in order to converge and can therefore result in a lower efficiency when the initial conditions are far from the optimal conditions (Yu et al., 2017). On the other hand, heuristic algorithms such as genetic, particle swarm optimisation, neural networks etc. have proven to be an alternative to numerical methods since they impose no restriction on the problem formulation. Furthermore, analytical methods are usually more preferable because such techniques are simpler to use and are able to provide comparable results under the normal operating conditions of PV devices (Chan et al., 1986; Ghani et al., 2017).

Although various parameter extraction techniques have been developed for conventional PV technologies, not much work has been done for CPV (Almonacid et al., 2016; Appelbaum and Peled, 2014; Ben Or and Appelbaum, 2013; Segev et al., 2012). In addition to this, all the parameter extraction methods related to CPV are based on numerical or heuristic modelling. The sole study applying analytical modelling techniques for CPV was recently published by the authors elsewhere (Fernández et al., 2016b) where, due to the aforementioned complexity of such systems, only a number of representative *I-V* curves was selected to conduct the study. This work however, moves one step beyond our previous study and long-term data (from Jaén, Spain) are accumulated using an in-house design for the *I-V* tracing. It is the first time that analytical methods used for the extraction of the five parameters in PV are applied in CPV and their performance is compared using long-term data of a monocrystalline Silicon (m-Si) and a CPV module, installed side-by-side. Such experiments can provide useful information about the applicability of simple analytical techniques, widely used in PV, on a more complicated technology such as the CPV eventually leading to improved energy yield predictions. Moreover, the sensitivity of the models against the dominant parameters that influence the behaviour of PV and CPV (i.e. irradiance, module temperature, T_{mod}, and air mass, *AM*) is also investigated for the first time. Finally, the influence of irradiance on the extracted parameters is analysed and the corresponding fitting equations and errors are derived; such analysis has been conducted only by Fernández et al. (2017) using indoor measurements under controlled environment for the case of CPV modules. The outcome of this research enables the selection of the most appropriate parameter extraction method in order to compare both technologies, and therefore, contribute to the optimum selection of PV technology according to the solar resource and atmospheric conditions of the site under consideration.

2. Materials and methods

In this section, the experimental campaign and methods used to conduct this study are presented. Initially, all the instrumentation used to collect the operational, meteorological and irradiance data is described. The methodology and chosen analytical methods are then presented along with their selection criteria.

2.1. Experimental campaign

The study was carried out at the University of Jaén in Southern Spain (N 37°27′36″, W 03°28′12″) from January to December 2016. This area is non-industrialized with low to medium values of precipitable water and aerosol content. The annual global solar irradiation is greater than 2000 kW h/m^2 and the annual direct normal irradiation is around 1800 kW h/m^2. The ambient temperature ranges from approximately 5 °C in winter to 40 °C in summer.

Two modules were installed side-by-side on a two-axis solar tracker designed by BSQ Solar as it is presented in the upper left picture of Fig. 2. The MJ-based CPV module manufactured by Daido Co. (model DACPV-150W25) and the m-Si module manufactured by Sharp Co. (model NU-E245) are shown on the left and right side of the upper left picture in Fig. 2, respectively. The CPV module consists of 25 triple-junction lattice-matched GaInP/GaInAs/Ge solar cells interconnected in series. The primary optics are PMMA dome-shaped lenses and the secondary optics are refractive pyramids. The geometric concentration is 550× and it is cooled passively without employing any extended surfaces (i.e. heat sink) (Theristis et al., 2012). The nominal output power of the module is 150 W. The maximum recommended temperature is 80 °C (Fernández et al., 2014; Micheli et al., 2016). On the other hand, the m-Si module is formed by 60 solar cells interconnected in series with a nominal output power of 245 W.

The irradiance was monitored using a Kipp & Zonen CMP11 pyranometer for the global normal irradiance (*GNI*) and a Kipp & Zonen CHP1 pyrheliometer for the direct normal irradiance (*DNI*). A four-wire PT100 was also placed at the centre of each module's back surface to measure a representative module temperature (i.e. the T_{mod}). A weather station, installed on the site, was measuring all the relevant meteorological parameters such as the ambient temperature, wind speed and direction, and relative humidity.

In order to obtain the five parameters of the single-diode model, a characterisation system consisting of an open platform was employed according to the schematic diagram exhibited in Fig. 2 (Montes-Romero et al., 2017). The monitoring and characterisation system in the