Renewable Energy 72 (2014) 105–112

Contents lists available at ScienceDirect

Renewable Energy

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

The numerical calculation of single-diode solar-cell modelling parameters

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

[a] School of Aerospace, Mechanical, and Manufacturing Engineering, RMIT University, Melbourne 3001, Australia
[b] Solimpeks Australia, Suite 18 Level 13, 3 Spring St, Sydney, NSW 2000, Australia
[c] School of Engineering, University of Waikato, Hamilton 3240, New Zealand

A R T I C L E I N F O

Article history:
Received 11 October 2013
Accepted 22 June 2014
Available online

Keywords:
Single diode
Cell parameters
Shunt resistance
Series resistance
Diode factor
Characterization

A B S T R A C T

The accurate simulation of a photovoltaic solar cell requires the precise determination of modelling parameters specific to the device under study. For the case of the single diode model, five parameters must be determined; I_{ph}, I_0, R_s, R_{sh}, and n. Generally speaking these values may be calculated either by analytical or numerical methods. Although analytical approaches are simple and fast to carry out, the assumptions and simplifications they introduce in order to deal with the non-linear characteristics of a solar cell may result in modelling inaccuracies. In this study a new approach is presented to calculate all five parameter values numerically minimising assumptions and simplifications. The method proposed is based on solving the single diode current–voltage equation expressed using the Lambert *W*-function at five experimentally obtained points along the current–voltage curve. To solve the system of non-linear equations, the multi-dimensional variant of the Newton–Raphson method is applied. All necessary first order partial differential equations are provided in closed form. Experimental validation of the proposed method revealed an improvement in modelling accuracy over one commonly used analytical approach. Furthermore, using TRNSYS software to simulate the annual energy output we show that modelling photovoltaic systems with small variations in solar cell parameters can result in non-trivial variations in annual energy output highlighting the importance of their calculation.

1. Introduction

Presently, manufacturers of photovoltaic devices provide the electrical characteristics of their products under predefined circumstances typically referred to as standard test conditions (STC). Under these conditions the temperature of the device during measurement is controlled at 25 °C, and incident irradiance fixed at 1000 W/m^2 possessing the spectral characteristics of sunlight attenuated through an atmospheric air mass value of 1.5. Although these values are beneficial for product assessment and benchmarking purposes, they serve little use for the estimation of actual annual energy yield due to their intrinsic non-linear electrical behaviour and the variability in environmental conditions (irradiance, temperature, etc.).

The output of any terrestrial photovoltaic system is dependent on a number of factors, such as the properties of the incidental irradiance (magnitude, spectral characteristics) and also the operating temperature, which is influenced by ambient temperature, environment (e.g. wind), and the manner in which the photovoltaic system is installed. Furthermore, the behaviour of a photovoltaic system will also be dependent on its type and manufacture.

Given this behaviour and the need to calculate their electrical output for varying conditions and design, it is important for both economic and technological reasons to utilise accurate mathematical models. Such models may then be applied to quantify the approximate output of the photovoltaic system for user defined conditions (e.g. temperature, irradiance, etc.). Currently a number of models exist to achieve this purpose ranging from those based on artificial neural networks [1–5] to the more traditional lumped parameter models [6–8]. The disadvantage with the former category is the initial collection of extensive training data which must be experimentally acquired for network training [9]. Lumped parameter models on the other hand do not require a training phase and therefore do not need the collection of training data. They do however require the calculation of the lumped parameter

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[*] Corresponding author. RMIT University, School of Aerospace, Mechanical, and Manufacturing Engineering, Melbourne 3001, Australia.

E-mail addresses: faisal.ghani@rmit.edu.au, faisal.ghani@solimpeks.com.au (F. Ghani).

http://dx.doi.org/10.1016/j.renene.2014.06.035
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values which represent various physical mechanisms taking place within the cell. Fig. 1 is the equivalent circuit diagram for the single diode lumped parameter model.

I_{ph} represents the photo-generated current, I_d is the reverse saturation current, and R_s and R_{sh} represent the series and shunt resistances respectively. The single diode model can be described by the modified Shockley diode equation incorporating a diode quality factor to account for the effect of recombination in the space charge region [10]. A commonly used alternative to this model is the double diode model shown by Fig. 2 [11]. This model additionally captures the effect of recombination of carriers and improves the accuracy over the single diode model [12,13]. Improved accuracy has been demonstrated to be particularly evident for low levels of illumination [10]. However the introduction of a second diode adds further complexity, particularly in regard to the calculation of modelling parameters [14]. Recently however, a simplified approach has been presented by Ishaque et al. [15] where only four parameters are required as opposed to the traditional seven (I_{ph}, I_{01}, I_{02}, R_{sh}, R_s, a_1, a_2). This simplification is achieved by setting the reverse saturation currents, I_{01} and I_{02}, equal in magnitude and providing a method of calculating the diode ideality factors a_1 and a_2. This method is an interesting alternative as it removes some of the complexity associated with the double diode model, though the introduction of assumptions and simplifications leaves some ambiguity.

Assuming the photovoltaic system under study is to be under normal levels of irradiance, the single diode model is stated to strike a good balance between modelling accuracy and complexity [8,16]. Applying Kirchhoff's laws to the single diode circuit shown in Fig. 1, we obtain the current–voltage characteristic equation for a solar cell shown 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 is the current output, V is the voltage output, n is the diode factor, and V_{th} is the thermal voltage (kT/q, $k = 1.381 \times 10^{-23}$ J/K, $q = 1.602 \times 10^{-19}$ C).

As stated in an earlier study by Carrero [17], modelling accuracy is not only dependent on which model is chosen, but also by the selection of parameter values used into Eq. (1), and how well they reflect the properties of the device under study. To use Eq. (1), five parameter values must be calculated; n, I_{ph}, I_0, R_s, and R_{sh}. These five parameters all play an influential role in the behaviour of Eq. (1). Therefore for the output of Eq. (1) to accurately reflect the output of a specific photovoltaic device, these parameters should closely represent the true behaviour of the device. These parameter values may either be determined analytically or numerically.

1.1. Analytical calculation of modelling parameters

The analytical approach in calculating solar cell parameters is commonly used due to its speed and simplicity. By introducing several assumptions, the complex non-linear relationships that define the behaviour of a solar cell can be reduced to analytically soluble equations. Parameters may then be calculated from these equations.

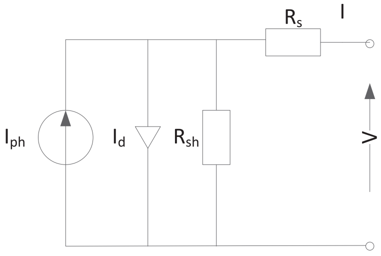

Fig. 1. Single diode equivalent circuit diagram of a photovoltaic cell.

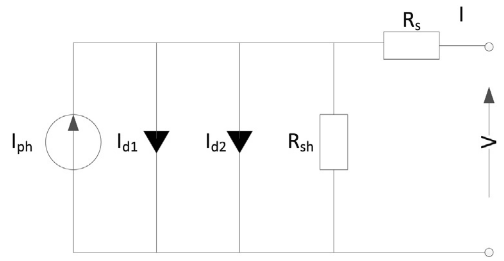

Fig. 2. Double diode equivalent circuit diagram of a solar cell.

The first parameter, the ideality factor n accounts for the differential mechanisms responsible for moving carriers across the junction [18]. The parameter n is 1 if the transport process is purely diffusion and approximately 2 if the primary process is recombination in the depletion region. Values are typically selected in between this range. Carrero [17] suggest a value of unity for example, while another study proposes an empirical approach [19]. One approach is to apply the analytical expression given by Phang et al. [20],

$$n = \frac{V_{mp} + R_{s0}I_{mp} - V_{oc}}{V_{th}\left\{\ln\left(I_{sc} - \frac{V_{mp}}{R_{sh0}} - I_{mp}\right) - \ln\left(I_{sc} - \frac{V_{oc}}{R_{sh}}\right) + \frac{I_{mp}}{I_{sc} - (V_{oc}/R_{sh0})}\right\}} \tag{2}$$

where V_{mp} is the voltage value at maximum power point (MPP), R_{s0} and R_{sh0} are estimates for R_s and R_{sh} respectively, I_{mp} is the current at MPP, V_{oc} the open circuit voltage, and I_{sc} is the short circuit current. Values for V_{mp}, I_{mp}, V_{oc}, and I_{sc} are typically provided by the manufacturer data sheets. The values for R_{s0} and R_{sh0} however must be calculated by examining the current–voltage (IV) curve. Slopes at short circuit current and open circuit voltage as shown by Fig. 3, provide the negative inverse values for R_{sh0} and R_{s0} respectively.

The analytical approach by Phang et al. assumes that the value of R_{sh} is equal to R_{sh0} (see Fig. 3) such that,

$$R_{sh} = R_{sh0} \tag{3}$$

The value for R_{s0} is adjusted to give R_s by using Eq. (4).

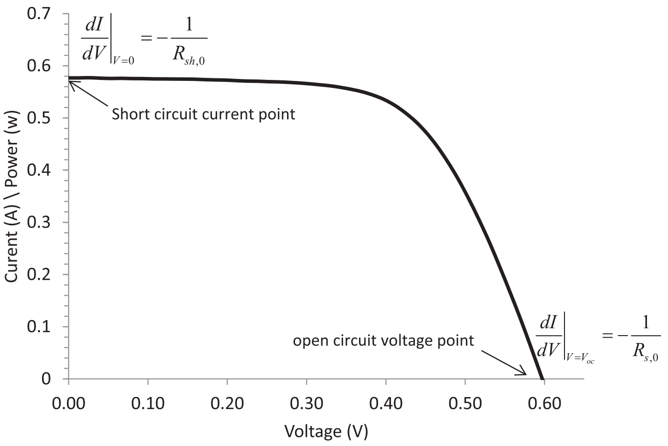

Fig. 3. Calculation of R_{s0} and R_{sh0} from the I–V curve using first order derivatives.