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Prediction of current and the maximum power of solar cell via voltage generated by light and irradiance using analytically invertible function

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Abstract

All simulation techniques of the relationship between output current and output voltage contain an implicit function before this work. Thus, understanding the relationship between current and voltage using an analytically invertible function is a key method of any predicative for designer in photovoltaic system. This paper develops a technique for determining the light generated current–voltage (*I–V*) characteristic of cell using a valid analytically invertible function. The technique neither involves any initial approximations nor iteration processes. The technique is employed for four experimental results of PV cells, Obtained *I–V* characteristics for the cells using the present technique are in well agreement with those of reported in the measurements. Meanwhile, the electric power is linked with voltage based on this approach so that the voltage at the maximum electric power point becomes predicative. In addition, the voltage at the maximum electric power point can be forecasted via irradiance. Moreover, the mathematical method of irradiance dependent on the reverse saturation current is found. All results confirm the analytically invertible function as a useful tool at the reliable comprehension on PV devices.

Keywords: Solar cell; *I–V* characteristics; Invertible function; Predict

1. Introduction

Because the photovoltaic (PV) performance of the packaged cells was evaluated by current and voltage generated via light when delivering power at its full capacity, there is growing evidence that the relationship between current and voltage produced by light play an important role in the solar cell and new energy source (Son et al., 2013; Junyan et al., 2013). In order to designer for optimizing the photovoltaic system performance and maximizing the effectiveness of the system, not only the output characteristics in form of output current–output voltage of PV should be measured, but also the accurate modeling of PV modules is of primary concern (Gaurav and Panchal, 2013; Junyan et al., 2013; Lambert et al., 2013). Works reported recently in the literatures have described many unified model for predicting output current with output voltage of PV system. Generally, there are two possible approaches to extract the solar module parameters: (1) the analytical and (2) numerical extraction techniques. However, before this work, it is fairly difficulty to analyze the *I–V* characteristic curve of solar cell using analytical method because these parameter function is not invertible (Valerio and Ciulla, 2013; Toledo et al., 2012), even if these parameter models were based on neural network models (Piliougine et al., 2013), double-diode model (Ishaque et al., 2012;

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Sandrolini et al., 2010), parallel and series connections (Kadri et al., 2012). Key parameters of photovoltaic (PV) module suggested by analytical method, such as photocurrent I_1, reverse saturation current I_{rs}, series resistance R_{sh}, diode quality factor n and shunt resistance R_s, can be extracted via commercially available software (Siddiquia and Abido, 2013; Bastidas-Rodriguez et al., 2013; El-Naggar et al., 2012) and the matrix equations (Kadri et al., 2012) as numerical extraction techniques. That is the reason why both analytical and numerical extraction techniques are not widely applied in engineering.

To meet the accuracy of commercially available software for PV module or system simulation, a model in form of invertible function without approximation (Lun et al., 2013) is derived step by step in this paper so that the measured I–V data at all operating conditions can be fitted by it and known as accurate. Because the number of parameters in the model decreases, the conventional extraction methods obtain their higher ability to provide accurate values. Based on the invertible function suggested in this paper, not only voltage at the maximum power point V_{mp} can be predicted via optimized parameters of invertible function, but also V_{mp} can be predicted by irradiance. Meanwhile, the contributions of irradiance to the reverse saturation current I_{rs} is explained through mathematical way.

2. Methodology

Both electrons and holes can be majority carriers in heterojunctions, and it is known that either electron or hole is fermions. Because majority carriers are fermions in solar cell, the Fermi–Dirac distribution should apply to majority carriers (Fowler, 1931; Kittel, 1996). Fermi–Dirac distribution is usually written as below:

$$f(E) = \frac{1}{1 + \exp\left((E - E_f)/kT\right)} \tag{1}$$

Here $f(E)$ is the probability that a carrier will have energy E, E_f is Fermi energy, T is Absolute temperature, and k is Boltzmann constant of value (1.38×10^{-23} J K^{-1}).

The maximum kinetic energy of majority carrier is $eV - e\varphi - e\delta - E_f$ after it escapes from semiconductor (internal photoelectric effect) and enters into the metal, semiconductor or insulator with internal electronic field with V. Here e is the electronic charge (1.602×10^{-19} C), E_f is the energy of a majority carrier at the Fermi level, $e\varphi$ is the Schottky Barrier Height of solar cell. δ is an additional contact potential because the interface state of junctions are different. A majority carrier has kinetic energy $eV - e\varphi - e\delta - E_f$, thus the probability that a majority carrier will have the kinetic energy $eV - e\phi - e\delta$ is

$$f(E) = \frac{1}{1 + \exp\left((E - E_f)/kT\right)} = \frac{1}{1 + \exp\left(\left(V - \delta - \varphi - \frac{E_f}{e}\right) \cdot \frac{e}{kT}\right)} \tag{2}$$

let

$$V_0 = \delta + \varphi + \frac{E_f}{e} \tag{3}$$

$$V_1 = \frac{kT}{e} \tag{4}$$

Function (2) becomes

$$f(E) = \frac{1}{1 + \exp((V - \delta - \varphi - \frac{E_f}{e}) \cdot \frac{e}{kT})} = \frac{1}{1 + \exp\left(\frac{V - V_0}{V_1}\right)} \tag{5}$$

One direct conclusion is that output current is proportional to the probability, $f(E)$, in PV system, therefore, output current, I, can be write mathematically as:

$$I(V) = \frac{I_2}{1 + \exp(\frac{V - V_0}{V_1})} \tag{6}$$

But mathematical result shows that:

$$\frac{1}{1 + \exp(\frac{V - V_0}{V_1})}\Big|_{V \to \infty} = 0 \tag{7}$$

Experimental results of output voltage–output current implies that as the voltage is high enough, the output current, $I(V)$, goes asymptotically to a constant value know as the forward saturation current, I_{fs}:

$$I(V)|_{V \to \infty} = I_{fs} \tag{8}$$

Boundary condition (8) predicts that the output current and output voltage should be related as:

$$I(V) = I_1 + \frac{I_2}{1 + \exp(\frac{V - V_0}{V_1})} \tag{9}$$

To define the significance of I_1 and I_2 not only depend on boundary conditions given by experiment, but also depend on mathematical considerations. Hence, as the voltage approaches very low corresponding to voltage V to tends to minus infinity in mathematics, the probability function $f(E)$ asymptotically to one:

$$\frac{1}{1 + \exp(\frac{V - V_0}{V_1})}\Big|_{V \to -\infty} = 1 \tag{10}$$

Meanwhile, experimental results of PV system shows that as the voltage approaches very low, the output current, $I(V)$, goes asymptotically to another constant value called the reverse saturation current, I_{rs}.

$$I(V)|_{V \to -\infty} = I_{rs} \tag{11}$$

Combining Eqs. (7)–(11) yields

$$I_1 = I_{fs} \tag{12}$$

$$I_2 = I_{rs} - I_{fs} \tag{13}$$

Substitution of Eqs. (12) and (13) into (9) leads to following expressions: