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A straightforward method to extract the shunt resistance of photovoltaic cells from current–voltage characteristics of mounted arrays

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ABSTRACT

A straightforward non-invasive method is proposed to accurately evaluate the shunt resistance of an elementary cell of a photovoltaic module connected in an installed string without requiring prior knowledge of the parameters of the intrinsic diodes. The approach relies on the measurement of the current–voltage characteristic of the whole string after intentionally shading the selected cell. Calibrated PSPICE simulations are employed to illustrate the method and test its reliability. As a case study, the shunt resistances of several cells belonging to a series array of 10 commercial panels are determined.

1. Introduction

The shunt resistance R_{sh} is a lumped component usually included in the equivalent circuits of a photovoltaic (PV) cell to describe the existence of alternative paths for the current flow through the inherent diode or along the cell edges. This parasitic parameter can be reviewed as an indicator of the cell quality, since the shunt paths are due to manufacturing defects as e.g., lattice imperfections or impurities in/near the depletion region [1], and penetration of the front contacts through the P–N junction [2,3], which can be non-uniformly distributed over the cell area [2–4]. If the value of R_{sh} is low, i.e., the shunt paths exhibit a high conductance, large leakage currents are undesirably derived. This in turn entails a performance degradation of the PV field due to the reduction in the power produced, especially at low irradiation levels (e.g., during cloudy days and/or far from noon) [5–7]. The shunt currents might also affect the open-circuit voltage V_{oc} and short-circuit current I_{sc} of cells characterized by intolerably low quality (i.e., with $R_{sh} < 0.5\ \Omega$). Moreover, low-R_{sh} cells are particularly susceptible to *hot-spot* formation when shaded [7].

It is commonly recognized that an accurate assessment of the shunt resistance (not usually provided by the manufacturer) and of the other key cell parameters is of utmost importance for the design optimization of PV systems due to the increased reliability of the models implemented in simulation tools, as well as for quality control and performance estimation. Several extraction approaches have indeed been developed and proposed in the literature, which are based on the measurement of current–voltage (*I–V*) characteristics of the individual cell under (different levels of) illumination or in the dark. In particular, R_{sh} is conventionally determined from the slope of the *I–V* curve where the behavior of the cell is assumed to be dominated by the shunt loss, namely, (i) at low forward voltages [8,9], (ii) in the short-circuit current point (either *directly* [10–16] or through the simultaneous solution of a system of non-linear equations derived under illumination [17–19] or in the dark [20]), and (iii) in the reverse region [13,21–24]. However, practical difficulties are to be faced when performing this extraction, since soft-breakdown phenomena often arising at low reverse voltages in silicon cells [6,25,26] may significantly reduce the voltage span within which the slope is solely determined by the shunt resistance, thus affecting the accuracy of the results. In other works, R_{sh} is evaluated concurrently with all other cell parameters on the basis of a single experimental *I–V* characteristic by adopting analytical relations describing the most relevant points of the curve [27], fitting procedures relying on the least-squares method [28,29], and even genetic algorithms [30]. Lastly, a direct technique, which makes use of the V_{oc} and I_{sc} values measured under very low irradiance conditions, was proposed in [31] and successfully compared to a traditional slope-based method in [8].

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An important issue concerns the measurement of the shunt resistance of individual cells embedded in a commercial module, which can be in principle carried out only after a critical cell de-encapsulation, or using a sophisticated two-terminal procedure that relies on the simultaneous application of a DC voltage source, an AC signal generator, and an operational amplifier connected to a phase-sensitive lock-in amplifier [5]. As an alternative, one could perform a gross (i.e., low-granularity) quality testing by determining the R_{sh} corresponding to the *whole* panel. However, this approach is particularly prone to errors due to the enhanced flattening of the *I–V* curve, combined with the unavoidable data noise and the limited current resolution of available measurement systems; besides, it does not allow the identification of an uneven cell quality distribution within the module, or the detection of a cell failure.

In this work, we propose a simple non-intrusive technique to accurately quantify the shunt resistance of a selected PV cell belonging to a module connected in an installed string. The method relies on the measurement of the *I–V* curve of the whole string by keeping the cell under ideally dark conditions. An extensive analysis supported by the widespread simulation tool PSPICE [32] is performed, which proves that the method provides a fairly good accuracy without the need of a preliminary assessment of the ideality factor of the inherent diodes, even though the array includes a large number of series-connected cells. The approach is applied to a string comprising 10 commercial silicon panels with the aim to determine the cell quality distribution.

2. Experimental material and simulation approach

The experimental investigation was conducted on an array composed by 10 encapsulated mono-crystalline silicon 50 Wp modules, each partitioned into two sub-panels provided with a bypass diode (located in the *junction box* mounted on the rear) and comprising 20 elementary cells (with area equal to 68 cm^2) connected in series. As shown in Fig. 1, the string was mounted on the rooftop of the department for experimental purposes. The PV panels were individually characterized through a self-powered monitoring circuit recently developed *in house* for diagnostic services [33]: the open-circuit voltage V_{oc} of the individual modules was found to range between 20 and 25 V, while the short-circuit current I_{sc} was detected to span from 2 (winter) to 3 A (summer) around solar noon. A custom version of the H&H ZS3060 electronic DC load [34] rated for 3 kW and 800 V was employed to measure the *I–V* curves of the overall string.

The popular tool PSPICE – sometimes successfully applied to the analysis of PV cells/modules [5,35] – was adopted to explain the features and verify the accuracy of the proposed extraction method. The elementary cell was described through the equivalent

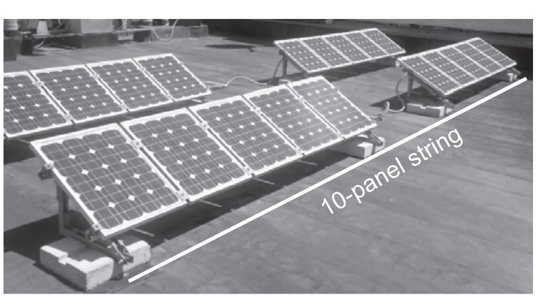

Fig. 1. Pair of 10-panel strings installed on the rooftop of the department. Each panel is partitioned into two 20-cell sub-panels equipped with a bypass diode located in the *junction box* mounted on the rear; the string includes 400 elementary cells.

lumped electrical circuit (often referred to as five-parameter single-diode model) represented in Fig. 2, which includes: a current source of photogenerated current I_{ph} (also denoted as photocurrent), an ideal (i.e., resistance-free) diode accounting for the dark *I–V* characteristic – fully defined by the reverse saturation current I_0 and the ideality factor n – and the parasitic series and shunt resistances, denoted with R_s and R_{sh}, respectively. This popular model, based on the so-called "superposition principle" [36], accurately describes the behavior of most PV cells under standard (i.e., non-stressed) operating conditions.

3. The extraction method

The method is based on a straightforward experimental procedure, which requires that the PV string is fully exposed to sunshine, and can be described as follows.

The total series resistance of the string, denoted as $R_{s,string}$, can be expressed as:

$$R_{s,string} = \sum_{i=1}^{N}\sum_{j=1}^{M} R_{s,ij} + R_{bus} + R_{cab} \tag{1}$$

where N is the number of panels connected in series, M is the number of cells belonging to a panel, $R_{s,ij}$ is the series resistance associated to the j-th cell of the i-th panel, R_{bus} is the aggregate resistance of the bus bars, and R_{cab} is the resistance of the cables that ensure the connection to the measurement system. In order to determine $R_{s,string}$, we extended widely accepted approaches conceived to extract the series resistance of an individual cell, namely, the *method of the slope at the* V_{oc} *point* [10–12,14,16,17,37] yielding:

$$\begin{aligned} R_{s,string} &= -\left.\frac{dV_{string}}{dI_{string}}\right|_{V_{string}=V_{oc}} - N \cdot M \cdot \frac{n \cdot V_T}{I_{ph}+I_0} \\ &\approx -\left.\frac{dV_{string}}{dI_{string}}\right|_{V_{string}=V_{oc}} - N \cdot M \cdot \frac{n \cdot V_T}{I_{sc}} \end{aligned} \tag{2}$$

where $V_T = kT/q$ is the thermal voltage, T being the temperature of the modules, and the *area method* [38] leading to:

$$R_{s,string} = 2 \cdot \left(\frac{V_{oc}}{I_{sc}} - \frac{P_A}{I_{sc}^2} - N \cdot M \cdot \frac{n \cdot V_T}{I_{sc}} \right) \tag{3}$$

where P_A is the area under the $I_{string} - V_{string}$ curve in the voltage range from 0 to V_{oc}.

As a first step, parameters I_{sc}, $\left.\frac{dV_{string}}{dI_{string}}\right|_{V_{string}=V_{oc}}$, V_{oc}, and P_A included in Eq. (2) and Eq. (3) are to be extracted from an experimental $I_{string} - V_{string}$ characteristic measured while the string is under full irradiation.

Afterward, a selected cell of the string is intentionally kept under ideally dark conditions (as shown in Fig. 3) and the $I_{string} - V_{string}$ characteristic is measured. A PSPICE simulation of a 2-panel string was performed to illustrate the behavior of the key electrical signals against string voltage; in particular, each panel is composed by 40 cells uniformly sharing R_{sh} = 30 Ω. For low V_{string} values, the voltage drop across the 20-cell sub-panel includ-

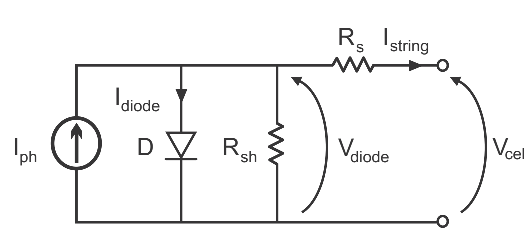

Fig. 2. Equivalent 5-parameter one-diode electrical circuit of a PV cell.