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The numerical computation of lumped parameter values using the multi-dimensional Newton-Raphson method for the characterisation of a multi-junction CPV module using the five-parameter approach

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ABSTRACT

The mathematical modelling of photovoltaic devices is heavily relied upon due to their highly variable yield while operating under varying environmental conditions. A number of methods currently exist to characterise the non-linear electrical behaviour of these devices, with the single-diode, five-parameter model extensively used. In this study, we examine the use of this model for a triple-junction III–V type solar cell operating under concentrated sunlight. In order to use this method, however, five characterisation parameters must be calculated for the specific device under study. Their calculation is difficult due to the intrinsic non-linear operational characteristics of these devices, as such a number of methods currently exist for this purpose. A new method is presented here based on the examination of the power-voltage data from which a system of five residual equations are derived and solved via the multi-variable Newton-Raphson method.

The new approach was validated experimentally by means of both qualitative and quantitative assessment. Results revealed that the proposed method was able to accurately model this device type and when compared to several alternative methods, yield the lowest average root mean square error (RMSE) with a 7–55% improvement offered over the alternative methods investigated. The proposed method will be useful to engineers and scientists who wish to characterise the performance of multi-junction photovoltaic devices using the single-diode, five-parameter model and require a method to extract the values of their characterisation parameters. A limitation with this approach is the computational effort required to solve the system of non-linear residual equations and the need for good initial estimates of the lumped parameters to initiate the search.

1. Introduction

The thermodynamic efficiency of the ideal single-junction photovoltaic cell is approximately 31% as determined by Shockley and Queisser (1961). This efficiency limitation is due to transmission losses of photons with energies below the bandgap and thermal relaxation of carriers generated by photons above the bandgap. As such, the architecture of the single junction solar cell is unable to efficiently utilise the total incident solar spectrum. However, by combining two or more cells of different bandgaps into a single multi-junction configuration, the work yield per photon can be increased, improving the output of the device. By arranging cells by order of their bandgaps, with the cell with the largest bandgap at the top, light is filtered as it is attenuated through the stack, ensuring that it is optimally absorbed by the cell with the best suited spectral response. Furthermore, by optimising the bandgaps of each of the constituent cell layers, their current outputs will be closely matched such that they may be coupled in a simple series connection scheme (Razykov et al., 2011).

The historical performance of both silicon and multi-junction solar cells for over two decades is shown in Fig. 1. From this graph, we can see that while only marginal improvements have been made to silicon solar cell types, considerable improvements have been achieved for the multi-junction cell type.

The efficiency upper limit of a multi-junction type solar cell will theoretically increase with the number of cells making the stack (Yamaguchi et al., 2008, 2005). This approach, however, will

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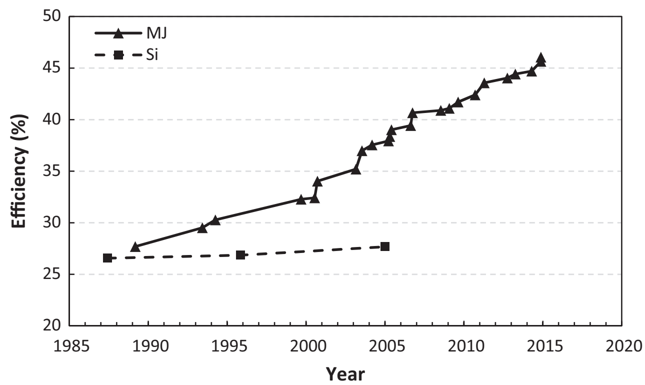

Fig. 1. Progress for both multi-junction and silicon solar cell conversion efficiencies adapted from (NREL, 2017).

eventually lead to diminishing gains due to the additional complexities introduced by cell layers such that a stack consisting of five or six cells is nowadays of practical limit due to factors such as current limitation (Bonnet-Eymard et al., 2013). Currently the state-of-the-art solar multi-junction cell commercially available is the lattice-matched triple-junction solar cell comprising of III-V semiconductor compounds (Guter et al., 2009; Helmers et al., 2013) capable of operating at efficiencies greater than 40% (King et al., 2012). The diagram of this device's structure is given in Fig. 2.

Due to the high manufacturing cost of this solar cell type, these devices generally require coupling with some means of optical concentration system to be economically viable. Presently, High Concentration Photovoltaic (HCPV) systems with concentration ratios greater than 500x are considered as one of the most promising research avenues to produce more cost-effective electricity compared to traditional Photovoltaic (PV) systems (Cotal and Frost, 2010; Haysom et al., 2015; Talavera et al., 2015; Verlinden et al., 2007). A number of methods may be used to concentrate sunlight onto the multi-junction solar cell using either lenses or reflectors, or a combination of both. Secondary optical elements may also be implemented to further concentrate as well as homogenise the distribution of solar flux and improve the sunlight acceptance angle (Shanks et al., 2016a). Methods utilised for optical concentration may be classified into three major groups based on their primary focusing method: (1) linear focusing lens, (2) two-dimensional focusing lens, and (3) central receiver system (Chong et al., 2013). The most common approach is to use a Fresnel lens (Almonacid et al., 2016; Shanks et al., 2016b; Xie et al., 2011) due to their combination of high optical efficiency, minimal weight, and relatively low cost (Leutz et al., 2000). In this study, an experimental procedure has been applied using such an optical system which will be discussed in detail in the methods section.

In addition to the optical concentration system, a HCPV system will require a thermal management system due to the detrimental

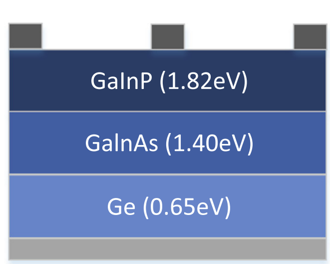

Fig. 2. Structure of the commercially available triple-junction lattice-matched solar cell typically manufactured with a silver back contact.

impact of increasing temperature on photovoltaic output and reliability of the concentrator (Ghani et al., 2015; Radziemska, 2003; Radziemska and Klugmann, 1999, 2002; Royne et al., 2005; Skoplaki and Palyvos, 2009; Wysocki and Rappaport, 1959). It was shown in several experimental studies that a linear drop in conversion efficiency with an increase in temperature for a triple junction GaInP/GaInAs/Ge type cell; while operating under concentration ratios within 100–1000 suns a temperature decay coefficient ranging from −0.14%/°C to −0.11%/°C is observed. In addition, high operating cell temperatures and extreme thermal cycles can damage the concentrator cells (Espinet-González et al., 2015) and the rest of the surrounding elements due to their different thermal expansion coefficients (Fernández et al., 2014a; Micheli et al., 2013). Currently, thermal management systems for multi-junction HCPV systems comprise primarily of passive methods utilising heat sinks (O'Neill et al., 2000) and spreader bars (Rumyantsev et al., 2000) due to their simple design and ability to keep the solar cell operating within an acceptable temperature range to minimise this impact (Micheli et al., 2016).

Due to the features commented above, the modelling of the electrical output of HCPV systems is inherently different and more complex than for conventional PV technology (Kurtz et al., 2015). Given the highly variable nature of factors influencing the yield of HCPV system such as: magnitude of solar irradiance, cell operating temperature, and the spectral characteristics of the incident sunlight (Fernández et al., 2014b, 2013; Theristis et al., 2016; Theristis and O'Donovan, 2015), modelling and simulation activities are extensively used for energy prediction, design, and economic analysis (Fernández et al., 2016b; Leloux et al., 2014; Rodrigo et al., 2014, 2013). Due to the non-linear behaviour of photovoltaic devices, characterisation methods such as the single-diode (Leloux et al., 2014; Phang et al., 1984; Villalva et al., 2009) and double-diode (Ishaque et al., 2011; Wolf et al., 1977) models are frequently employed in the literature to model the single-junction type solar cell. It has been demonstrated in a previous study that both models may be employed for modelling the triple junction GaInP/GaInAs/Ge solar cell (Segev et al., 2012).

The single-diode model, described by the modified Shockley diode equation, incorporates a diode ideality factor, m, to account for the effect of recombination in the space-charge region (Sah et al., 1957). The double-diode model simulates the space charge recombination effect by incorporating a separate current component with its own exponential voltage dependence. Each p-n junction of a multi-junction solar cell can be represented by the equivalent circuit model expressed by the single or double diode equation. Due to the series connection of the p-n junctions, the I-V curve of multi-junction solar cells is similar in shape than those of conventional solar devices. Bearing this in mind, multi-junction solar cells can be modelled as a single-junction device expressed by the Shockley diode equation (Fernández et al., 2015b). This approach has proven to be valid for modelling the electrical characteristics and explain the fundamental dependencies of triple-junction solar cells under temperature and irradiance variations (Ben Or and Appelbaum, 2013) (Or and Appelbaum, 2014). More recently, it was shown by Almonacid et al. that conventional techniques, such as the single exponential model, are also adequate to model concentrator modules made up of multi-junction solar cells in outdoors by using the effective irradiance and cell temperature of the system (Almonacid et al., 2016).

The equivalent circuit diagram for the single exponential model is shown in Fig. 3. By applying Kirchhoff's laws, we can express current (I) as a non-linear implicit function, Eq. (1).

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