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Comparative study of methods for the extraction of concentrator photovoltaic module parameters

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ABSTRACT

The modelling and outdoor evaluation of high concentrator photovoltaic (HCPV) systems is complex due to the use of multi-junction solar cells and optical devices. At the same time, the single exponential model (SEM) is widely used for predicting the IV characteristics of PV systems. In this paper, several conventional analytical methods for extracting the five parameters of the SEM model of non-concentrating PV devices are applied and evaluated for the electrical characterization of a HCPV module for the first time. Among the different approaches, three simple analytical methods have been selected with the aim of offering rapid and easy solutions for the characterization of HCPV systems. The selected methods are: the method of Phang et al., the method of Blas et al. and the method of Khan et al. In addition, these methods are compared with a numerical extraction method previously introduced by the authors. Results show that all the methods investigated can be valid for predicting the IV curve of a HCPV module except the method of Khan et al., which tends to underestimate the IV curve and maximum power of the module. The dependence of the extracted SEM model parameters with the input irradiance is also discussed.

1. Introduction

The most widely used approach for the electrical characterization of photovoltaic (PV) solar cells and modules is based on the equivalent circuit shown in Fig. 1. From this circuit, the relation between the current (I) and the voltage (V) is given by the so-called single exponential model (SEM) according to the following mathematical expression:

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

where the solar cell or module is characterized by a set of 5 parameters, namely: the photo-generated current (I_{ph}), the diode saturation current (I_o), the diode ideality factor (m), the series resistance (R_s) and the shunt (or parallel) resistance (R_{sh}). V_T in Eq. (1) is the thermal voltage of the PV device, given by $V_T = kT/q$, being k the Boltzmann constant with a value of 1.38E−23 J/K and q the electron or elementary charge with a value of 1.60E−19 C.

The current-voltage (IV) characterization provides the most information of the performance of any type of PV device (Almonacid et al., 2015). In this context, the accurate estimation of the characteristic parameters of Eq. (1) is crucial for the modelling, evaluation, quality control concerns, degradation studies, optimization of fabrication process and for scientific research in general (Kichou et al., 2016a,b; Ishibashi et al., 2008; Lo Brano et al., 2010; Celik and Acikgoz, 2010; Gasparin et al., 2016). Bearing this in mind, the scientific community have devoted big efforts in developing tools capable to estimate the characteristic parameters of solar cells and modules for decades (Cotfas et al., 2013; Ciulla et al., 2014; Humada et al., 2016; Li et al., 2013). The different extraction methods can be divided in analytical or semi-analytical methods (Chegaar et al., 2006; Ishibashi et al., 2008; Tivanov et al., 2005; Wolf and Benda, 2013) and in numerical methods (Ghani et al., 2014, 2016) such as vertical optimization (Easwarakhanthan et al., 1986), electric conductance optimization (Chegaar et al., 2004), co-content function (Ortiz-Conde et al., 2006), Lambert-W function (Zhang et al., 2011; Ghani and Duke, 2011), genetic algorithms (Sellami and Bouaïcha, 2011) or particle swarm optimization algorithms (Ye et al., 2009). The numerical methods are supposed to be more accurate and adaptable to the particular solar cells and modules under study. Despite of this, Chan et al. (1986) have pointed out that the analytical methods can be more accurate than sophisticated curve fitting and numerical methods under the normal operating conditions of PV devices.

High Concentrator Photovoltaics (HCPV) is considered as one of the most promising research avenues to produce more

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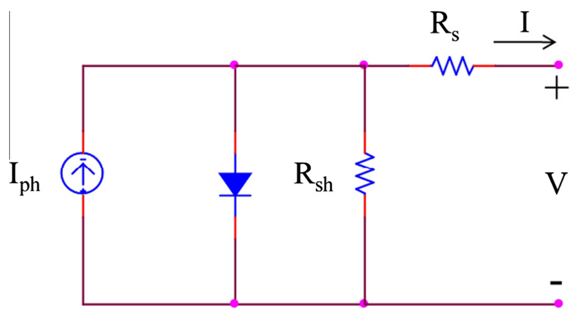

Fig. 1. Equivalent circuit of the single exponential model of a PV device.

cost-effective electricity than PV technology by replacing the amount of semiconductor material by using less expensive optical elements (Friedman et al., 2013; Perez-Higueras and Fernández, 2015) and has already shown promising results at locations with high solar resource (Talavera et al., 2015; Haysom et al., 2015; Fernández et al., 2016a). The HCPV module is the fundamental unit of HCPV technology to convert the direct non-concentrated sunlight into electricity and, nowadays, largely consists of (Rodrigo et al., 2015b): high efficiency multi-junction III–V solar cells made up of several p-n junctions to increase the absorption of the incident solar spectrum (Fernández et al., 2013a; Yamaguchi et al., 2008), and therefore, the efficiency of the system (Fernández et al., 2015a; Yamaguchi et al., 2005), a primary optical concentrator element, a secondary optical element to homogenize the luminous power on the solar cell surface and to improve the acceptance angle of the system (Shanks et al., 2016), and a passive cooling mechanism able to dissipate the heat produced by the high energy fluxes impinging on the solar cells surface (Micheli et al., 2016). Due to the features commented above, the modelling and electrical characterization of HCPV devices is inherently different and more complex than in conventional PV systems (Rodrigo et al., 2013, 2014; Theristis and O'Donovan, 2015) and the understanding of the performance of HCPV modules when operating in real world conditions is clearly lower than conventional PVs (Soria-Moya et al., 2015; Kurtz et al., 2015; Fernández et al., 2013b).

At the present, the studies concerning the extraction of the five parameters of Eq. (1) in HCPV technology are essentially limited to the work presented in (Segev et al., 2012; Ben Or and Appelbaum, 2013; Appelbaum and Peled, 2014; Almonacid et al., 2016). Segev et al. (2012) proposed a semi-empirical numerical method to extract the characteristics parameters of triple-junction InGaP/InGaAs/Ge solar cells under different concentrations and temperatures. The study of the Newton-Raphson method, the Levenberg-Marquardt method combined with Lambert-W function and a Genetic-Algorithm for the extraction of the key parameters of a triple-junction InGaP/InGaAs/Ge solar cell under different concentration levels was conducted by Ben Or and Appelbaum (2013) and Appelbaum and Peled (2014). Recently, Almonacid et al. (2016) proposed a numerical method to extract the parameters of a whole HCPV module under real different operating conditions of irradiance and temperature.

This paper goes deep in the previous study of the authors commented above. For the first time, the simple conventional analytical solutions for the extraction of the five parameters of non-concentrating PV devices are applied and analysed for HCPV technology. The selected extraction methods have been chosen according to the two following criteria: (a) easy and fast to implement and (b) extract the five parameters of the SEM model. Moreover, the methods under study are compared with the numerical method previously introduced by the authors. The final aim of this work is to examine simple and rapid solutions for the modelling and evaluation of HCPV technology. In addition, the dependence of the extracted parameters with the incident irradiance is investigated to contribute to the discussion of the fundamental dependencies of concentrator solar cells with light intensity (Fernández et al., 2015b; Kinsey et al., 2008; Siefer and Bett, 2014). These topics are critical to achieve a better understanding of this technology under real working scenarios, and then, to help in its market expansion and large scale deployment.

2. Experimental set-up

To conduct this study, the data available of a HCPV module monitored during six months from July to December 2013 at the Centre for Advanced in Energy and Environment at the University of Jaen in Southern Spain have been used. Jaen is a non-industrialised medium size city with low-medium values of precipitable water and turbidity, periodically affected by Saharan dust and burning of olives trees branches. It also has a high annual energy resource, more than 2000 kW h/m^2, and an extreme range of air temperatures that usually go from around 5 °C in winter to more than 40 °C in summer. Thus, it is possible to evaluate the performance of PV and HCPV devices under a wide range of atmospheric conditions. The HCPV module, see Fig. 2, is formed by 20 triple-junction lattice-matched GaInP/GaInAs/Ge solar cells interconnected in series. The primary optics consists of silicone-on-glass Fresnel lenses and the secondary optics of reflective truncated pyramids. The efficiency of this optical configuration is 80%. The module has also a geometric concentration of 700× and uses natural convective finned aluminium heat exchangers to ensure that the cells are working on their recommended temperature range, which is usually within 50–80 °C (Fernández et al., 2014a). Fig. 3 shows a schematic diagram of a single solar receiver integrated with the primary and secondary optics, as well as the different materials that compose the different layers of the solar receiver. It is worth mentioning that the features of the module described above represent the most wide-spread concentrator nowadays (Rodrigo et al., 2015b). Hence, the results of this work can be considered representative of the current HCPV technology.

The HCPV module was mounted of a high-accurate pedestal two-axis solar tracker designed by BSQ Company, see Fig. 2, for point focus Fresnel Lenses. The current-voltage characteristics were recorded with a high-precise four-wire PVPV 1000 C40 IV tracer (less than 1 s and 100 points per IV curve for the electrical range of the module under study). Also, two four-wire PT100 temperature sensors were installed on the back of the module and on a solar cell receiver to record, respectively, the heat-sink and cell temperature, as previously discussed in (Fernández et al., 2014b). In addition, an atmospheric station MTD 3000 from Geonica Company equipped with different sensors recorded all the relevant parameters necessary for the outdoor evaluation of concentrator photovoltaic modules. All the parameters were monitored every 5 min. The days on which the system was stopped by failure, maintenance or because an experiment was carried out have not been considered to avoid any distortion on the data. Also, the module was cleaned once a week and after rainy days, and the alignment of the tracker was periodically calibrated to avoid possible electrical losses and noise in the recorded data. Further information of the experimental set-up above can be found, for instance, in (Fernández et al., 2013b).

Table 1 shows the maximum, minimum and average values of cell temperature (T_C) and spectrally corrected direct normal irradiance (DNI_C), or simply effective irradiance, gathered during the experiment. This irradiance may be defined as the portion of the spectrum that the HCPV module is able to convert into electricity