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A three-point-based electrical model and its application in a photovoltaic thermal hybrid roof-top system with crossed compound parabolic concentrator

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ABSTRACT

A new coupled optical, thermal and electrical model is presented in this study and applied to a concentrating photovoltaic thermal (PV/T) system for predicting the system performance under various operational conditions. Firstly, a three-point-based electrical model and a method for extracting its five model parameters are developed by using the currents and voltages at the short-, open-circuit and maximum power points provided in usual PV module/panel datasheets. Then, the model and method are validated with the existing six flat-plate PV modules and subsequently are used to predict the hourly electrical performance of the CPV/T roof-top system designed by us under outdoor conditions on four clear days by integrating with a scaling law developed by us. Additionally, transient effect and water temperature on the storage tank are examined. It turned out that the CPV system could operate for 6 h a day with a peak instant electrical power of 50W/m^2 and could generate 0.22kWh/m^2 electricity a day in May–July. The error in hourly electrical energy gained between the predictions and observations is in a range of (3.64–8.95)% with the mean of 5.53% in four days, and the estimated water temperature in the storage tank agrees with the monitored one in range of 0.2–1 °C. The proposed methods as well as the electrical models could potentially be applied widely across the solar energy field for the management and operation of the electrical energy production from any CPV/T roof-top system.

1. Introduction

Electrical parameters at short- and open-circuit, and maximum power points are contained in all the flat-plate photovoltaic (PV) module datasheets which are usually measured under standard test condition (STC) (1 kW/m^2 irradiance, 25 °C cell temperature), whilst their current-voltage (I–V) curves are presented occasionally. Therefore, establishing their I–V curves with the parameters at the three points will be very attractive for the PV module operational management. This problem has been tackled since 2000's based on only a single-diode electrical model for monocrystalline silicon PV modules. Existing approaches for solving this problem can be classified into three types, i.e. analytical method, analytical plus optimization method, and optimization method. These existing methods are summarised in Table 1 based on the work presented in Refs. [1–21]. Most methods are of analytical and usually associated with a variety of approximations as well as algorithms. However, application of the last two methods, such as analytical plus optimization and optimization methods, is appeared to be very limited. Nevertheless, these methods have provided with a useful tool for modelling the PV monocrystalline silicon PV modules.

Investigation utilising an analytical method for the PV electrical model based on the three points in the PV product datasheet albeit started from 2001 and since then, various analytical methods have been proposed for extracting the five model parameters namely photocurrent I_{ph0}, ideality factor n_0, saturated reversal current I_{d0}, series resistance R_{s0} and shunt resistance R_{sh0} for flat-plate PV cells/modules/panels. In Ref. [1], let $R_{sh0} = +\infty$ and $I_{ph0} = I_{sc0}$, and n_0 was fixed, but I_{d0} and R_{s0} were decided analytically by an I–V equation and subsequently, dI/dV at the open-circuit point (OCP). In Refs. [2–4], however, R_{s0} and R_{sh0} were given, then n_0, I_{d0} and I_{ph0}

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Table 1
Existing methods for determining the five parameters in a single-diode electric model based on the measured *I*, *V* at three points under standard test condition.

Type of method	No. of method	Contributor	Algorithm
Analytical method	1	Walker (2001) [1]	1) $R_{sh0} = +\infty$, n_0 is selected and fixed, $I_{ph0} = I_{sc0}$; 2) I_{d0} is decided by the I–V equation at OCP, and R_{s0} is determined by the slope of I–V curve at OCP.
	2	1) de Blas et al. (2002) [2] 2) Celik & Acikgoz (2007) [3] 3) Saloux, Teyssedou & Sorin M (2011) [4]	1) R_{s0} and R_{sh0} are selected and fixed; 2) n_0, I_{ph0} and I_{d0} are determined explicitly at three points.
	3	Villalva, Gazoli and Filho(2009) [5]	1) n_0 is selected and fixed; 2) R_{s0}, R_{sh0}, I_{ph0} and I_{d0} are determined explicitly and iteratively by increasing R_{s0} with a proper step size until the maximum power is achieved.
	4	Lo Brano at al. (2010) [6]	1) $I_{ph0} = I_{sc0}$; 2) Determine R_{s0}, I_{d0}, n_0 and R_{sh0} explicitly and iteratively by increasing R_{s0} and n_0 alternatively with a proper step size until they are convergent.
	5	Carrero et al. (2010) [7]	1) n_0 is selected and fixed; 2) R_{s0}, R_{sh0}, I_{ph0} and I_{d0} are determined explicitly and iteratively at three points.
	6	Carrero et al. (2011) [8]	1)n_0, R_{s0} and R_{sh0} are determined explicitly and iteratively at three points; 2) I_{ph0} and I_{d0} are determined explicitly at two points at SCP and OCP.
	7	Lo Brano, Orioli & Ciulla (2012) [9]	1) R_{sh0} and n_0 are given; 2)R_{s0}, I_{ph0} and I_{d0} are determined solving three *I–V* equations at three points.
	8	Orioli & Di Gangi (2013) [10]	1) R_{sh0} is given empirically, and $I_{ph0} = I_{sc0}$; 2) I_{d0}, n_0 and R_{s0} are determined by solving *I–V* equations at open circuit point and MPP, and the slope equation at OCP iteratively until R_{s0} is convergent.
	9	Bonkoungou et al. (2015) [11]	1) $I_{ph0} = I_{sc0}$, n_0 and I_{d0} are calculated at open-circuit point; 2) R_{sh0} is determined explicitly and iteratively by increasing R_{s0} with a proper step size until the maximum power is achieved.
	10	Mares, Paulescu m and Badescu V (2015) [12]	1) Provide n_0, R_{s0} and R_{sh0} initial values; 2) Calculate n_0, R_{s0}, R_{sh0}, I_{ph0} and I_{d0} are determined explicitly and iteratively until R_{s0} is convergent.
	11	Senturk and Eke (2017) [13]	1) n_0 is selected and fixed; 2) R_{s0}, R_{sh0}, I_{ph0} and I_{d0} are determined explicitly and iteratively until R_{sh0} is convergent.
	12	Wang et al. (2017) [14]	1) n_0 is selected and fixed; 2) R_{s0}, R_{sh0}, I_{ph0} and I_{d0} are determined explicitly and iteratively until the slope of power curve at MPP is zero.
	13	Bai et al. (2014) [15]	1)$R_{sh0} = +\infty$, n_0, R_{s0}, I_{ph0}, and I_{d0} are determined explicitly with the *I–V* equations at three points and the slope equation of power curve at MPP; 2)Five parameters are decided explicitly with the *I–V* equations at three points and the slope equations of power curve at MPP and OCP.
Analytical plus optimization	1	Xiao, Dunford and Capel (2004) [16]	1)$R_{sh0} = +\infty$, calculate I_{ph0} and I_{d0}; 2) R_{s0} and n_0 are determined numerically by minimising the slope of power curve at MPP with an optimization algorithm.
	2	Sera, Teodorescu & Rodriguez (2007) [17]	1)Solve the slope equation of power curve and *I–V* equation at MPP and the slope equation at OCP numerically with an optimization algorithm to obtain R_{sh0}, R_{s0} and n_0; 2)Calculate I_{ph0}, and I_{d0}.
	3	De Soto, Klein and Beckman (2006) [18]	1)$I_{ph0} = I_{sc0}$; 2)Solve four nonlinear equations at three points numerically with an optimization algorithm to obtain n_0, I_{d0}, R_{s0} and R_{sh0}
	4	Ding et al. (2014) [19]	1)$I_{ph0} = I_{sc0}$, and introduce parameter *k* which is a function of I_{sc0}, R_{sh0}, V_{oc0} and I_{d0}; 2)Solve the slope equation of power curve at MPP and the slope equation at OCP numerically with an optimization algorithm to obtain R_{s0} and R_{sh0}, then *k*.
Optimization	2	Lo Brano & Ciulla (2013) [20]	Solve five nonlinear equations (3 *I–V* equations at three points, 2 slopes equations at MPP and OCP) numerically with an optimization algorithm to obtain n_0, I_{ph0}, I_{d0}, R_{s0} and R_{sh0}.
	3	Ma, Yang and Lu (2014) [21]	Solve six nonlinear equations (3 *I–V* equations at three points, one slope equation at MPP, two slope equations at OCP and SCP) numerically with an optimization algorithm to obtain n_0, I_{ph0}, I_{d0}, R_{s0} and R_{sh0}.

Note that: I_{ph0} n_0, I_{d0}, R_{s0} and R_{sh0} are respectively the photocurrent, ideality factor, saturated reversal current, series resistance and shunt resistance of a single-diode electrical model, I_{sc0} is the current at the short circuit point, subscript 0 indicates the value under a standard test condition, MPP-maximum power point, OCP-open circuit point, SCP-short-circuit point.

were calculated from the *I*, *V* values at the OCP, short-circuit point (SCP) and maximum power point (MPP). In Ref. [5], n_0 was fixed, and the rest of the parameters were determined iteratively until the maximum electrical power was reached while increasing R_{s0} progressively at the OCP, SCP and MPP. In Ref. [6], let $I_{ph0} = I_{sc0}$, the rest four parameters were decided iteratively by adjusting both R_{s0} and n_0 alternately until their convergence at the three points was reached. Whereas, in Ref. [7], n_0 was fixed, I_{ph0}, I_{d0}, R_{s0} and R_{sh0} were calculated iteratively at three points.

In Ref. [8], n_0, R_{s0} and R_{sh0} were calculated at three points, but I_{d0} and I_{ph0} were determined at SCP and OCP. In Ref. [9], R_{sh0} and n_0 were given, but R_{s0}, I_{ph0} and I_{d0} were estimated by solving *I–V* equations at three points. In Ref. [10], R_{sh0} was prescribed and let $I_{ph0} = I_{sc0}$, then R_{s0}, n_0 and I_{d0} were calculated iteratively by solving I–V equations at OCP and MPP as well as dI/dV equation at OCP. In Ref. [11], let $I_{ph0} = I_{sc0}$, n_0 and I_{d0} were calculated at OCP firstly, then R_{sh0} was determined by updating R_{s0} at MPP. In Ref. [12], n_0, I_{ph0}, I_{d0}, R_{s0} and R_{sh0} initial values were specified, then they were iteratively updated by using their expressions derived at three points until R_{s0} is convergent. In Ref. [13], n_0 was given, but I_{ph0}, I_{d0}, R_{s0} and R_{sh0} were determined iteratively with their expressions at three points. Similarly, in Ref. [14],n_0 was selected, I_{ph0}, I_{d0}, R_{s0} and R_{sh0} were determined iteratively until $dI/dV = 0$ at MPP. In Ref. [15], R_{sh0} was supposed to be infinitive, and I_{ph0}, I_{d0}, R_{s0} and R_{sh0} were calculated with *I–V* equations at three points and the power curve slop dP/dV equation at MPP initially; then the five parameters were updated with I–V equations at three points and dP/dV equation at MPP and dI/dV equation at OCP.