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A method for the fast estimation of the maximum power points in mismatched PV strings

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ABSTRACT

The power vs. voltage curve of a photovoltaic string operating under mismatched conditions can exhibit more than one maximum power point (MPP). In this paper, a direct method for the estimation of these points using explicit equations is introduced. The method employs a piecewise linear approximation of the current vs. voltage curve of each photovoltaic panel in the string and assumes that the open circuit voltage and the position of the maximum power points of each panel are known. Numerical results comparing the performances of the proposed approach with those offered by the adoption of the accurate single diode model show that the computational burden is reduced by almost four orders of magnitude. The approach is validated by experimental results exhibiting estimation errors lower than 5%. The satisfactory trade-off between accuracy and computation time provided by the proposed method is illustrated using two application examples: reconfiguration and long-term power production of PV strings. Moreover, an in-depth comparison of the existing simplified methods to estimate the MPPs has been performed.

1. Introduction

The analysis and simulation of photovoltaic (PV) arrays operating under mismatched conditions is widely discussed in the literature, as well as the detrimental effect of the mismatching phenomena on the energy production [1]. A reasonable compromise between accuracy and simulation time is not easily achievable because a detailed model requires long simulation time for the solution of the relevant non-linear systems of equations. In turn, on-line simulations, which are of interest for analyzing the PV plant productivity under real-world, specific operating conditions, cannot be based on accurate equations. Indeed, the evaluation of the expected PV energy productivity requires the consideration of many intercorrelated influential factors, such as the type of PV panels used, the electrical connections among the panels, the irradiance and temperature profiles, the performances of the Maximum Power Point Tracking (MPPT) algorithm, the installation conditions and orientation, the environmental albedo, the presence of nearby bodies causing shadows, and the type of shadows. Such problems are much more evident in PV systems for urban applications, where high obstacles densities reduce the number of areas that are not affected by any shadow during all the days of the year. Moreover, PV panels are installed on available surfaces, which might have different orientations with respect to the sun's rays.

Evaluating the economic viability of installing a single/multi string PV systems facing shading conditions requires to simulate the energy production of months or years under the periodic shading pattern. Two possible approaches can be used to evaluate the power of such PV strings under mismatched conditions. Detailed models are usually dedicated to the short-term analysis and reconstruction of the current vs. voltage (I–V) curve of the whole PV field. These approaches guarantee an accurate simulation, but they require the tuning of many parameters, which involves substantial computational processing [2–6].

A second option relies on simplified models of the PV string, where a long-term energetic analysis becomes possible with a reasonable computation time. A small number of parameters are involved, and thus, the implementation in embedded systems, which can be used for diagnosis purposes and reconfiguration applications, becomes simpler. There are two trends in these simplified solutions: one uses the known simplified single-diode model

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of the PV modules [7,8]; and the other approach is based on a set of polynomial equations which are parameterized using data of particular cases of study [9–12].

In [9], the PV field is divided into blocks, each being characterized by a geometric shading factor depending on the number of partially shaded cells and on the number of totally shadowed cells. The series-parallel interconnection among the blocks is also considered. The model used to predict the MPPs does not require elaboration of the full *I*–*V* curve of the PV generator; the parameterization process is realized once, and it involves heuristic deductions based on simulations and statistical approximations. Although the method takes into account that the modules could be subjected to different irradiance values, the percentage of errors reported are constrained between −9.87 and 15.91.

The approach shown in [10] is based on empirical equations characterizing PV plants affected by different shadowing extensions and depth. The comparison with a detailed *I*–*V* curve simulation reveals that the simple analytical model exhibits a small error in the estimation of the energy yield in single shaded PV strings; a maximum error of 2–6% is obtained for larger PV fields with conventional panels. This approach is currently implemented in the National Renewable Energy Laboratory's System Advisor Model program, and it is used by many professionals in the field of photovoltaics. A further advantage of this analytical approach is that unlike numerical simulations, the computation time does not increase significantly with the size of the PV field. Unfortunately, the proposed model is based on rectangular shadow profiles, which is not applicable in many cases where the shadow is not homogeneous in the modules of different strings.

In [11], another simple modeling approach is proposed. This approach allows estimation of the Maximum Power Points (MPPs) of PV arrays with different types of connections among the panels; series-parallel (SP), total-cross-tied (TCT) and bridge-link (BL) configurations are considered. This method requires the values of the panels' open-circuit voltage, bypass diode voltage, and actual irradiance and temperature obtained using experimental data and equations. The main drawback of this approach is the rough approximation of the operating point for PV panels that are not operating in their own MPP. Thus, depending on the type of electrical connections among the panels, the error in the prediction of the MPPs in the PV field reaches up to 15%. This error might lead, for instance, to a sub-optimal selection of the electrical connections among the PV panels in a dynamical reconfiguration application.

The method proposed in [12] is simple to implement due to the polynomial model adopted. Moreover, the parameterization process is based on linear equations depending on shaded area of the modules. However, this approach is based on the assumption that the PV string exhibits only two MPP peaks, which is not applicable in many cases where different levels of shading affect the modules in the same string. The relative error of the power estimation is classified in a medium scale in comparison with others methods, achieving values lower than 10%.

In [13] the estimation of MPPs in a PV string is carried out by using a set of equations based on the single-diode model, the power conservation law, and a practical value of efficiency when the PV generation system is connected to the line. Finally, an implicit exponential model has been derived. Nevertheless this model requires the values of at least five parameters for each module, thus by increasing the complexity and the computational burden. The power losses due to bypass diodes are not taken into account, however the validation section shows that the prediction errors in current and voltages are lower than 1%.

In [7] a numerical algorithm is used to estimate the parameters of the model, but in contrast only one current sensor is required for each string, thus decreasing the complexity of the measurement process. On the other hand, in [8] the parameterization is based on the data sheet values, but a Newton-Raphson's method have to be executed for each irradiance value to be tested. However, these methods do not have any limitation in the irradiance profile, and the error in the power estimation is low, thus they presenting a good balance between accuracy and robustness.

Other interesting topic in PV applications concerns to find the best electrical configuration of a PV field. This kind of analysis involves several aspects such as power production of the panels, number of sensors and converters, scalability and maintenance. The central based MPPT systems requires only one inverter and few sensors, however this configuration works far away of the optimal operating point under mismatched conditions. A comparison between string and centralized systems is provided in [14,15]. In the first paper three PV array configurations are tested: 10 × 3, 15 × 3 and 20 × 3. Moreover, three DC/DC converters (one per each string of each configuration) and a control based on neural intelligent algorithms are used to find the MPP of each string. The results show an improvement of (30–60%) of the extracted power in comparison with conventional centralized configurations. In [15] simulations of the impact of moving clouds on large scale PV-plants are presented: in a PV systems of 108 kWp, an increment of 40% of power production is achieved using the string inverter configuration compared with a centralized configuration. Other applications such as multilevel converters [16,17], Distributed Maximum Power Point Tracking (DMPPT) [18] and reconfiguration [19] put in evidence the advantages in power production and quality of string configurations commanded by independent MPP controllers. In the same way, commercial products from [20,21] exhibit other advantages of using string inverters instead of centralized configurations. For example, a string inverter with two independent inputs enable optimal energy harvesting from each string installed with different inclination (tilt angle) and direction (azimuth angle) [20]. On the other hand, string inverters enable a detailed string monitoring and module faults isolation [21].

Therefore, string-based PV inverters (single strings or isolated multi-strings) are commonly offered by commercial manufacturers, which leads to a large number of string-based PV systems available in urban environments.

In this paper, a fast method for estimating the global MPP, and any other MPP, appearing in the power vs. voltage (*P*–*V*) characteristics of a string of *N* series-connected PV panels operating under mismatched conditions is proposed. The method employs a piecewise linear approximation (PLA) of the *I*–*V* curve. The data needed by the method are limited to the position of the MPPs of each PV panel in the string. The paper has focused on the connection of PV panels in series to address the problem related to string inverters. The proposed PLA method is compared in accuracy and computation time with existing methods. Additionally, two applications examples of long-term power production and reconfiguration are developed.

2. MPP identification in a mismatched PV string

Fig. 1(a) shows the typical electrical arrangement of the PV cells in a PV panel. N_M elementary blocks, named *PV modules*, composed of a number of series-connected PV cells protected by an antiparallel bypass diode, are connected in series. The sub-division of the PV panel into modules is usually adopted to reduce the occurrence of hot-spot phenomena [22] in the presence of a mismatch between PV modules.

A PV panel is usually simulated by means of the well-known single diode model (SDM). In the presence of a partial shadowing, the *I*–*V* curve of each PV panel can be well reproduced by assuming that each PV module of each PV panel operates under uniform irradiance conditions by considering an equivalent average irradiance