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Accurately Extracting the Shunt Resistance of Photovoltaic Cells in Installed Module Strings

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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 the need of preliminary knowledge of the intrinsic diode parameters. 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 both illustrate and test the method. As a case study, the shunt resistances of several cells belonging to a series array of 10 commercial modules are determined.**

***Index Terms* — Photovoltaic (PV) cell, PV array, series resistance, shunt resistance.**

I. Introduction

The shunt resistance R_{sh} in a photovoltaic (PV) cell is a parasitic parameter that can be reviewed as an indicator of the cell quality, since it describes the existence of an alternative (shunt) path for the current flow through the inherent cell diode or along the cell edges due to non-uniformly distributed manufacturing defects as e.g., lattice imperfections or impurities in/near the depletion region [1]. If the R_{sh} of the cells 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) [2]-[4]. The shunt currents might also affect the open-circuit voltage V_{oc} and short-circuit current I_{sc} in cells characterized by intolerably low quality (i.e., with R_{sh}<0.5 Ω). Moreover, low-R_{sh} cells are particularly susceptible to *hot-spot* formation when shaded [4].

It is commonly recognized that an accurate extraction of the shunt resistance (not usually provided by the module manufacturer), as well as 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. Most conventional approaches are based on the measurement of the I–V characteristics of the PV cell under (different levels of) illumination or/and in the dark. In particular, R_{sh} is usually determined from the slope of the I–V curve in the short-circuit current point [5]-[8] or in the reverse region [9]-[11]. However, this approach is unviable when the slope is influenced also by the soft-breakdown phenomenon often arising at low reverse voltages in silicon cells [3], [12]. An alternative technique has been also proposed, which makes use of the V_{oc} and I_{sc} values measured under very low irradiance conditions [13].

Another 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 adopting 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 [2]. 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 procedure to accurately quantify the shunt resistance of a selected cell belonging to a PV module connected in an installed string. The method relies on the measurement of the I–V curve of the whole string by keeping the chosen cell under ideally dark conditions. The approach is applied to a string comprising 10 commercial silicon modules.

II. Experimental

The experimental investigation was conducted on an array composed by 10 encapsulated mono-crystalline silicon 50Wp modules, each partitioned into two sub-panels provided with a bypass diode (located in the *junction box* mounted on the rear) and comprising 20 68 cm^2 elementary cells 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 [14]: 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) at sunny midday. A custom version of the H&H ZS3060 electronic DC load [15] rated for 3 kW 800 V was employed to measure the I–V characteristics of the overall string.

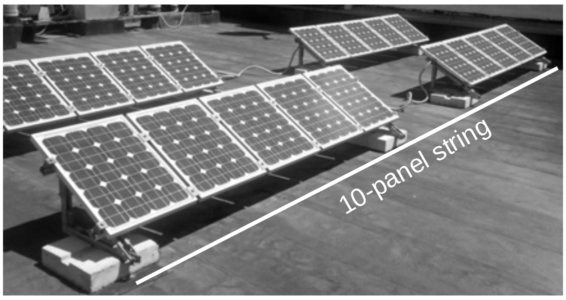

Fig. 1. Pair of 10-panel strings installed on the rooftop of the Department. Each panel is partitioned into two 20-cell sub-panels equipped with a bypass diode located in the *junction box* mounted on the rear; the string includes 400 elementary cells.

III. SIMULATION STRATEGY

The widespread simulation tool PSPICE [16] was extensively adopted to explain the features and verify the accuracy of the proposed extraction method. The elementary cell was described through the equivalent 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 shunt and series resistances, denoted with R_{sh} and R_s, respectively. This popular model, based on the so-called "superposition principle" [17], accurately describes the behavior of most PV cells under standard (i.e., non-stressed) operating conditions. The 10-panel PV array introduced in Section II was built in the PSPICE environment; the resulting network – which also includes the estimated resistances of the cables – involves more than 1600 components.

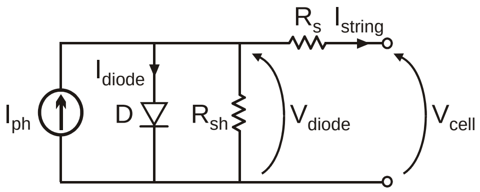

Fig. 2. Equivalent 5-parameter one-diode electrical circuit of a PV cell.

IV. THE EXTRACTION APPROACH

The method relies on a straightforward measurement 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 determined by resorting to a proper *string-oriented* generalization of a widely accepted approach devised for an individual cell [6], [8], [18], [19] as

$$R_{s,string} = -\left.\frac{dV_{string}}{dI_{string}}\right|_{V_{string}=V_{oc}} - N \cdot M \cdot \frac{n \cdot V_T}{I_{sc}} \qquad (1)$$

where N and M are the numbers of panels and cells belonging to a panel, respectively, and V_T=kT/q is the thermal voltage, being T the temperature of the modules.

As a first step, an I_{string}–V_{string} characteristic is measured so as to extract the short-circuit current I_{sc} and the slope at the V_{oc} point. 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} curve is measured again. A PSPICE simulation of the 10-panel string was performed to illustrate the behavior of the key electrical signals against string voltage. For low V_{string} values, the voltage drop across the sub-panel including the dark cell becomes negative, thereby enabling the bypass diode to support the conduction of the portion of the current imposed by the illuminated cells that can no longer flow through the sub-panel (≈2.1 A, as can be seen in Fig. 4a). The weak sub-panel current (I^*=0.11 A) is then forced to flow through the shunt resistance of the dark-induced cell. This scenario is schematically depicted in Fig. 3a. During the bypass phase, the negative sub-panel voltage drop (≈-0.6 V due to the diode activation, as shown in Fig. 4b) unevenly distributes across the 20 cells: in particular, the dark cell is subject to a high *negative* voltage (≈-11.5 V) that allows the conduction of the sub-panel current via shunt resistance (Fig. 3c); instead, the other 19 sunny cells in the sub-panel share a *positive* drop (≈0.57 V) needed to activate the inherent (i.e., parasitic) cell diodes, which must counteract the photocurrent in order to reduce the current of the cells to the level imposed by the shading (i.e., by the dark cell). For string voltages higher than 120 V, also the cell diodes of the illuminated modules start conducting, and the string current I_{string} decreases; as the voltage reaches 217 V, I_{string} equates the current I^* flowing in the dark cell, and the bypass diode is switched off (Fig. 3b). By further increasing the string voltage, the current almost linearly reduces before annihilating (at V_{string}=V_{oc}) and then becoming negative. The circuit behavior within the voltage range comprised between the bypass deactivation and V_{oc} (also denoted as "quasi-linear" region in the following) can be explained as follows. The increase in V_{string} gives rise to a growth in the voltage drops over (i) the dark cell (i.e., across the shunt resistance to be extracted, referred to as $R_{sh,dark}$ in this description), (ii) the total series resistance $R_{s,string}$, and (iii) the parasitic diodes of the $M{\cdot}N$-1 sunny cells in the string, which must conduct an increasingly higher current; in particular, the purely resistive contributions (i) and (ii) reach 0 V as I_{string}=0 A. It can be also observed that the voltage drop across the sub-panel including the dark cell becomes positive and increases up to 11.5 V, while those corresponding to the sub-panels exposed to sunlight somewhat grow (of about 100 mV) to reduce the drops over the series resistances and enhance the current conduction aptitude of the inherent cell diodes (Fig. 4b). The resistance R_{ql}, defined as the absolute value of the reciprocal of the I_{string}–V_{string} slope within the quasi-linear region, can be expressed as follows:

$$R_{ql} = -\frac{dV_{string}}{dI_{string}} = R_{sh,dark} + R_{s,string} + \left(N \cdot M - 1\right) \cdot R_{diode} \qquad (2)$$

where R_{diode} is the differential resistance associated to the parasitic diode of a sunny cell in the linear region. The expression of this parameter – which depends on the operating point of the diodes, and therefore on the I_{string} level – can be derived by resorting to the single-diode model in Fig. 2 and is given by

$$R_{diode} \approx \frac{n \cdot V_T}{I_0 + I_{diode}} = \frac{n \cdot V_T}{I_{sc} - I_{string}} \tag{3}$$

As a result, the shunt resistance of the dark cell $R_{sh,dark}$ can be expressed as

$$R_{sh,dark} \approx R_{ql} + \left.\frac{dV_{string}}{dI_{string}}\right|_{V_{string}=V_{oc}} - N \cdot M \cdot n \cdot V_T \cdot \left(\frac{1}{I_{sc} - I_{string}} - \frac{1}{I_{sc}} \right) \tag{4}$$

Hence, the shunt resistance of the intentionally-obscured cell $R_{sh,dark}$ can be determined by evaluating a resistance R_{qlm} from the slope of the straight line that guarantees the best fit with the measured I_{string}–V_{string} behavior within the whole quasi-linear region (R_{qlm} can be interpreted as the medium value of the current-dependent resistance R_{ql}) and subsequently adopting the following expression:

$$R_{sh,dark} \approx R_{qlm} + \left.\frac{dV_{string}}{dI_{string}}\right|_{V_{string}=V_{oc}} - N \cdot M \cdot n \cdot V_T \cdot \left(\frac{1}{I_{sc} - I^*/2} - \frac{1}{I_{sc}} \right) \tag{5}$$

where $I^*/2$ is the average value of I_{string} in the quasi-linear region (I^* is known from the measurement) and is usually a small fraction of the short-circuit current I_{sc}.

The following remarks can be made: (i) the proposed approach does not require the de-encapsulation and removal of the selected cell from the module; (ii) the extraction of R_{qlm} is not prone to errors due to the wide voltage range within which the quasi-linear behavior arises (>10 V regardless of the number of panels connected in series); (iii) the procedure can be applied without knowing the value of the ideality factor *n*; an extensive PSPICE-based analysis – which will be presented elsewhere – was carried out to demonstrate that an excellent degree of accuracy can be obtained by simply adopting *n*=1.2 or 1.3 in (5) even though the total number of cells in the string (*N·M*) is as high as 500 and a rather low value of R_{sh} (e.g., 20 Ω) is shared by all cells.

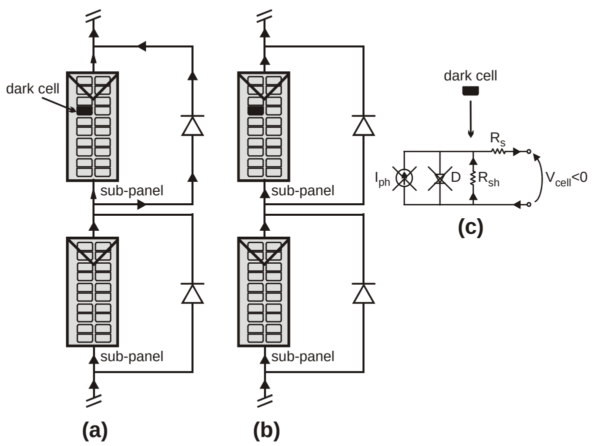

Fig. 3. Schematic representation of the PV panel (partitioned into two 20-cell sub-panels) including the cell intentionally kept under ideally dark conditions: (a) current flow for the V_{string} range wherein the diode is enabled to conduct the bypass current; (b) current flow corresponding to the quasi-linear I_{string}–V_{string} behavior; (c) circuit representation of the dark cell, within which the sub-panel current is forced to flow through the shunt and series resistances.

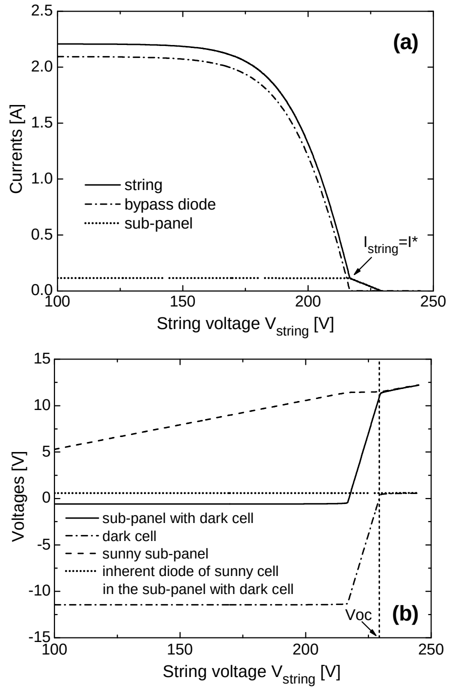

Fig. 4. Evolutions of the key electrical signals, namely, (a) currents and (b) voltages as a function of string voltage, as obtained through calibrated PSPICE simulations by keeping one cell under ideally dark conditions – which is achieved by setting the photocurrent to zero.

V. Results and Discussion

PSPICE simulations were employed to illustrate the impact of R_{sh} on the current–voltage characteristic of the 10-panel string. In this analysis, all the elementary cells were assumed to share the same R_{sh} value. Fig. 5 shows the I_{string}–V_{string} curves as obtained by varying R_{sh} from 25 to 400 Ω and obscuring a chosen cell. It can be inferred that the curve is almost insensitive to R_{sh} as long as the bypass action is carried out; conversely, a perceptible reduction in the absolute value of the slope arises in the linear region, which shrinks from 15 to 10 V due to the lowered current handling capability of the dark cell. The figure also reports the experimental and simulated (the latter with uniform R_{sh}=100 Ω) string characteristics as obtained under full illumination; the fairly good agreement allows excluding that the 10-panel string is characterized by cells evenly sharing very low R_{sh} values (i.e., <10 Ω).

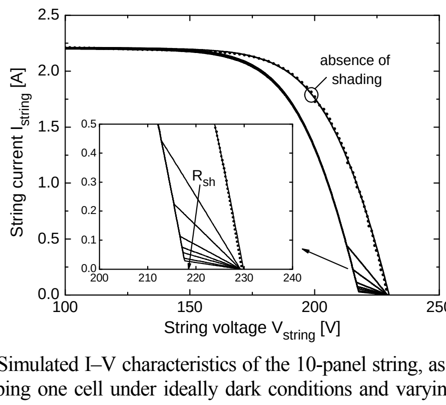

Fig. 5. Simulated I–V characteristics of the 10-panel string, as obtained by keeping one cell under ideally dark conditions and varying the R_{sh} commonly shared by all cells. Also shown are (dotted line) the experimental curve as measured by the electronic load and (solid) the PSPICE counterpart, both determined in the absence of shading.

The proposed extraction approach was applied to the 10-panel string described in Section II. As a first step, the I_{string}–V_{string} characteristic was measured at sunny midday in the absence of shading. The series resistance $R_{s,string}$ was evaluated to be about 5.2 Ω by invoking (1). The parameters I_{sc} and $\left.\dfrac{dV_{string}}{dI_{string}}\right|_{V_{string}=V_{oc}}$ needed to apply (5) were also available.

Afterward, a prescribed cell was obscured with an opaque tape and the current–voltage curve of the string was measured in order to extract R_{qlm} from the quasi-linear region; $R_{sh,dark}$ was then evaluated from (5) by assuming the ideality factor n equal to 1.2. The procedure was then repeated for a large number of cells so as to achieve an exhaustive map of R_{sh} values over the whole string. The experimental quasi-linear regions corresponding to a few cases are reported in Fig. 6; it must be noted that the slopes are considerably different, although virtually identical PV modules are connected in series. Fig. 7 reports the extracted R_{sh} values; in particular, the data corresponding to two cells per panel are shown.

The results of this investigation can be summarized as follows: (i) the shunt resistances are found to fall in a surprisingly wide range spanning from 30 to 300 Ω, which implies that the specific resistance spreads from 2 to 20 kΩcm^2; (ii) thus, the average cell quality is relatively low, since values larger than 500 Ω are expected in good silicon PV cells [20]; (iii) over a prescribed module, the cells exhibit a quite uniform R_{sh} (i.e., cell quality) distribution; (iv) the R_{sh} values were found to be almost insensitive to the irradiation intensity, consistently with the conclusion reached in [10].

IV. Conclusion

In this work, a simple non-intrusive approach to accurately assess the shunt resistance of a chosen PV cell embedded in an installed string is proposed, which does not require preliminary evaluation of the parameters associated to the intrinsic diodes. The technique relies on the measurement of the I–V characteristic of the whole string while intentionally keeping the assigned cell under ideally dark conditions. The shunt resistance is evaluated from the slope of the curve in the voltage range where the string exhibits a quasi-resistive behavior. In particular, the slope extraction is not affected by uncertainty since this range can be 10–15 V wide, regardless of the number of series-connected panels.

The proposed method has been adopted to evaluate the shunt resistance of prescribed cells of a PV array composed by 10 commercial silicon modules; the estimated specific resistances are found to span from 2 to 20 kΩcm^2, while being almost uniform over a given panel. This allows concluding that the impact of defects can be considerably different, even for panels belonging to the same family.

The procedure can be exploited for undemanding performance characterization, quality testing, and failure analysis of the module at a cell level; in particular, the degrading effect of the prolonged exposure to light can be monitored over long times.

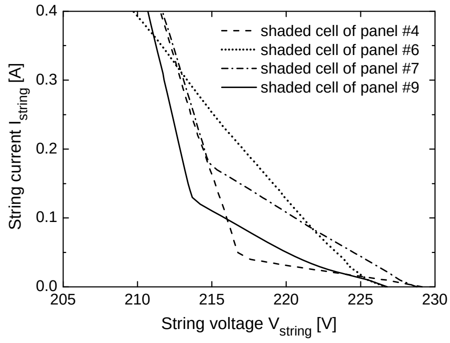

Fig. 6. Experimental string current as a function of voltage as obtained by intentionally shading assigned individual cells.

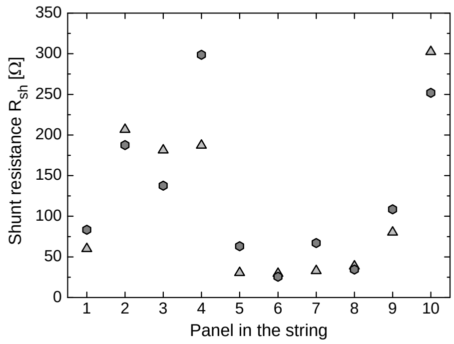

Fig. 7. Experimentally extracted shunt resistance values for the 10 panels composing the string; for each panel, two cells were measured.

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