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A parameter extraction technique exploiting intrinsic properties of solar cells

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HIGHLIGHTS

- With two intrinsic properties, a simple parameter extraction is proposed.
- The proposed method requires less measured points than the existing ones.
- Mean Absolute Error is lower than that of the existing methods.

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ABSTRACT

This paper presents a parameter extraction technique for the five-parameter solar-cell model. It only requires the priori knowledge of three load points: the open circuit, the short circuit, and the maximum power points. An intrinsic property of solar cells helps to construct an extra equation. A cost function is formulated with another intrinsic property. A search algorithm for minimizing the cost function is proposed. The best set of parameters is revealed at the end of searching. Two load scanning experiments are performed on two different solar panels. The simulated *I–V* curves, produced with the obtained parameters, match the empirical measured results nicely. When compared to other existing techniques, our proposed method usually yields less mean absolute error.

1. Introduction

Over the last few decades, the world has witnessed a significant increase in the installed capacity of photovoltaic (PV) systems. Because every PV system is composed principally of solar cells. Knowing parameters of solar cells at various operating conditions is of great importance, as it helps to produce the *I–V* curve of the PV system. Then its maximum power point may be estimated. Manufacturers of solar cells or PV panels usually publish the curves at only a few operating conditions. Some publish only the *I—V* pairs at a few load points. Fortunately, a solar cell can be represented by a model, which is composed of a few electrical components [1]. Parameters for the model may be extracted from that limited information. Then the *I—V* relation at other operating conditions and/or operating loads can be estimated.

There have been a large number of studies on solar cell models (and parameter extraction) in recent years [2–4], but only a few models are widely accepted. The single-diode model (see Fig. 1) is the most favorite one, because its relevant equations are simpler, and for most commercial PV panels, it is almost as accurate as the double diode (two diodes in parallel) or the triple model (three diodes in parallel). It only has five parameters: (1) the induced current (or photo generated current) I_{ph}, (2) the saturation current (or dark current) I_S, (3) the emission coefficient (or ideality factor) n, (4) the series resistance R_s, and (5) the shunt (or parallel) resistance R_p.

Almost all parameter extraction methods rely on the well-known *I—V* equation of solar cells. Based on their complexity, these studies can be categorized into two groups. Methods in the first group usually estimate value of one or two parameters and require just a few measurements. So they are quite simple, but their extraction results are not accurate. Methods in the second group require a lot of measurements and complex calculation, so they yield good extraction.

For the first group, all methods exploit the fact that some parameters can be estimated with good accuracy when the solar cells are forced to operate at the short-circuited point (SCP) and/or the open-circuited point (OCP). A parameter extraction method called “Five Points” [5], uses two approximations: $R_p \approx -\frac{dV}{dI}\big|_{I=I_{SC}}$ and $R_s \approx -\frac{dV}{dI}\big|_{V=V_{OC}}$, where I_{SC} and V_{OC} denote the current when the cells

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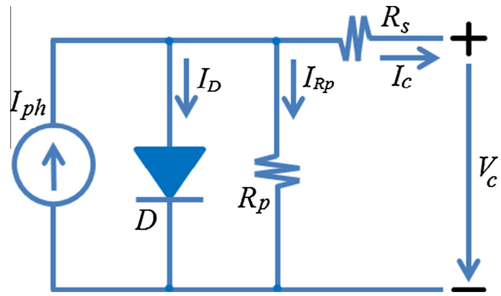

Fig. 1. An equivalent circuit of a solar cell, which is composed of a diode.

are short-circuited, and the voltage when they are open-circuited (no load) respectively. These parameters are employed to construct the I—V equations at three points: OCP, SCP, and the maximum power point (MPP). For convenience, these three special points will be later called OSMP. Solving these three equations reveals the values of three remaining parameters: I_S, I_{ph}, and n. Another method [6] also approximates R_p in the same way as [5], and it employs the fact that $e^{-\frac{V_{OC}-I_{SC}R_s}{nV_T}} \approx 0$ to formulate an expression of δ as a function of n and R_S. Then n and R_s are scanned to find the most suitable set of parameters. The I–V curve computed from each parameter set is compared against the I–V curve constructed from numerous measurements of I–V points. The set that yields minimum mean squared error is the end result. The method in [7] uses only one approximation: $I_{ph} \approx I_{SC}$. Measured values at four load points are employed to calculate a and b. Both are then combined with I_{SC} and V_{OC} in order to determine the values of n, R_s, R_p and I_S. In [8] R_p is estimated by two measured points near the SCP. The "curve fitting" method is also utilized there. The other parameters are obtained by fitting at least three more load points to a curve of a special function. The extraction method in [9] uses the fact that $I_{ph} \approx I_{SC}$ and assumes that $I_{SC} \gg I_S$ to determine the values of all five parameters. The "Analytical and quasi-explicit four arbitrary point" method in [10] is a recent technique, which can be used to extract five parameters, but requires fewer measured load points.

Methods in the second group yield the parameters based on several measured points without any approximation. In [11], "polynomial curve fitting technique and Lambert W function" are employed. In [12], a modified Newton–Raphson method (with the Levenberg parameter) is employed together with the nonlinear least squares optimization algorithm. The measured values presented in [12], are later used as standard datasets by many papers. With the datasets, computation techniques such as least squares [13,14], Differential Evolution (DE) [15], a modification of DE technique (P-DE) [16], Genetic Algorithm (GA) [17], Pattern Search (PS) [18], Teaching–Learning [19], Bird Mating Optimizer (BMO) [20], Chaos Particle Swarm Algorithm (CPSO) [21], Artificial Bee Swarm Optimization (ABSO) [22], and Simulated Annealing algorithm (SA) [23], are employed to find the most suitable parameters. The "mutative-scale parallel chaos optimization algorithm" (MPCOA) with crossover and merging operation is presented in [24]. Another method, which combines Levenberg Marquardt algorithm with simulated annealing, is presented in [25].

We proposed a parameters extraction technique that does not require a lot of measurements nor complex computation. In other words, it belongs to the first group, but it yields highly accurate results. This can be observed by lower mean absolute of error (MAE) when compared to a few methods in the second group. Exploiting two intrinsic properties of solar cells, it requires only measured voltages and/or currents at the OSMP. This requirement is less than or equal to that of existing methods.

Next section reviews the mathematical expressions of a conventional solar cell and PV panel. Section 3 recalls three I—V equations, when solar cells operate at the OSMP. The fourth equation is derived from an intrinsic property at the MPP. Exploiting another property, a cost function is also derived. Moreover, a searching algorithm is proposed in order to minimize the cost. In Section 4, the parameters obtained by the technique in previous section are used to produce the I—V curves, and then the results are compared with the outcomes of other existing methods. The extraction results of some commercial solar panels at STC and/or NOCT are also shown to confirm the usefulness of proposed technique.

2. Mathematical models

A solar cell can be equivalently modeled by a circuit of few discrete electrical components. PV panels are basically solar cells connected in series, so their mathematical model can easily be derived from that of solar cells.

2.1. Solar cells

Almost all conventional solar cells can be viewed as large-area p–n junctions that are subject to being hit by photons. A cell produces the photo-generated current I_{ph}, in respect of the photon flux or irradiance Ir. Hence, an ideal solar cell can be seen as a current source in parallel with a diode. The diode D includes two parameters: the ideality factor n and the saturation current I_S. In practice, a solar cell is built such that it contains parasitic components, which can be modeled as a shunt or parallel resistor R_p and a series resistor R_s. The equivalent circuit of a realistic PV cell is depicted in Fig. 1. The cell output current I_c is equal to I_{ph} minus I_D and I_{Rp}, which are the current flowing through D, and through R_p respectively. Relation between I_c and the cell terminal voltage V_c is given by

$$I_c = I_{ph} - I_S(e^{\frac{V_c+I_cR_s}{nV_T}} - 1) - \frac{V_c + I_cR_s}{R_p} \tag{1}$$

where $V_T = \frac{kT}{q}$ is the thermal voltage, which depends on the junction temperature T, the Boltzmann's constant k, and the elementary charge constant q.

2.2. PV panels

A panel is conventionally composed of $\mathcal{C}$ cells connected in series (Fig. 2). Hence, the current of the panel I is always equal to I_c. Assuming that all the cells are identical and they receive the same level of photon flux, so they produce the same current and voltage.

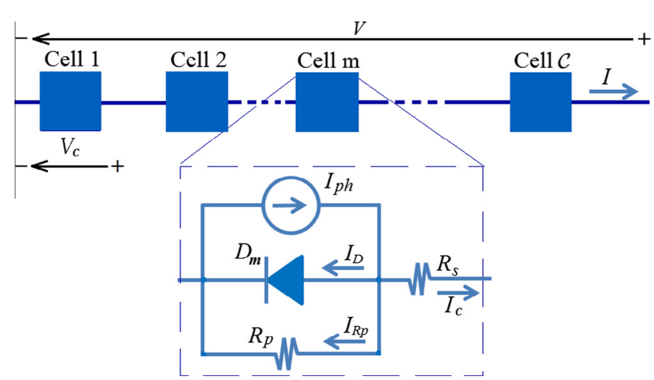

Fig. 2. Typical electrical structure of solar panels.