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ScienceDirect

Solar Energy 112 (2015) 437–445

SOLAR ENERGY

www.elsevier.com/locate/solener

On the influence of temperature on crystalline silicon solar cell characterisation parameters

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Received 13 November 2014; accepted 9 December 2014
Available online 7 January 2015

Communicated by: Associate Editor Nicola Romeo

Abstract

The crystalline silicon type cell is at present the most commonly used photovoltaic device on the market. These solid state devices are only capable of converting a portion of the solar spectrum into electricity. Disregarding reflection losses, the remaining portion is absorbed by the cell thus elevating its operating temperature. It has been shown in a number of previous studies that the overall electrical performance of these cells will deteriorate with temperature, with power output dropping linearly with temperature. In this study, we examine this issue in closer detail by investigating how temperature affects each of the five characterisation parameters required to characterise their electrical behaviour using the single diode five parameter model. Collecting current–voltage data from a mono-crystalline silicon cell at constant irradiance but at temperatures varied within the range of 25 and 70 °C (the typical range experienced in the field), we calculated the five modelling parameters using a unique numerical approach which takes into consideration several points taken from the experimental current–voltage data. It was found that all five modelling parameters were influenced by temperature, with the reverse saturation current followed by the series and shunt resistances being affected most significantly, in that order. Photovoltaic device modelling will be enhanced by taking into account the influence of temperature on each of these characterisation parameters.

Keywords: Characterisation; Photovoltaic; Modelling; Temperature; Solar; Parameter selection

1. Introduction

The environmental conditions and consequently the operational state of any terrestrial photovoltaic (PV) system are subject to large fluctuation over its working life. Ambient temperature and the characteristics of the incidental irradiance (magnitude, spectral characteristics, etc.) will constantly vary due to weather, seasonal loading, and time of day influencing the output of the photovoltaic device. As the electrical characteristics of photovoltaic systems are typically provided only under standard test conditions (STC), where the magnitude and spectral characteristics of the light source and temperature are fixed at predetermined values (1000 W/m^2 and AM1.5 respectively), these values cannot be explicitly used for any meaningful energy forecasting purpose. Simulating the performance of the PV system is therefore needed to approximate the energy yield of a photovoltaic system deployed outdoors. This is important for both technological and economic reasons.

At present a number of models have been applied to simulate photovoltaic behaviour with the most common approaches being based on the single and double

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http://dx.doi.org/10.1016/j.solener.2014.12.018
0038-092X/

exponential models, both of which assume lumped parameter values to capture the cell's unique performance characteristics. The single-diode model described by the modified Shockley diode equation which incorporates a diode ideality factor (n) to account for the effect of recombination in the space-charge region. The second variant, the double-diode model, simulates the space-charge recombination effect by incorporating a separate current component with its own exponential voltage dependence (Chan and Phang, 1987). Although one early study reported that greater accuracy is obtained using the double-diode model (Handy, 1967), improved accuracy is generally obtained under the lower illumination scenario when cell output is reduced (Chan and Phang, 1987).

Regardless of the model selected (i.e. single or double diode), the application of the model requires the calculation of the lumped parameter values which are not typically provided by photovoltaic cell manufacturers. The number of parameters required is dependent on the model used and the number of simplifications/assumptions implemented. In this regard, the single diode model has one significant advantage over the double-diode model in that it requires the calculation of two less parameters. As we will discuss in Section 1.1, the calculation of these parameter values can be complex which is why the single-diode model is currently a popular choice. This approach has been reported to strike a good balance between modelling complexity and accuracy (Villalva et al., 2009). Modelling with the single-diode model may be further simplified using the four parameter approach where the shunt resistance (R_{sh}) is assumed to be infinite. But this ideal scenario assumption is generally unrealistic and does not reflect the true behaviour of a solar cell. An investigation carried out in Turkey which compared the simulated output from both the four and five parameter models against the experimental data revealed the five parameter model offered a noticeable improvement in modelling accuracy, particularly during solar noon when cell output is at its peak (Celik and Acikgoz, 2007).

Examining Fig. 1, the single-diode five parameter model equivalent circuit diagram for a PV cell, we can apply Kirchhoff's laws and obtain the single diode, five parameter characteristic equation Eq. (1).

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

I is the current, V is the voltage, n is the diode ideality or quality factor, I_{ph} is the photogenerated current, I_0 is the reverse saturation current, and V_{th} is the thermal voltage of the cell.

The reverse saturation current, I_0, is a measure of the leakage or recombination of minority carriers across the p–n junction in reverse bias. The reverse saturation current is therefore the pre-dominant factor affecting the open circuit voltage, V_{oc}. As minority carriers are thermally generated, I_0 is highly sensitive to temperature.

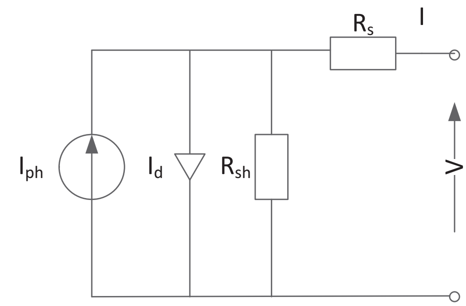

Fig. 1. Equivalent circuit diagram for the single diode, five parameter model.

The photo-generated current, I_{ph}, is the result of photon absorption and the generation of mobile charge carriers within the semiconductor. It is linearly dependent on irradiation and is also influenced by temperature (Chenni et al., 2007).

The series (R_s) and shunt resistances (R_{sh}) represent various ohmic losses which occur within the cell as a result of the intrinsic characteristics of the semi-conductor material and device construction. The series resistance of a cell represents resistances in cell solder bonds, emitter and base regions, cell metallisation, cell-interconnect busbars and resistances in junction box terminations (Wenham et al., 2008). An increase in series resistance due to thermal cycling results in the undesirable reduction in voltage output and fill factor ($FF = P_{max}/I_{sc}V_{oc}$) of the photovoltaic device (van Dyk and Meyer, 2004). Work by van Dyk and Meyer (van Dyk and Meyer, 2004) demonstrated that by increasing the series resistance by five times (from 0.36 Ω to 1.8 Ω), both maximum power output and fill factor were reduced by approximately 25%. The second parasitic loss, shunt resistance, represents any parallel shunt paths across the solar cell p–n junction or on the cell edges present due to crystal damage and impurities in and near the junction. These shunt paths direct current away from its intended load and therefore reduce device output. In summary, both series and shunt resistances result in a degradation in the current–voltage performance of the cell.

Finally, the diode ideality factor, n, is a term introduced into the characterisation Eq. (1) to account for the non-idealities of the diffusion diode. According to the Shockley theory of diodes, n should take the value of unity, but in reality a value of $n > 1$ is appropriate to account for imperfections introduced during the manufacturing process. Altering the value of the diode factor will have a particularly strong influence in the vicinity of the IV curve 'knee' corresponding to the maximum power point (P_{max}).

Examining Eq. (1), we note that the equation is non-linear and implicit in nature. Numerical methods such as the Levenberg–Marquardt algorithm must therefore be applied to solve this equation which may become computationally demanding if the entire current–voltage curve is to be simulated (i.e. $V = 0 \ldots V_{oc}$). Using the Lambert W-function (Lambert, 1758), (Banwell and Jayakumar, 2000) derived