ARTICLE IN PRESS

Energy xxx (2014) 1–9

Contents lists available at ScienceDirect

Energy

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

New procedure and field-tests to assess photovoltaic module performance

Marius Paulescu [a,*], Viorel Badescu [b,d], Ciprian Dughir [c]

[a] Physics Department, West University of Timisoara, V. Parvan 4, 300223 Timisoara, Romania
[b] Candida Oancea Institute, Polytechnic University of Bucharest, Spl. Independentei 313, 060042 Bucharest, Romania
[c] Electronics and Telecommunications Faculty, "Politehnica" University of Timisoara, Mihai Viteazu Ave. 2, 300222 Timisoara, Romania
[d] Romanian Academy, Calea Victoriei 125, Bucharest, Romania

ARTICLE INFO

Article history:
Received 28 December 2013
Received in revised form
18 March 2014
Accepted 20 March 2014
Available online xxx

Keywords:
PV module
Modeling
Performance
Field-test

ABSTRACT

The theoretical performance of a photovoltaic (PV) module is typically evaluated by using models based on equivalent circuits whose parameters are derived from data listed in manufacture's datasheet. Few manufactures provide detailed enough datasheets to allow using highly accurate models. In many cases simplified models have to be used due to missing information. This paper proposes a new procedure to evaluate PV modules performance. The procedure is based on the four-parameter model, which can be used with input data provided by most manufactures. Firstly, the parameters extraction in standard test conditions is discussed. Secondly, an algorithm for PV module performance estimation under real weather conditions is proposed. The procedure is validated on a commercial PV module. Estimations and field-test data are found to be in good agreement. The difference between the response time of the pyranometer (tens of seconds) and the response time of the PV module (almost instantaneous) is found to be an important source of errors. This aspect has not been previously discussed in literature with sufficient detail. The proposed procedure represents a feasible tool for calculating the performance of PV modules described by a limited set of data, operating in arbitrary weather conditions.

1. Introduction

The performance of a photovoltaic (PV) module primarily depends on the amount of solar radiation incident on its surface and on solar cells temperature. Thus, understanding the PV module operation under specified weather conditions is of great importance for estimating its actual output power (see e.g. Refs. [1,2]).

Generally, PV modules are delivered by manufacturers accompanied by datasheets containing information about several parameters (such as: short circuit current intensity, open circuit voltage, maximum power current intensity and voltage, and temperature coefficients) measured in standard test conditions (STC). STC specify a global solar irradiance at normal incidence $G_{STC} = 1000\ W/m^2$ with a spectral distribution AM1.5G and a cell temperature $T_{STC} = 25\ ^\circ C$. In practice, further modeling is necessary since PV modules do not normally operate at STC. The common approach is based on the analytical description of PV module current–voltage (I–V) characteristics in terms of solar irradiance and ambient temperature. The module I–V characteristics come from the I–V characteristics of the solar cells. Thus, modeling the solar cell I–V characteristics becomes the basic task in estimating the output power of a PV module. Many efforts were devoted to this topic (for few recent works see, e.g. Refs. [3–10]). Partial success has been obtained, as shown next.

Sometimes, a challenge in the accurate description of the I–V curve is the reduced information provided by PV module's datasheet. Many studies were dedicated to overcome this aspect. An important finding is that the predictive capability of the one diode model could be improved when the manufacturer datasheet provides information for two irradiance levels [3]. The same idea is found in Ref. [6] where a one diode model is used to describe analytically the I–V characteristic of a PV module operating in specified weather conditions. The parameters of the equivalent electrical circuit are extracted by solving (with a trial and error process) a system of equations based on data issued by manufacturers at STC. In addition, the model needs information about (i) the open circuit voltage at the lowest available irradiance and (ii) the maxim power point coordinates at other temperature than STC. These data can be extracted from the available I–V curves. However, only few PV module manufactures provide such curves. The problem persists, as outlined recently in

* Corresponding author. Fax: +40 256 592383.
E-mail address: marius@physics.uvt.ro (M. Paulescu).

http://dx.doi.org/10.1016/j.energy.2014.03.085
0360-5442/

Ref. [10] in terms of the usual dilemma faced by PV system designers. They have to choose between cheap PV modules whose datasheets are scarce in information (for which reliable energy predictions is not possible, since their manufacturers do not spend significant financial resources to provide reliable graphical data, requiring accurate laboratory measurements) and more expensive modules whose datasheets are rich in information (for which high performance predictive tools may be used).

Currently, there is no general consensus on which particular model should be used to calculate PV module performance. Most models deal with the one diode model (e.g. Ref. [6]) based on Shockley's theory of p–n junction (see e.g. Ref. [11]). As an alternative, Ref. [7] uses evolutionary algorithms. Ref. [12] identifies the parameters of PV cells/modules by using multiple linear regression and iteration. Also, there are some attempts to use empirical models for straightforward computing the power delivered by PV modules [13,14].

The main objective of this paper is to propose a simplified procedure for estimating the performance of a PV module operating in arbitrary weather condition (specified by solar irradiance and cell temperature). The procedure works in two steps. First, based on data listed in PV module's datasheet, the equation of the I–V curve of a component solar cell operating at STC is established. Second, an algorithm for translating the I–V curve from STC to an arbitrary operating point is presented. The advantage of the proposed algorithm is that it needs a very limited set of data, which is found in the PV module's datasheet provided by the manufacturer.

The present approach brings several improvements as far as the practical application is concerned. For instance, the model proposed in Ref. [6] requires as input data measurements performed at STC, as well as some additional data. No such additional data is needed to run our procedure. In order to compute the I–V curve parameters, the combined statistical and analytical model proposed in Ref. [12] requires many points from a single I–V curve. Our procedure uses three points only from the I–V curve measured at STC. The procedure proposed here requires data listed in manufacture's datasheet only, as the model [3] does. However, our procedure is simpler: only four parameters are computed instead of the five parameters computed in Ref. [3]. Solving the equation systems associated with parameters identification is a problem by itself. Some authors are using evolutionary algorithms (EA), which have the ability to locate the global optimum [15]. These algorithms are powerful but they are rather unfamiliar for most engineers involved in practical applications. Also, running EA algorithms requires preliminary assumptions on some control variables. This is not a trivial task and has important consequences on model's performance. The procedure proposed here does not involve any additional parameter assumption.

The paper is organized as follows. The next section shortly presents the four-parameter model and describes the procedure. Section 3 shows the experimental validation of the procedure. Finally, Section 4 draws the conclusions.

2. Model formulation

A PV module consists of a grid series/parallel of solar cells, having a compact structure and environmental protection. Let V^m and I^m denote the voltage and current at module terminals, respectively. Here we assume that all cells are identical and operate under identical external conditions (defined by in-surface irradiance and ambient temperature). In this case, the same current I and voltage V apply for each cell. Using the simplest PV module model (Fig. 1), one can write:

$$I = I^m/N_p, \quad V = V^m/N_s \tag{1a,b}$$

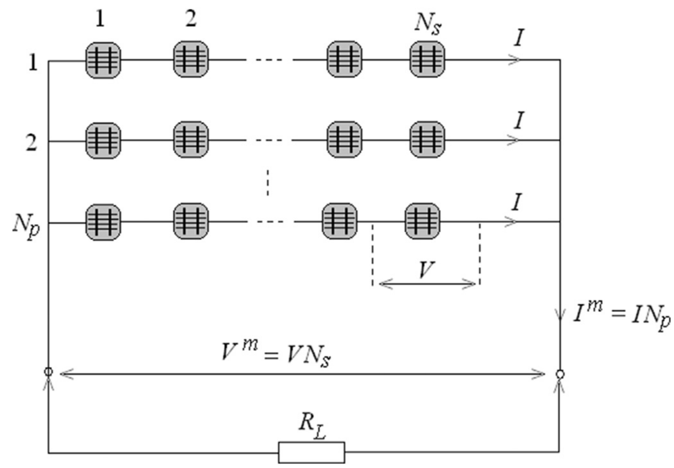

Fig. 1. Schematic of a PV module, consisting of N_p strings connected in parallel, each string consisting of N_s cells connected in series. R_L is the load connected at PV module terminals.

Eqs. (1a,b) express the approximate relationships between voltage and current through a cell and through the whole module, respectively.

2.1. The Shockley PV cell model

The standard equivalent electrical circuit of a solar cell is shown in Fig. 2a. This circuit emerges from understanding the physical processes underlying solar cell operation (see e.g. Ref. [16]). The photocurrent I_L is generated by a current source mainly dependent on the incident radiation level. The two diodes stand for the dark current losses (D_1) and the effect of generation – recombination in the space charge region (D_2), respectively. Current losses caused by increased junction conductivity at cell edges are modeled by the shunt resistance R_P. The effective voltage on the parallel group components is larger at terminals, where equals $V + IR_S$. The series resistance R_S encapsulates resistive losses in the cell. According to Shockley's theory, in the usual regime of solar cell operation (larger forwarded biases) the diffusion current dominates over the generation-recombination current and, therefore, the diode D_2 from Fig. 2a can be omitted (see e.g. Ref. [17]). This approximation is used in most studies related to PV module modeling (e.g. Refs. [3,6,10]) and has also been considered here. In this case, the I–V curve is given by the equation:

$$I = I_L - I_0\left[\exp\left(\frac{e(V + IR_S)}{mk_BT}\right) - 1\right] - \frac{V + IR_S}{R_p} \tag{2}$$

where e is the elementary charge and k_B is the Boltzmann constant. Eq. (2) defines the so-called five-parameter model (5PM). These parameters are: I_L, I_0, m, R_P and R_S.

The basic approach to find the values of the parameters in Eq. (2) is to consider the information usually listed in manufacturers' datasheet: short circuit current, open circuit voltage and maximum power point (MPP) current and voltage, all of them measured at STC. This information fixes three points on the I–V curve which, therefore, satisfy Eq. (2). A fourth equation can be written by taking into account that the first derivative of the delivered power is zero at MPP. The result is a non-linear system of four equations, which can be solved for four unknowns. However, Eq. (2) includes five parameters. In order to solve models with more than four parameters additional hypotheses are needed.