Electrical Power and Energy Systems 59 (2014) 23–28

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

A modeling method for photovoltaic cells using explicit equations and optimization algorithm

Yonghai Xu, Xiangyu Kong *, Yawen Zeng, Shun Tao, Xiangning Xiao

State Key Laboratory for Alternate Electrical Power System With Renewable Energy Sources, Department of Electrical and Electronic Engineering, North China Power Electric University, 2 Beinong Road, Huilongguan Town, Changping District, Beijing 102206, China

ARTICLE INFO

Article history:
Received 3 April 2013
Received in revised form 7 January 2014
Accepted 18 January 2014
Available online 19 February 2014

Keywords:
Photovoltaic cells
Five-parameter model
Explicit equation
Optimization algorithm
Lambert *W* function

ABSTRACT

A numerical method for determining the five-parameter model of photovoltaic cells is presented in the paper. Explicit equations are applied to analyze the relations between parameters which are solved by an optimization algorithm. Lambert *W* function is implemented to convert the *I–V* characteristic implicit equation to an explicit one, so the output current and voltage of photovoltaic cells can be obtained by substituting the five parameters into the explicit *I–V* equation. Several cells are used to verify the accuracy of the proposed method from different aspects. It is found that the proposed method gives precise results and can be applicable to various types of photovoltaic cells.

1. Introduction

Photovoltaic system directly converts sunlight into electricity. As one of distributed sources, the PV power is increasingly connected to the grid due to concerns related to environment, global warming, energy security, technology improvements and decreasing costs [1,2]. The basic device of a photovoltaic system is the photovoltaic cell. Cells may be grouped to form panels or arrays. The modeling for photovoltaic cells plays an important part in the study of the dynamic analysis of converters, in the study of the maximum power point tracking algorithms and mainly to simulate the photovoltaic system and its components using circuit simulators [3,4].

Photovoltaic cell model is usually equivalent to the four or five-parameter model in related studies. The five-parameter includes the determination of light current (I_{PV}), diode reverse saturation-current (I_0), diode ideality factor (a), series resistance (R_s) and shunt resistance (R_p), whereas the four-parameter model assumes R_p as infinite and then can be neglected. The five-parameter model has been widely researched because of its good compromise between accuracy and simplicity [5–10].

The study of photovoltaic cells has been focusing on the method of getting parameters exactly. Various analytic and numerical methods have been proposed. The method of keeping the value of a as constant is applied in many papers. For instance, in [9] the values of R_s and R_p are analytically obtained with an estimation formula of R_s used. And in [10] an iterative process is used to calculate the values of R_s and R_p. However, the problem of iterative convergence and the selection of initial values should be solved, also the assumption of a value as a constant will decrease the accuracy of the model undoubtedly. Two approximate resistance values are used to transform the nonlinear equation to linear one in [11], the parameters being then simply and exactly obtained. However, it is very difficult to get the values of the resistance exactly without experimental data. Recently, several authors focus on extracting the parameters using artificial neural network (ANN) [12] and evolutionary algorithm (EA) [13]. Despite the promising research prospects, the applications are restricted by some disadvantages such as the needs of large amounts of data and the computational difficulties. For example, King [14] presents an algebraically method to get the photovoltaic cells parameters exactly, but large amounts of data are required which are very difficult to obtain from the manufacturer.

Another defect is that the solving of the methods mentioned above are based on implicit *I–V* characteristic equations which are difficult to solve. Fortunately, Lambert *W* function can solve this problem due to its effectiveness of solving the implicit transcendental equation. Jain and Kapoor [15] and Ghan and Duke [16] describe the behavior of the photovoltaic cell using Lambert *W* function and present the explicit *I–V* characteristic equations. On this basis, Ding [17] presents a method for converting complex

* Corresponding author. Tel.: +86 18810438322; fax: +86 01051971407.
E-mail address: 45195710@qq.com (X. Kong).

http://dx.doi.org/10.1016/j.ijepes.2014.01.017
0142-0615/

transcendental equations to algebraic equations. However, the values of coefficients in the algebraic equations cannot be gained without experimental data.

In general, the analytic method cannot work well without experimental data and the problems of imprecision and complexity need to be solved for numerical method. So, two issues should be solved in order to obtain an accurate photovoltaic cell model with limited data. The first one is how to handle equations and solve them easily without affecting the model accuracy, the other one is to work only with the data provided by the manufacturer.

Apparently, the values of the five parameters can be extracted simply and accurately based on an explicit equations. Considering the above requirements, this paper proposes a model based on the explicit equations to characterize PV cells and calculate the values of parameters. In the approach, two explicit equations of the relation between R_p and two parameters (R_s, a) are proposed which are used to analysis effects of a for output characteristic of PV cells and obtained values of the five parameter through optimization algorithm. Then the I–V equations based on Lambert W function are implemented to calculate the values of output current and voltage. Unlike previous methods, this proposed approach makes the computation simple meanwhile the results more precise. Finally, the verifications of I–V characteristics and maximum power are taken and the results show that the method is effective and precise for most types of cell.

2. Five-parameter calculation methods based on explicit equations and optimization algorithm

2.1. Equations extracted from the manufacturer data

The equivalent circuit of photovoltaic cells is shown in Fig. 1. The equation describes the relation between the output current (I) and voltage (V) can be written as:

$$I = I_{pv} - I_0\left[\exp\left(\frac{V+R_sI}{aV_t}\right) - 1\right] - \frac{V+R_sI}{R_p} \tag{1}$$

where I_{pv} and I_0 are the light–current and the reverse saturation current respectively, $V_t = N_skT/q$ is the thermal voltage of the module with N_s cells connected in series, q represents the electron charge (1.6×10^{-19} C), k is the Boltzmann constant (1.38×10^{-23} J/K), a represents the ideality factor of the diode and T means the temperature of the P–N junction.

Eq. (1) is an implicit transcendental equation. It is usually solved by iterative method such as Newton–Raphson, which is very complex. So, two explicit equations are proposed by means of Lambert W function:

$$I = \frac{R_p(I_{pv}+I_0) - V}{R_s+R_p} - \frac{aV_t}{R_s}W(Y) \tag{2}$$

$$W(Y)\exp(W(Y)) = Y \tag{3}$$

$$Y = \frac{R_sR_pI_0}{aV_t(R_s+R_p)}\exp\left(\frac{R_p(R_sI_{pv}+R_sI_0+V)}{aV_t(R_s+R_p)}\right) \tag{4}$$

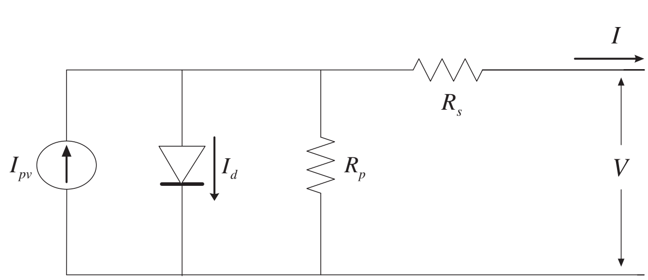

Fig. 1. Equivalent circuit of the five-parameter model.

$$V = R_p(I_{pv}+I_0-I) - IR_s - aV_tW(Z) \tag{5}$$

$$W(Z)\exp(W(Z)) = Z \tag{6}$$

$$Z = \frac{R_pI_0}{aV_t}\exp\left(\frac{R_p(I_{pv}+I_0-I)}{aV_t}\right) \tag{7}$$

The value of output current (I) can be calculated easily using Eq. (2) for a given value of voltage (V). Characteristic curves of I–V and P–V based on Eq. (2) are showed in Fig. 2.

The values of the short current (I_{sc}), the open circuit voltage (V_{oc}), the maximum power current (I_m) and voltage (V_m), view Fig. 2, are normally supplied by manufacturer. Several equations are extracted here.

For the case of the short circuit, we have: $V = 0$ and $I = I_{sc}$, and then:

$$I_{pv} = \frac{R_p+R_s}{R_p}I_{sc} + I_0\left[\exp\left(\frac{R_sI_{sc}}{aV_t}\right) - 1\right] \tag{8}$$

In Eq. (8), I_0 can be ignored because of its very small value, therefore, a simplified equation is shown as follows:

$$I_{pv} \approx \frac{R_p+R_s}{R_p}I_{sc} \tag{9}$$

For the case of open circuit, we have: $V = V_{oc}$ and $I = 0$, and then the expression of I_0 is obtained:

$$I_0 = \frac{(R_p+R_s)I_{sc} - V_{oc}}{C_1R_p} \tag{10}$$

where

$$C_1 = \exp[V_{oc}/(aV_t)] - 1 \tag{11}$$

At the maximum power point, $V = V_m$ and $I = I_m$, the following relation can be obtained based on Eqs. (1) and (9)–(11):

$$R_p = \frac{V_m + R_sI_m - C_2V_{oc}/C_1 + R_sI_{sc}(C_1-C_2)/C_1}{(C_1-C_2)/C_1I_{sc} - I_m} \tag{12}$$

$$R_p = \frac{V_m - C_2V_{oc}/C_1}{(C_1-C_2)/C_1I_{sc} - I_m} - R_s$$

where

$$C_2 = \exp[(V_m + I_mR_s)/(aV_t)] - 1 \tag{13}$$

It can be seen in Fig. 1 that the derivative with respect to power at the maximum power point is zero. So we can get another equation:

$$\left.\frac{dP}{dV}\right|_{V_m} = V_m\left.\frac{dI}{dV}\right|_{V_m} + I_m = 0 \tag{14}$$

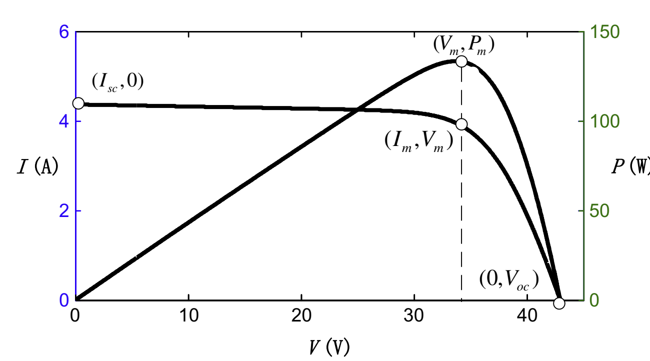

Fig. 2. I–V and P–V characteristic curves of a PV module with 72 cells connected in series.