



Parameter estimation for five- and seven-parameter photovoltaic electrical models using evolutionary algorithms



M.U. Siddiqui^{a,*}, M. Abido^b

^a Department of Mechanical Engineering, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

^b Department of Electrical Engineering, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

ARTICLE INFO

Article history:

Received 28 June 2012

Received in revised form

21 December 2012

Accepted 7 July 2013

Available online 22 July 2013

Keywords:

Photovoltaic

Five parameter model

Parameter estimation

Equivalent circuit model

Evolutionary algorithms

Hybrid evolutionary algorithms

ABSTRACT

Equivalent electric circuit modeling of PV devices is widely used to predict PV electrical performance. The first task in using the model to calculate the electrical characteristics of a PV device is to find the model parameters which represent the PV device. In the present work, parameter estimation for the model parameter using various evolutionary algorithms is presented and compared. The constraint set on the estimation process is that only the data directly available in module datasheets can be used for estimating the parameters. The electrical model accuracy using the estimated parameters is then compared to several electrical models reported in literature for various PV cell technologies.

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1. Introduction

Accurate modeling tools are a key to designing efficient and cost-effective PV systems. In total, three different models are required to model the electrical power output of a PV system for given irradiance and ambient temperature. These include a thermal model for finding the PV cell temperature, a radiation model for finding the solar energy absorbed in the PV cells and an electrical model for calculating the electrical characteristics of the PV system for the calculated absorbed radiation and cell temperature. Over the years, electrical models for varied complexities and accuracies have been developed for PV system. These include analytical models based on PV cell physics, empirical models and a few models which combine these two approaches.

An empirical model was developed by King et al. [1] capable of predicting the electrical current and voltage of a PV device at five key points on the I - V curve. Hishikawa et al. [2] and Marion et al. [3] used interpolation techniques for determining the I - V curves at the input conditions using the I - V curves at known conditions. A different approach for modeling PV devices is to represent it by an equivalent electric circuit. Any PV device can be modeled using

the equivalent circuit model by using the correct model parameters (I_L , I_o , a , R_s , R_{sh}). Townsend [4] presented an electric circuit model called the Four Parameters model for predicting the performance of PV devices in which he assumed the shunt resistance (R_{sh}) to be infinite which reduced the nonlinearity of the model. Duffie and Beckman [5] improved the model by Townsend by including an additional parallel resistance in the electric circuit. Their five parameters model gave improved prediction accuracies for thin film PV cell types. De Soto et al. [6] developed a methodology for finding these five model parameters using only manufacturer data. Valerio et al. [7] modified the five parameters model to capture changes in operating temperature and solar irradiance more accurately.

In order to use the electric circuit models, the model parameters (I_L , I_o , a , R_s , R_{sh}) which are different for every PV device need to be first determined. A variety of techniques have been used to find these electrical model parameters. For the single diode five parameters model, De Soto et al. [6] and Boyd et al. [8] used a specialized non-linear equation solver to get a solution. Villalva et al. [9] explicitly defined one parameter, a , and then solved for the remaining parameters by minimizing the error in the maximum power prediction. Townsend [4] simplified the model by assuming the shunt resistance to be infinite which reduces the non-linearity of the system. He then solved for the remaining parameters iteratively. Carrero et al. [10] used an iterative procedure to find all five parameters, (I_L , I_o , a , R_s , R_{sh}). Their method only requires the

* Corresponding author. Tel.: +966 38602096.

E-mail addresses: musiddiqui@kfupm.edu.sa (M.U. Siddiqui), mabido@kfupm.edu.sa (M. Abido).

Nomenclature

a	modified diode ideality factor (V)
A	diode ideality factor
AM	air mass
AOI	angle of incidence
E	irradiance (W/m ²)
E_g	band-gap energy of PV cell material (eV)
FF	fill factor
f_d	fraction of diffuse radiation absorbed in the module
I	PV module output current (A)
I_L	light current (A)
I_o	diode reverse saturation current (A)
k	Boltzmann's constant, 1.38066E-23 (J/K)
m	irradiance dependence parameter for I_L
n	temperature dependence parameter for a
NCS	number of cells in series in a module's cell-string
N_p	number of cell-strings in parallel in module
N_s	number of cells in series in a module's cell-string
P	electrical power (W)
q	elementary charge, 1.60218×10^{-19} (coulomb)
R_s	series resistance (Ω)
R_{sh}	shunt resistance (Ω)
S	plane-of-array absorbed solar radiation at operating conditions (W/m ²)
T	temperature ($^{\circ}$ C)
V	voltage (V)

Greek letters

α_{imp}	Temperature coefficient of maximum power point current
α_{isc}	temperature coefficient of short circuit current
β_{Voc}	temperature coefficient of open circuit voltage
β_{Vmp}	temperature coefficient of maximum power point voltage
$\delta(T_c)$	thermal voltage per cell at temperature T_c
μ_{Voc}	temperature coefficient of open circuit voltage
γ	overall diode ideality factor of PV module

Subscripts

0	reference cell condition
amb	ambient
b	beam radiation
c	PV cell
diff	diffuse radiation
e	effective radiation; experimental
m	module back surface; modeled
mp	maximum power point
oc	open circuit point
ref	reference cell condition
sc	short circuit point
x	IV point at module voltage equal to half of open circuit voltage
xx	IV point at module voltage equal to average of max. power and open circuit voltages
amb	ambient

I - V data of three points i.e. the short circuit, open circuit and maximum power points. Their method uses simplified forms of the I - V equation written at the three points and provides fast convergence.

Various optimization techniques also been used for determining the five model parameters. Ikegami et al. [11] used the Levenberg–Marquardt multi-variable optimization technique with

experimentally determined I - V curve to determine the model parameters. The objective function used by Ikegami et al. was the error in the current prediction at known voltages as calculated by Eq. (1).

$$\text{error} = \sqrt{\frac{\sum_{i=1}^n (I_m(V_i) - I_e(V_i))^2}{n}} \quad (1)$$

Siddiqui [12] used the simplex search algorithm to find the five model parameters by minimizing the fitness function defined by Eq. (2). The objective function calculates two errors whose sum is minimized. First, the currents (I) at short circuit, maximum power point and open circuit conditions are calculated using Eq. (4) and known voltages from the module datasheet.

$$\text{error} = \sqrt{\frac{\sum_{i=1}^3 (I_m(V_i) - I_e(V_i))^2}{3}} + \left| \frac{dP}{dV} \right|_{MPP} \quad (2)$$

With the recent advancement in computing, the use of intelligent computing techniques has increased greatly. Intelligent techniques include Fuzzy control [13–18], evolutionary algorithms [19–21] and Neural Networks [22,23] which are being applied to engineering problems ranging from control to optimization with impressive success. For the estimation of PV electrical model parameters, genetic algorithm is the most widely used evolutionary algorithm [24–26]. The objective function used in all these works was the error in the current prediction at known voltages. Moldovan et al. [24] and Zagrouba [26] carried out similar works in which they used genetic algorithm to minimize the error in the current prediction at known voltages. Jervase [25] used genetic algorithm to find seven parameters for the two-diode electric circuit model. Ishaque et al. [27,28] used several evolutionary algorithms to find the model parameters for a two-diode equivalent electric circuit PV model and found that penalty-based differential evolution showed good accuracy and consistency of solution, good speed of convergence and required very low control parameters.

For their Seven Parameters model, Siddiqui [12] used the simplex-search algorithm to first find the five parameters. The two additional parameters m and n were found using a secondary optimization in which the original five parameters did not change. Eq. (3) was used as the objective function for the secondary optimization process.

$$\text{error} = \sqrt{(P_m - P_e)^2} \Big|_{\text{Low Irradiance}} + \sqrt{(P_m - P_e)^2} \Big|_{\text{High Temperature}} \quad (3)$$

In this paper, a methodology to estimate the model parameters using only manufacturer supplied electrical performance data is presented and the effectiveness of various evolutionary algorithms, including standard evolutionary algorithms as well as hybrid methods, in estimating the model parameters is evaluated. Finally, the accuracy of the parameter estimation methodology is checked by comparing the results of the electrical model to other models from literature as well as the same model using different parameters estimation methodologies.

2. Electric circuit modeling of PV devices

Any PV device can be represented by an equivalent electric circuit [5]. The equivalent circuit, shown in Fig. 1, comprises of a light dependent current source, a p-n junction diode and two resistances.

I - V relationship in the equivalent circuit of Fig. 1 is governed by Eq. (4). The characteristic of any PV device are included in the model by five model parameters (I_L , I_o , a , R_s and R_{sh}). The model that

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