Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 103 (2014) 96–107

SOLAR ENERGY

www.elsevier.com/locate/solener

Discrete I–V model for partially shaded PV-arrays

Eloy Díaz-Dorado, José Cidrás, Camilo Carrillo *

University of Vigo, Spain

Received 19 November 2012; received in revised form 24 September 2013; accepted 29 January 2014

Communicated by: Associate Editor Hari Mohan Upadhyaya

Abstract

Photovoltaic systems that are partially shaded show changes in their I–V curve that makes its shape is different from that typically shown in unshaded PV panels. The effects of shading depend on several factors like electrical connections between elements or the geometry of the PV-cells.

This paper presents a generalized, quick and simple method for modelling and simulating the electrical behaviour of PV installations under any shading situation which is mainly based in the Bishop modelling. So, the proposed method models PV-systems by discretizing currents and voltages in PV-cells which are connected in series and parallel associations (PV-cells, PV-groups, PV-modules, PV-strings and PV-array). For the PV-cell, a non-linear and implicit function which takes into account forward and reverse biasing is considered. Bypass diodes have also been included in the model. The relationship between discrete currents and voltages is established using the Newton–Raphson algorithm, analytical approximations and interpolation methods.

The proposed method is used to provide a complete analysis of current, voltage and power in several PV systems under partial shading conditions.

Keywords: Photovoltaic systems; Photovoltaic cells; Partial shading

1. Introduction

The shading of a photovoltaic (PV) installation implies that may have PV-cells working in different irradiance conditions within the same installation. Thus, elements (cells or diodes) that are normally working forward (or reverse) biased could change its polarization. Furthermore, other working parameters (e.g. the PV-cell temperature) could be different between neighbouring elements. As a consequence, for a detailed analysis of the electrical behaviour of partially shaded PV installations, it is necessary take into account their simplest elements, cells and diodes, and the different parallel and series associations between them. The system of equations derived from this analysis is characterized by its large dimension and by being formed by non-linear equations. This system of equations usually presents convergence problems due to their strong nonlinearity.

Some authors propose several methods to study the PV systems based on Newton–Raphson (Karatepe et al., 2006; Quaschning and Hanitsch, 1996; Kawamura et al., 2003), Gauss–Seidel (Chatterjee et al., 2011), Lambert W-function and Newton–Raphson (Petrone and Ramos-Paja, 2011; Petrone et al., 2007) and piecewise-linear technique (Wang and Hsu, 2011).

Most authors have studied the behaviour of partial shading on individual photovoltaic modules (Quaschning and Hanitsch, 1996; Kawamura et al., 2003; Bishop, 1988; Caluianu et al., 2009; Alonso-García et al., 2006a;

* Corresponding author. Tel.: +34 986813912; fax: +34 986812173.
E-mail addresses: ediaz@uvigo.es (E. Díaz-Dorado), jcidras@uvigo.es (J. Cidrás), carrillo@uvigo.es (C. Carrillo).

http://dx.doi.org/10.1016/j.solener.2014.01.037
0038-092X/

Silvestre and Chouder, 2008; Chen and et al., 2010; Silvestre et al., 2009). Other authors have analyzed PV systems with various modules (Karatepe et al., 2006; Petrone and Ramos-Paja, 2011; Petrone et al., 2007; Bishop, 1988; Silvestre et al., 2009; Díaz-Dorado et al., 2010a, 2010b) but their results cannot generalized to model a PV array. Previous papers analyse the behaviour of modules or installations considering the actuation of the bypass diodes. However, only some authors have considered the behaviour of cells in reverse bias caused by shading and its effect on the generation (Quaschning and Hanitsch, 1996; Bishop, 1988; Silvestre et al., 2009; Alonso-García and Ruíz, 2006; García et al., 2008). In Bishop (1988), three types of interconnection circuits of PV-cells are considered including bypass diodes and blocking diodes.

In other cases, approximated values or limit values are considered to analyse the power losses of photovoltaic systems (Díaz-Dorado et al., 2010b, 2011; Alonso-García et al., 2006b; Narvarte and Lorenzo, 2008; Gordon and Wenger, 1991; Woyte et al., 2003; Martínez-Moreno et al., 2010; Di Piazza and Vitale, 2010; Perpiñán, 2012).

As an alternative method to avoid trying to solve large systems of non-linear equations, this paper presents a discrete method for modelling the *I–V* characteristics of PV-arrays under any shading condition. The proposed discrete method is an improvement, generalization and systematization of that introduced by Bishop (1988). The proposed one considers the Newton–Raphson algorithm to solve the implicit non-linear equations related to PV-cells, unlike the Bishop method that uses a two-step iterative process.

This allows to define the *I–V* characteristic of each PV-cell by means of discretized model. Consequently, a generic PV-array can be solved taking into account the electrical characteristics of series and parallel associations by using discretized models.

As a result, the proposed method overcomes the needing of solving a large system of non-linear equations (Karatepe et al., 2006). So, the typical problems of convergence and large time-consuming computations are overcame. Furthermore, this method does not require to do approximations to represent diodes and PV-cells, e.g. null voltage during forward biasing of diodes. It must be taken into account that the accuracy of the results only depends on the discretization step used for current and voltage variables.

This paper is organized into five sections. Section 2 presents the equations of the PV-cell, bypass diode and shading modelling. In Section 3, the proposed discrete model is developed, starting from the discretization of series associations (PV-cells, PV group, PV-module and PV-string) to the parallel association (PV-array). Section 4 analyses the behaviour of three PV installations with different partial shading conditions. Finally, the conclusions are presented in Section 5.

2. Modelling of PV-cells and shadows

A PV-array can be considered as a set of PV-cells and diodes with different series and parallel associations (Fig. 1). In general, a PV-array can be defined as a set of $NxRxMxL$ of PV-cells connected as follows: N PV-cells in series with a bypass diode form a PV-group, R PV-groups in series form a PV-module, M PV-modules in series form a PV-string and L PV-strings in parallel form the PV-array. From a mathematical point of view, a PV-array is an electrical network with two types of non-linear elements connected in series and/or parallel: PV-cells and bypass diodes.

The following paragraphs discuss the PV-cell model, the equation of the bypass diode and a proposed model for partial shading on a PV-array.

2.1. Modelling of PV-cell and bypass diode

Generally a PV-cell can be expressed by means of a non-linear relationship between four variables: current (I in A), voltage (V in V), irradiance (G in W/m^2) and cell temperature (T in K). In this paper, a non-linear implicit function is used for PV-cell, where T and G are supposed to be known, and V and I are the variables of the *I–V* model. The PV-cell is modelled using the following equation that allows the analysis of forward and reverse biasing (Bishop, 1988):

$$I = I_L - I_0\left(e^{\frac{qV+IR_s}{nk_BT}} - 1\right) - \frac{V+IR_s}{R_p}\left(1 + \frac{\alpha}{(1-\frac{V+IR_s}{V_{br}})^m}\right) \quad (1)$$

$$I_L = \frac{G}{G_0} I_{L0}$$

where G_0 is the irradiance under Standard Test Conditions (STC), k_B is Boltzmann constant, R_p is the cell shunt resistance, R_s the cell series resistance, V_{br} is the junction breakdown voltage, α is the fraction of ohmic current involved in avalanche breakdown, m is the avalanche breakdown exponent and q is the electron charge.

For the sake of simplicity, the temperature has been supposed to be constant in the PV-array. As a consequence, this equation in its implicit form can be written as:

$$f(V, I, G) = 0 \quad (2)$$

In Appendix A, experimental PV-cell curves and the parameters for this equation are shown.

Finally, for the bypass diode used in PV-group clusters, which are typically standard silicon rectifier diodes, the following equation can be used:

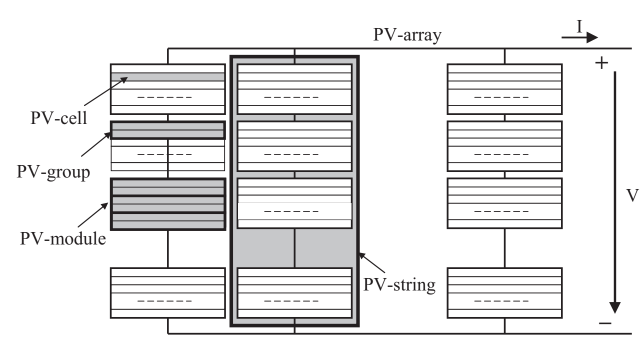

Fig. 1. Elements of a PV array.