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PV panel single and double diode models: Optimization of the parameters and temperature dependence

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ABSTRACT

Photovoltaic (PV) cells induce current–voltage (*I*–*V*) characteristics dependent on the PV cell technology, the thin film structure and their eventual flaws during the elaboration process. The operation conditions also have a relevant impact on electrical curves characterizing these devices. The electrical parameters can be extracted from a PV panel standard datasheet using the commonly encountered single and double diode equivalent models representing the PV cell. This was done, in the present paper, at the most fundamental expression of these two models using evolutionary algorithms implemented in MATLAB (i.e. metaheuristic optimization methods). Four different *I*–*V* characteristics were available for the investigated commercial PV panel. They were fitted separately using the diode models and then taken as a whole to obtain parameters as physically meaningful as possible for the whole temperature range. The metaheuristic methods performed well for this problem, especially the cuckoo search algorithm. However, even with a good fitting of the fundamental behavior of the *I*–*V* characteristics, the presented approach may yield optimized solutions not as physically correct as it was expected. Thus, care must be taken for correctly interpreting the optimization results.

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1. Introduction

Nowadays, photovoltaic (PV) conversion devices are major players in industrialized countries towards the production of more sustainable energy in their energy mix, also with possible applications outside the frame of conventional electrical grids. Within the so-called green economy, projects for PV plants/farms, or the integration of PV panels into buildings, all have a budget that is sensitive to the electricity output prediction over the life span of the PV devices. Numerous numerical models are applied to achieve such estimations by means of the PV panel's performance and its mounting geometry, thus making it possible to establish the PV module operating temperature as a function of service conditions simulation (see for example the model of King et al. [1] or of Sánchez Barroso et al. [2]).

Using these multi-physics models, the electrical power outputs are easy to quantify from the solar irradiance on the PV panels, assuming that the maximum electrical power is extracted from the PV device. Practically, it should be noted that this assumption is equivalent to a perfect operation of the maximum power point tracking device coupled to the PV inverter. From a theoretical point of view, establishing the maximum power point (P_{Max}) for a given model of a PV panel requires certain knowledge of the current–voltage (*I*–*V*) characteristic of this device. However, the *I*–*V* curve of a given PV panel/module/cell greatly depends on its temperature, real light irradiance, and is also a function of the PV cell technology. PV cells, as the core of this photoconversion process, are indeed manufactured as multilayered thin films of semiconductors with complex electronic features and dependence to the service conditions.

The approach proposed in this paper relies on the extraction of the intrinsic parameters which accurately describe the experimental *I*–*V* curves through the formalism of semi-empirical functions of these parameters (these semi-empirical functions apply well to the PV devices in general). Fundamentally, these semi-empirical relations consider the PV cell as an equivalent electrical circuit that can be the single-/one-diode model illustrated in Fig. 1 or the double-/two-diode model represented in Fig. 2 (see for instance [3,4]). These two equivalent circuits are well-established concepts that have been used for decades to extract the parameters of the illuminated PV cell *I*–*V* characteristics. In the 1980s, for example, a Newton–Raphson method was presented to resolve deterministically the one- and two-diode models of different PV cells [5]. Fitting techniques were exploited 10 years earlier on silicon solar cells [6] (even for the two-diode model). Our approach aims at finding good solutions using metaheuristic methods (implying stochastic schemes) for the same systems of semi-

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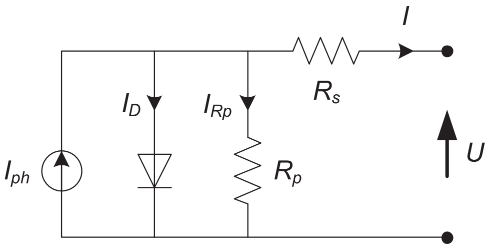

Fig. 1. One-diode equivalent circuit.

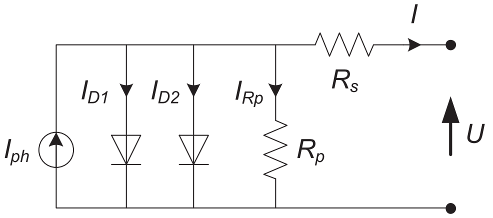

Fig. 2. Two-diode equivalent circuit.

empirical relations. This method can be applied to any kind PV cell. Similar techniques, based on evolutionary algorithms, have been widely applied to problems in the field with great success [7–17].

It should be noted that the parameters, used to describe the system, are physically based within their well-established context, using relations of the literature that are described in Section 2. Because of this fact, the optimization methods will only explore parameter values that are physically viable. To be exact, we will explore domains for each of them that are equivalent to the ones used in literature, at least in the order of magnitude.

In general, experimental *I–V* curves are characterized using common electrical equipments for different fixed temperatures and irradiance conditions [3]. For instance, these conditions can be defined by the conventional “standard test conditions” (STC) which imply that the PV cell receives 1000 W/m^2 of solar irradiance at 25 °C (the light spectrum being of an optical air mass at AM1.5). In a PV panel datasheet, provided by the manufacturer, details on the *I–V* characteristics are easily found at STC but also at other test conditions with other temperatures. We rely here on these kinds of data. We may use many experimental data, but we need at least three sufficiently different points on each *I–V* characteristic for fitting purpose. This requirement is easy to achieve since the datasheet generally contains reports of the maximum electrical power point P_{Max} and of the extreme values of the *I–V* characteristic under solar irradiance (namely, they are I_{SC} the short circuit (SC) current of the device and V_{OC} its open circuit (OC) potential/voltage).

Methods with different optimization (i.e. fitting) schemes and with physically-based parameters settings (e.g. from measurements) are commonly used in the literature to approximate the *I–V* characteristics. At their core, they are expressed with more or less unknown values of key parameters at the given reference temperature T_{Ref}, e. g. $T_{Ref} = 25$ °C for the STC, as in the case of the method based on the 5-parameter model proposed by De Soto et al. [18]. The aim of these methods is to use known data, generally provided by the manufacturer, to extrapolate the electrical performance of the PV devices to other atmospheric conditions than the STC. The point of these methods is to make it possible to simulate the electrical behavior in real service conditions. In their work, De Soto et al. [18] have shown that, for several types of PV technologies, the extrapolations can be done using common semi-empirical relations.

The semi-empirical expressions lying behind this field (of the extraction of electrical parameters relative to the PV technologies) are not particularly in focus here by themselves, but the literature is abundant on the subject. New developments or emergence of different expressions are also possible within the field, see for instance the recent improvement proposition related to the temperature and irradiance relation in Ref. [19], or another proposition to consider R_s in the one-diode model proportional to the current with $R_s(I) = R_{s0}(1 + K \times I)$ [17]. Taking this concern into consideration, it should be noted nevertheless that the proposed approach does not critically depend on eventual modifications made to the semi-empirical relations used explicitly in Section 2.

Here, we will use in the same fundamentals as the aforementioned semi-empirical approaches, but as much as possible with less relations correlating the parameters (or parameters anchored to physical measurements). Instead, we only rely on the optimization techniques to search for the fundamental physically based parameters.

At first, we apply this approach to the isothermal *I–V* characteristic data given at different T_{Ref} using only a PV panel datasheet. On the other hand, we want to take into account the temperature dependence of these parameters with more refined semi-empirical relations and parameters. This is still achievable within the framework of optimization techniques by considering the data set of the different isothermal conditions as a whole anisothermal set. It should be noted that the same approach could also be applied to solar irradiance variations (which are outside the scope of this paper). Both approaches were for example undertaken by Ma et al. [11] using the single diode model.

The proposed approach takes then into account the temperature effects. By doing so we can extrapolate judiciously to totally different atmospheric conditions in comparison to the STC. This can be done without favoring the accuracy of only one type of atmospheric conditions among low, STC, mid-high or higher temperature conditions. This is particularly pertinent for countries like Qatar, since summer temperatures and solar irradiance induce a PV cell temperature up to around 70 °C. In this study, we are less focused on very low temperatures or aerospace conditions but the proposed approach would remain valid.

2. Electrical modeling of PV panels

PV panels are modular devices assembled by connecting the solar cells in series and parallel following the design chosen by the manufacturer. We mentioned above the single or double diode equivalent circuits, but these models are applied mostly at the PV cell level. In our study, we focus however on using the data from a solar panel (BP 350 U [20]), which is comprised of two strings of PV cells connected in parallel. Each string for this particular panel has 36 PV cells connected in series. The PV cell *I–V* characteristic can then be directly taken from the panel's experimental *I–V* curves by dividing the current *I* by 2, the number of parallel strings, and by dividing the potential *U* by 36, the number of PV cells in series in each string [4]. The experimental *I–V* curves are available in the datasheet at four different temperatures. There exist also an alternative to using such experimental data for testing/validating purposes of these kinds of approaches, for instance see Ye et al. [7] with their use of synthetic data points elaborated for frankly different cases of *I–V* curves.

Regarding the equivalence used in the framework of the one- and two-diode models, we assumed here that the electrical parameters are relative to the concerned PV cell's total surface area, but it should be noted that the correct generalized values would be in terms of currents as Ampere per unit area ($A/\mathcal{A}$), and for the electrical resistances units of $\Omega\times$ unit area $\mathcal{A}$. The scope of this paper is to present an optimization method to be applied to solar cells samples, solar cells, PV modules/panels/arrays, so this approach is unconcerned here with the changes in unit or formalism over the physical grounds of these equivalent circuits.

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