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General modeling procedure for photovoltaic arrays

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ABSTRACT

Photovoltaic (PV) arrays are usually formed by strings of panels connected in parallel creating the series-parallel (SP) configuration. Additional connections can be implemented among the strings of the SP configuration to mitigate a particular mismatching profile. Those connections may follow regular or irregular patterns to form *regular configurations*, e.g. Total Cross-Tied (TCT), Honey-Comb (HC) or Bridge-Linked (BL), or *irregular configurations*, respectively. In literature there are proposed models for particular array configurations; however, there has not been reported yet a general model capable to describe the behavior of any regular or irregular configuration. Therefore, testing multiple configurations require to parameterize or design multiple models. This paper introduces a procedure for reproducing the electrical behavior of any PV array operating under uniform or mismatched conditions, which eliminates the requirement of using multiple models to evaluate different configurations. The procedure is based in dividing the array into sub-arrays to construct a system of non-linear equations for each sub-array, which is solved by using the Trust-Region Dogleg method. The proposed approach is validated by comparing the results provided by the proposed model with the circuital implementation of the same PV array in a commercial software and with the data produced with an experimental test bed. Such comparisons put into evidence the satisfactory performance of the general modeling procedure in the reproduction of the electrical behavior of both regular and irregular arrays.

1. Introduction

The advantages of photovoltaic (PV) systems (free energy source, zero emissions, modularity, etc.) as well as policies and subsidies to incentive the grow of PV installations have produced an important increase in the installed PV power all over the world. During 2016 a total of 75 GW were installed, 50% more compared to 2015, increasing the installed global PV capacity to 300 GW [1] approximately.

The basic unit that form a PV array is the PV module, which is a set of series connected cells with a protection diode (bypass diode) connected in anti-parallel. Usually two or more PV modules connected in series into a single mechanical structure is denominated a PV panel, which is the commercially available unit to construct a PV array [2].

In a typical PV system, the PV panels are connected in series to form strings, and multiple strings are connected in parallel to form the array. Such a configuration is denominated series-parallel (SP) and it is the most widely adopted configuration [3]. Additional ties can be implemented between two strings of a SP array to mitigate the effects of a particular shading profile. Such additional ties can be implemented following a regular or irregular patterns to form, what in this paper are denominated as, *regular* or *irregular* configurations, respectively.

Total Cross-Tied (TCT), the Bridge-Linked (BL) and the Honey-Comb (HC) [4] are three widely adopted regular configurations. The strict definition of TCT, BL and HC assume an array formed by modules instead of commercial panels [5,6]. On the other side, if a PV array configuration does not match with a regular configuration, i.e.

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SP, TCT, BL, HC or similar, then such a configuration is considered as irregular in this paper.

For a given operating condition each configuration, either regular or irregular, provide a particular power vs. voltage (P–V) curve, which may contain different number of local maximum power points (LMPPs) and a different global maximum power point (GMPP). Therefore, for a given operating condition, there is at least one configuration that provides the largest GMPP or, in other words, that best mitigates the effects of a particular mismatching condition [7].

In literature different modeling procedures for regular array configurations like SP [8–11], TCT [11,12], BL [11,13] or HC [4,11,14,15] have been reported. Picault et al. [16] mention the effects of the ties between the strings in the construction of a nonlinear equations system that describe an array, while Liu et al. [17] propose a model for a SP array with modules formed by different number of cells and/or modules without bypass diodes. However, in all these papers, the authors have not found a general modeling procedure able to reproduce the electrical behavior of any regular or irregular PV array configuration. This is evidenced in some papers aimed at comparing the performance of different regular configurations operating under mismatching conditions, since those works use circuital implementations of the arrays in electrical simulators, as in [11,15], or interpolations to calculate the arrays' power vs. voltage (P–V) and current vs. voltage (I–V) curves, this introducing numerical errors.

This paper introduces a novel methodology for modeling and calculating the current of any regular or irregular PV array configuration, with N rows and M columns ($N \times M$) of panels, operating under uniform or mismatched conditions. In comparison with other methods presented in literature, the proposed procedure allows to simulate, in an efficient way, irregular topologies, which can be more effective than regular ones when some shading patterns occur. From such basic calculation it is possible to obtain the I–V and P–V curves or to perform dynamic simulations. In the proposed model the connections between consecutive strings are represented by an $(N-1) \times (M-1)$ matrix named *connection matrix*, which is used to divide the array into smaller arrays, named sub-arrays, connected in parallel. A system of nonlinear equations is constructed for each sub-array using nodal analysis to calculate the sub-array currents from the node voltages. Finally, the array current is calculated by adding the sub-arrays' currents.

This modeling procedure is suitable to be implemented in standard programming languages such as Matlab script, C or C++, which makes it easy to use in different applications like the evaluation of MPPT techniques, the design of PV plants based on the estimation of the energy production or the implementation of reconfiguration algorithms without using costly and computing demanding circuital simulators. The paper is organized as follows: Section 2 describes the proposed modeling approach, Section 3 illustrates the use of the proposed model for a particular PV array configuration. Section 4 validates the performance of the proposed approach through different simulation and experimental tests. Finally, the conclusions close the work.

2. Proposed model

This section presents the main elements of the proposed modeling procedure, which is supported with a general flow chart and the pseudo-codes required for its implementation.

2.1. PV module representation

The operation of a PV device can be modeled through electrical [9,18,19] or thermal models [20,21] considering the dynamic weather conditions. In this paper, the widely adopted single-diode (SD) equivalent circuit, shown in Fig. 1, is adopted to represent a PV module due to its accuracy [18,22]. The associated bypass diode [8,22,23] has been also modeled. In the PV module, the current source (I_{ph}) represents the photovoltaic current, the diode includes the P–N junction nonlinear behavior, and the resistances R_h and R_s represent the leakage currents and ohmic losses, respectively. Moreover, e_a and e_b are the array node voltages at the positive and negative terminals of the PV module with respect to the array reference voltage.

The relationship between the current (I) and voltage ($V_e = e_a - e_b$) of the PV module can be obtained using the Kirchhoff voltage (KVL) and current (KCL) laws [24,25]. However, such relationship is not explicit and strongly non-linear; therefore, it is necessary to use the Lambert-W function, denoted by W_o, to express the module current as function of e_a and e_b as shown in (1). Moreover, the derivatives of (1) with respect to e_a and e_b are presented in (2) and (3), respectively. In (1)–(3) N_s is the number of series-connected cells into the module, I_{sat} is the inverse saturation current of the PV module diode, and $V_t = n \cdot k \cdot T/q$ in which n is the ideality factor, k is the Boltzmann constant, q is the electron charge, and T is the module temperature in Kelvin. $I_{sat,db}$ is the inverse saturation current of the bypass diode and $V_{t,db} = n_{db} \cdot k \cdot T/q$ in which n_{db} is the ideality factor of the bypass diode.

$$\begin{aligned} I &= -\frac{N_s \cdot V_t \cdot W_0\left(\theta\right)}{R_s} + I_{sat,db} \cdot \left[\exp\left(\frac{-(e_a - e_b)}{V_{t,db}}\right)\right] - I_{sat,db} \\ &\quad + \frac{R_h \cdot \left(I_{ph} + I_{sat}\right) - (e_a - e_b)}{R_h + R_s} \\ \theta &= \left(\frac{R_h \cdot R_s}{R_h + R_s}\right) \cdot \frac{I_{sat}}{N_s \cdot V_t} \cdot \\ &\quad \exp\left[\frac{(R_h + R_s) \cdot \left(I_{ph} + I_{sat}\right) + R_h \cdot (e_a - e_b)}{N_s \cdot V_t \cdot (R_h + R_s)}\right] \end{aligned} \tag{1}$$

$$\begin{aligned} \frac{\partial I}{\partial e_a} &= \left(\frac{-R_h}{R_s \cdot (R_h + R_s)}\right) \cdot \left(\frac{W_0\left(\theta\right)}{1 + W_0\left(\theta\right)}\right) - \left(\frac{1}{R_h + R_s}\right) \\ &\quad - \left(\frac{I_{sat,db}}{V_{t,db}}\right) \cdot \exp\left(\frac{e_b - e_a}{V_{t,db}}\right) \end{aligned} \tag{2}$$

$$\begin{aligned} \frac{\partial I}{\partial e_b} &= \left(\frac{R_h}{R_s \cdot (R_h + R_s)}\right) \cdot \left(\frac{W_0\left(\theta\right)}{1 + W_0\left(\theta\right)}\right) + \left(\frac{1}{R_h + R_s}\right) \\ &\quad + \left(\frac{I_{sat,db}}{V_{t,db}}\right) \cdot \exp\left(\frac{e_b - e_a}{V_{t,db}}\right) \end{aligned} \tag{3}$$

The values of I_{ph}, I_{sat}, n, R_s, R_h, $I_{sat,db}$ and n_{db} can be calculated by means of systematic procedures as the ones introduced in [18,19,26], which use the datasheet information of a PV panel and the bypass diode as well as the weather conditions. The parameters n, R_s, R_h, $I_{sat,db}$ and n_{db} can be considered constant while I_{ph} and I_{sat} depend on the irradiance S and temperature T as shown in (4) and (5).

$$I_{sat} = \frac{I_{sc,STC} + K_{Isc} \cdot (T - T_{STC})}{\exp\left(\left(V_{oc,STC} + K_{Voc} \cdot (T - T_{STC})\right)/V_t\right) - 1} \tag{4}$$

$$I_{ph} = \left(S/S_{STC}\right)\left(I_{ph,STC} + K_{Isc} \cdot (T - T_{STC})\right) \tag{5}$$

In (4) and (5), $I_{sc,STC}$ and $I_{ph,STC}$ are the short-circuit current and photovoltaic current in standard test conditions (STC), respectively, $V_{oc,STC}$ is the open-circuit voltage in STC, K_{Isc} and K_{Voc} are the temperature coefficients of the short-circuit current and open-circuit