Available online at www.sciencedirect.com
ScienceDirect
Solar Energy 132 (2016) 15–24
SOLAR ENERGY
www.elsevier.com/locate/solener

The characterisation of crystalline silicon photovoltaic devices using the manufacturer supplied data

F. Ghani [a,*], G. Rosengarten [b], M. Duke [c]

[a] *Institute of Mechanical, Process, and Energy Engineering, Heriot-Watt University, Edinburgh, United Kingdom*
[b] *School of Mechanical, Manufacturing, and Aerospace Engineering, RMIT University, Melbourne, Australia*
[c] *Department of Engineering, The University of Waikato, Hamilton, New Zealand*

Received 8 September 2015; received in revised form 21 February 2016; accepted 3 March 2016
Available online 14 March 2016

Communicated by: Associate Editor Arturo Morales-Acevedo

Abstract

Currently, the single diode, five parameter model is extensively used to mathematically model the electrical behaviour of a photovoltaic device. The accuracy of this model is, however, strongly dependent on a number factors but particularly the quality of the five parameters used to characterise the devices unique performance behaviour. These are; the series and shunt resistances, the photogenerated and reverse saturation currents, and the diode factor. In this study, a new method is presented to determine four of the five parameter values using the data typically provided by the manufacturer. The proposed method is based on calculating the values for the series and shunt resistances and the photogenerated and reverse saturation currents by solving the underlying non-linear equations at short-circuit, maximum-power-point, and open-circuit conditions numerically.

The proposed algorithm was experimentally validated against a crystalline silicone type solar cell. The characterisation parameter values were calculated using the proposed algorithm in Matlab, and then used to generate the simulated *I–V* data. When the experimental data was compared against the generated simulated data, it was found that the simulated data closely matched the experimental data at the three chosen points (short circuit current, maximum power point, and open circuit voltage), with a minor disparity emerging outside these locations. This disparity was quantified using a root mean square error (RMSE) approach which revealed a maximum RMSE value of 0.0072 when assuming a diode factor (n) of one. By incrementally adjusting the diode ideality factor from $n = 1$ to 1.5, the RMSE was reduced further to 0.0008.

Keywords: Solar cell; Photovoltaic; Characterisation; Parameter values; Modelling

1. Introduction

Photovoltaic systems are non-linear power supplies whose output, is strongly dependent on the environmental conditions in which it is installed. Primary environmental factors of influence include the magnitude and spectral characteristics of the incidental sunlight, the ambient temperature, and wind velocity (Skoplaki and Palyvos, 2009). As all these factors are highly variable, mathematical models are heavily utilised to approximate the electrical output of a photovoltaic system design taking into consideration specific details of the installation (i.e. technology, weather of installation site, etc.).

A number of mathematical models currently exist in the literature for this purpose with the lumped circuit model type prevalent (Chan and Phang, 1987). Within this type are the single and double diode models, which together

---

[*] Corresponding author.

http://dx.doi.org/10.1016/j.solener.2016.03.008
0038-092X/

represent the majority of models that are currently used for the simulation of photovoltaic systems. The single-diode model is described by the modified Shockley diode equation which includes a diode quality factor term (n) to account for the effect of recombination in the space-charge region. The second model, frequently referred to as the double-diode model, includes an additional diode so that it may take into account both space charge and recombination effects. Although stated to offer superior accuracy over the single diode model (Wolf et al., 1977), the additional diode adds greater complexity to the modelling process over the single diode alternative. The additional complexity is due to the number of characterisation parameters or lumped parameter values that must be calculated. The double-diode model requires the calculation of seven parameters, while the single diode model needs only five. These values, regardless of the model, attempt to numerically capture the unique behaviour of the device under study, and will vary significantly due to their dependence on material, manufacturing/quality, and overall design. For this reason, the single-diode model is frequently used based on the excellent balance it achieves between modelling accuracy and complexity (Villalva et al., 2009) and is therefore the focus of this study.

The equivalent circuit diagram of a photovoltaic cell using the single-diode model is depicted in Fig. 1. By applying Kirchhoff's laws to this circuit, the non-linear implicit characteristic equation is given by Eq. (1).

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

where i and V represent the current and voltage values respectively, I_{ph} is the photogenerated current, I_0 is the reverse saturation current, R_s and R_{sh} are the series and shunt resistance values respectively, n is the diode factor, and V_{th} is the thermal voltage.

The challenge in applying Eq. (1) promptly arises when calculating the values for R_s, R_{sh}, I_{ph}, I_0, and n, (henceforth referred to as the characterisation parameters) as they are not typically provided by the manufacturer. These parameters must therefore be individually calculated for the device under investigation. Each of these parameter values represents various aspects of the device and of the conversion process.

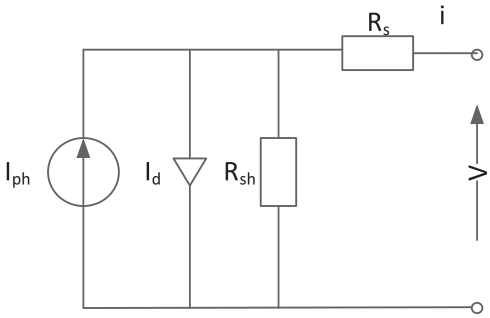

Fig. 1. The equivalent circuit diagram for the single-diode model.

The series resistance, R_s, represents resistances in the cell solder bonds, emitter and base regions, cell metallisation, cell-interconnect busbars and resistances in junction box terminations (Wenham et al., 2008). Photovoltaic device manufacturers aim to minimise the value of R_s as it reduces the voltage output of the device, however, it is not possible to have this equal to zero. Furthermore, daily thermal cycling of modules deployed outdoors has been demonstrated to increase its value (van Dyk and Meyer, 2004). The influence of increasing the series resistance on the electrical behaviour of a photovoltaic cell results in the reduction of the voltage and consequently the output power (P).

The shunt resistance, R_{sh}, represents any parallel high conductivity paths (shunts) across the solar cell p–n junction (Rummel and McMahon, 1996) due to crystal damage and impurities in vicinity of the junction. The net effect of these shunt paths is the diversion of current from the intended load, particularly under low illumination. The impact of reducing the shunt resistance leads to a reduction in current and consequently the power output from the device.

The third parameter of interest is the diode factor, n. Similar to the series and shunt resistances which attempt to average out the effect of several mechanisms taking place within the cell, the diode or ideality factor is used to average out the current transport mechanisms through the diode junction. The diode current is the sum of the variety of diode currents: a diffusion component in the quasi-neutral regions of the junction, a generation recombination component in the bulk-space charge layer and a surface component (Hamdy and Call, 1987). Some of these components attain a dominating influence in different portions of the current–voltage characteristic curve (Wolf and Wolf, 1981). The diffusion component for example dominates at large forward biases and is best represented with a diode factor of 1 (Neugroschel et al., 1977). Generally speaking, a diode/ideality factor value between 1 and 1.3 for crystalline silicon modules is used (Tsai et al., 2008; Bellia et al., 2014).

Given the importance of accurately calculating the characterisation parameter values of the device under study, a number of methods currently exist to perform this task. The majority of methods may be categorised as either analytical or numerical types. The analytical approach introduces a number of simplifications to reduce the complexity of the governing mathematics yielding a simple and fast approach. It has therefore been applied to previous studies (Chan and Phang, 1987; de Blas et al., 2002). However, the introduction of simplifications logically introduces some error into the analysis. Alternatively, the number of simplifications and assumptions may be reduced to improve accuracy by making a switch to more computationally demanding numerical methods. The numerical approach is investigated further in this study as accuracy is desired while making use of low cost, modern day