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The Relevance of the Cell's Breakdown Voltage in the DC Yield of Partially Shaded PV Modules

Andres Calcabrini, Viswambher Kambhampati, Patrizio Manganiello, Miro Zeman, and Olindo Isabella
PVMD, ESE, Delft University of Technology, Delft, Zuid-Holland, Mekelweg 4, 2628CD, The Netherlands

***Abstract*—In this manuscript, we discuss the relevance of the reverse characteristics of solar cells in the energy yield of partially shaded photovoltaic modules. We characterize the reverse I-V curves of commercially available cells and we simulate the energy yield of photovoltaic modules using an experimentally validated simulation framework. Results suggest that cells with low breakdown voltages can boost the energy yield up to 74% in modules that are heavily shaded. Also, yield gains larger than 1% can be achieved for modules that are partially shaded only 7% of the time.**

***Keywords*—Shade tolerant, Low breakdown voltage, Urban PV**

I. Introduction

One of the major technical challenges for the deployment of photovoltaic (PV) systems in the urban environment is the highly irregular distribution of solar irradiance. Partial shading, understood as the uneven irradiance distribution on the surface of a PV module, has a disproportionate negative effect on the PV module's output electrical power. Owing to the irradiance mismatch, urban PV systems generally present significantly lower specific yields (and higher costs) than utility scale PV power plants where partial shading is not a major issue.

The negative effect of partial shading on the module's electrical performance is mainly due to the reverse I-V characteristics of solar cells and how solar cells are arranged and interconnected in the PV module. Most c-Si PV modules currently available in the market have all their solar cells connected in series and include 3 bypass diodes. The addition of bypass diode effectively reduces the breakdown voltage of the solar cells, which is typically in the range between $-20\,\mathrm{V}$ to $-10\,\mathrm{V}$ for front/back contacted (FBC) c-Si solar cells. Therefore, bypass diodes reduce the probability of hot-spot damage and increase the shade tolerance of PV modules.

A simple approach to increase the resilience against shading is to increase the number of bypass diodes in a module [1]. However, adding more bypass diodes to a PV module makes the manufacturing process more complex and increases the cost of PV modules. While the integration of bypass diodes in the same structure of solar cells has also been proposed [2], [3], to the authors' knowledge, these type of cells have not yet reach industrial production.

In the last decade, with the development of interdigitated back contact (IBC) solar cells based on n-type wafers, it has been possible to design solar cell structures that present significantly lower reverse breakdown voltages [4] than conventional FBC solar cells. These low reverse characteristics are related to the regions between the n+ back surface field (BSF) and the p+ emitter as shown in Figure 1a. While avalanche is the dominant breakdown mechanism in conventional c-Si FBC solar cells, in the IBC solar cell in Fig. 1a tunneling is the preponderant breakdown mechanism due to the high doping of the BSF and the rear side emitter [5]. As a result, some IBC solar cells present low breakdown voltages as shown in Fig. 1b. Under reverse bias, power dissipation in these solar cells is significantly limited, which reduces the chances of hot-spots and the need for bypass diodes.

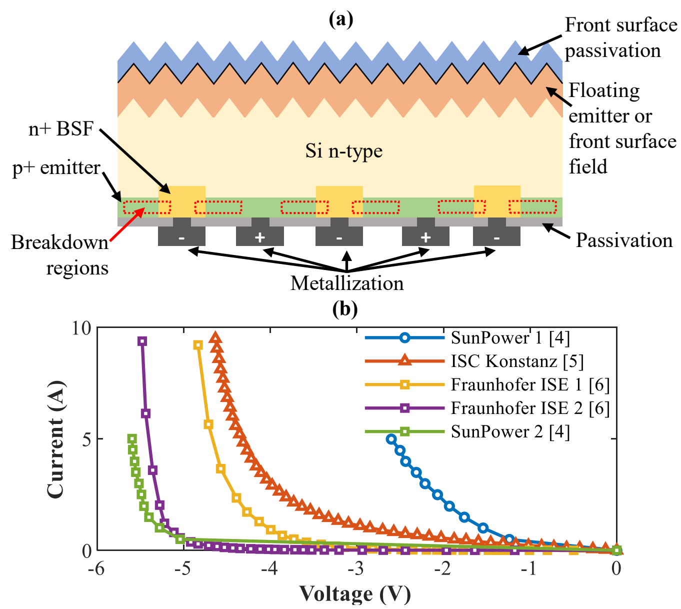

Fig. 1. Low breakdown voltage IBC solar cells. (a) Typical structure of an IBC solar cell with low breakdown voltage. (b) Dark I-V reverse characteristics of various IBC solar cells reported in the literature.

It should be noticed that forward and reverse characteristics cannot be independently optimized in the cell structure in Fig. 1a. When the reverse breakdown voltage is reduced, the cell efficiency tends to drop due to shunting [2], [5]. This implies a trade-off between the efficiency of the solar cells and the response of the PV module under partial shading.

In this work, the reverse characteristics of solar cells are modeled and their impact on the annual electrical yield is investigated. Furthermore, the reverse behavior of commercially available solar cells is characterized under varying irradiance and temperature conditions to simulate the annual yield of different type of cells in realistic conditions.

II. Energy Yield Simulation

The annual energy yield of the PV modules is simulated using an experimentally validated framework [7] that computes the I-V curves of the PV module at every minute of the year given the operating temperature and the effective irradiance incident on every cell of the PV module. The framework combines an optical model based on Radiance, with a thermal and an electrical model with cell-level resolution. The electrical model, distinguishes between two cases. When a solar cell is forward biased, the I-V curve is modeled using the 2-diode electrical equivalent model which takes into account the effects of temperature and irradiance. On the other hand, under reverse bias the I-V characteristics of the solar cell are modeled according to:

$$I(V,G,T) = I_{sc}(G,T) + k_1 \cdot \left(e^{k_2 \cdot V} - 1\right) + k_3 \cdot V \;, V \leq 0 \quad (1)$$

where, I_{sc} is the short-circuit current at irradiance G and temperature T, and k_1, k_2 and k_3 are fitted with I-V experimental measurements. In the simplest version of this reverse model, the coefficients are numerical constants. However, these coefficients can also be expressed as functions of G and T to include the effects of irradiance and temperature on the breakdown characteristics.

The I-V curves of each solar cell in the module are combined together with the I-V curves of the bypass diodes and the resistances of the tabbing wires according to the electrical interconnections (i.e., series and parallel) to generate the I-V curve of the PV module and compute the maximum power point at every time instant.

III. Results

A. Fixed Forward Characteristics

As it was mentioned before, in practice, the breakdown beahavior of a solar cell cannot be tuned without simultaneously modifying its forward I-V characteristics. Nevertheless, in a preliminary analysis, it is worth calculating the yield of a partially shaded PV module assuming solar cells that have the same forward but different reverse characteristics.

For this preliminary analysis, the annual yield of different PV modules is simulated considering the shading scenario

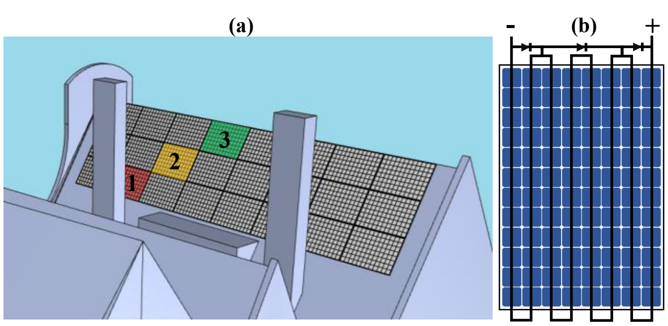

Fig. 2. (a) Shading scenario. The roof is tilted 57° and facing approximately Southwest (214° East from North). The electrical performance of the PV modules is evaluated at the 3 positions indicated on the rooftop. (b) PV module layout studied. The module has 96 5-inch solar cells connected in series and 3 bypass diodes.

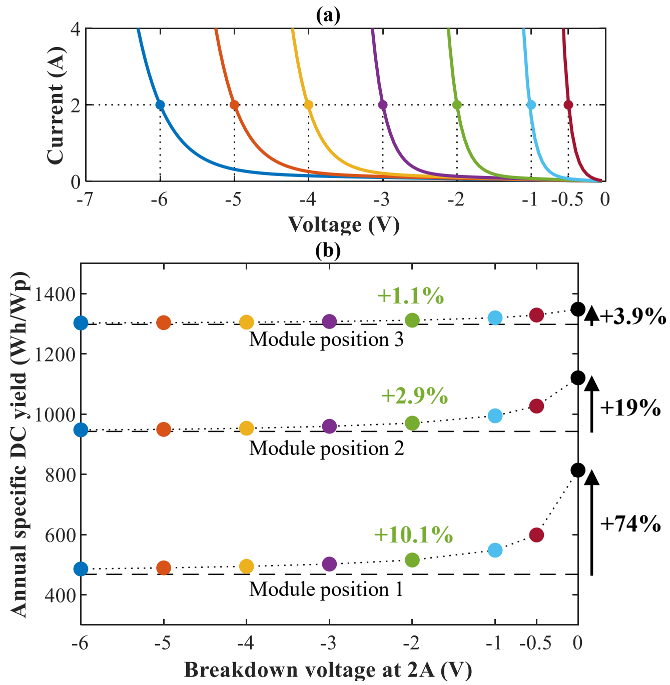

Fig. 3. Annual yield simulations. (a) Dark I-V of the simulated solar cells in reverse bias. (b) Annual DC yield generated by the modules in Fig. 2 for the different reverse I-V curves. The horizontal dashed lines indicates the yield of a PV module with an infinite (negative) breakdown voltage. The dotted lines are guide to the eye. The black and green values indicate relative gains with respect to the dashed lines.

shown in Fig. 2a using 1-minute resolution typical meteorological year (TMY) data for Barcelona, Spain generated with METEORNOM. Three particular module positions in the PV array are analyzed. The fraction of the annual daytime that each module in Fig. 2a is partially shaded is 40 %, 20 % and 7 % for module positions 1, 2 and 3 , respectively. All the modules studied consist of 96 5-inch solar cells and three Schottky bypass diodes as depicted in Fig. 2b. The simulated solar cells are 19.3 % efficient at Standard Test Conditions (STC) with the 2-diode parameters given in [8]. The simulated maximum power of the modules at STC is 278.2 W. In addition to the forward characteristics, the 8 reverse I-V curves shown in Fig. 3a are combined with the same forward characteristics to obtain a complete description of the the electrical behavior of the solar cells. In this first analysis, the effect of irradiance and temperature on the reverse characteristics is neglected, hence coefficients k_1, k_2 and k_3 are assumed to be constants.

Simulation results are presented in Fig. 3b. It can be noticed that at module position 1, which is 40 % of the time partially shaded, the annual specific yield could be increased up to 74 %, if the cell had ideal reverse characteristics. Likewise, at the position of the least shaded module, the DC yield could be boosted by almost 4 %.

Although this work does not focus on the feasibility of manufacturing cells with low breakdown characteristics, it should be noticed that the cell with the lowest breakdown voltage in Fig. 1b is comparable to the cell with a breakdown

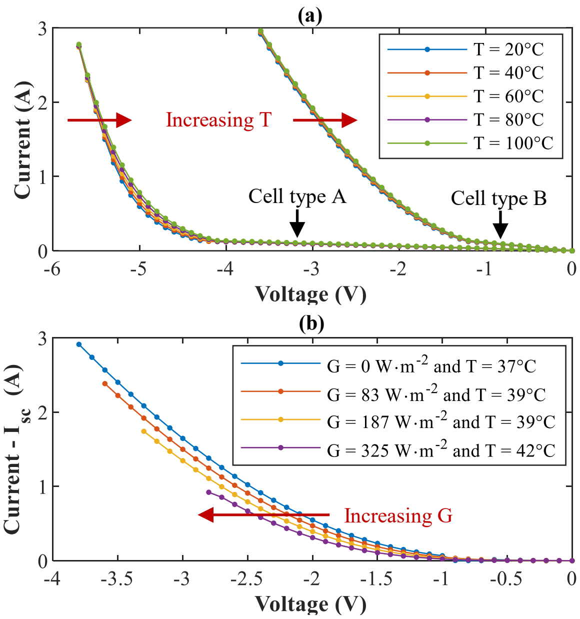

Fig. 4. Experimental measurements. (a) Dark I-V measurements of solar cell types A and B under reverse bias at different temperatures. (b) I-V measurements of cell type B under reverse bias at different illumination levels.

of $-2\,\mathrm{V}$ (at $2\,\mathrm{A}$) depicted in green in Fig. 3a. At rooftop position 1 (or 3), a PV module made with these cells can generate $1.1\,\%$ (or $10.1\,\%$) more energy than a cell with a very high breakdown voltage. Another way of interpreting this gain is as an effective $0.2\,\%$ (or $1.9\,\%$) absolute increase in the cell efficiency due to the low reverse characteristics. This type of analysis can be crucial for the optimization of solar cell designs. The design of a solar cell should not only aim at maximizing its conversion efficiency but it also taking into consideration the influence of the reverse characteristics on the annual yield of a PV module.

B. Characterization and Evaluation of Real IBC Solar Cells

For a more realistic evaluation of cells with low breakdown voltages, two different types of commercially available solar cells with low breakdown voltages (henceforth referred to as A and B) have been characterized under varying temperature and irradiance. In total 10 cells of each type were measured to confirm the uniformity of the reverse characteristics in each batch of cells.

The STC efficiencies of cell types A and B are $22.4\,\%$ and $24.8\,\%$, respectively. The parameters for the 2-diode electrical equivalent model for both cell types were fitted using dark I-V measurements under forward bias and the external parameters reported in the datasheets. Both cell types have the same I_{sc}, V_{oc} and P_{mpp} temperature coefficients.

Dark I-V measurements under reverse bias at different temperatures are presented in Fig. 4a. The breakdown voltages at $2\,\mathrm{A}$ and $25\,°\mathrm{C}$ are $-5.5\,\mathrm{V}$ and $-3.1\,\mathrm{V}$ for cells A and B, respectively. The temperature coefficient of the breakdown voltage is positive and as expected from previous studies [5]. On the other hand, the magnitude of the breakdown voltage

TABLE I
SIMULATION RESULTS WITH COMMERCIALLY AVAILABLE SOLAR CELLS

Module position on rooftop	1	2	3
DC Yield type A (kWh/yr)	155.4	305.3	421.1
DC Yield type B (kWh/yr)	180.6	349.3	479.1
Specific yield type A (Wh/Wp)	470.9	925.1	1275.9
Specific yield type B (Wh/Wp)	489.5	946.9	1298.7
Gain in DC yield (B to A)	16.2%	14.4%	13.8%
Gain in specific yield (B to A)	3.94%	2.35%	1.79%

increases with irradiance as shown in the measurements of cell type B in Fig. 4b. The effect of both irradiance and temperature on the reverse characteristics were included in the simulation by replacing the coefficients in 1 with polynomial functions of G and T.

Using the forward and reverse fittings, the annual yield was simulated for the same scenario presented in section III-A. Simulation results are summarized in Table I. The gains in specific yield reported in Table I are comparable to the results presented in Fig. 3 and can be mainly attributed to the lower irradiance mismatch losses in the PV module with cell B since both type of cells have the same temperature coefficients under forward bias. These results suggest that a reduction from $-5.5\,\mathrm{V}$ to $-3.1\,\mathrm{V}$ in the cell breakdown voltage can lead to a significant increase (about $1.8\,\%$) on the specific energy yield, even when the PV module is only $7\,\%$ of the time affected by partial shading.

IV. CONCLUSION

This study highlights the importance of the reverse characteristics of c-Si solar cells on the annual energy yield of a partially shaded PV module. The presented results suggest that the best performing cell in a partially shaded PV module is not necessarily the one with the highest efficiency. Breakdown characteristics are clearly relevant and should be assigned a higher weight in the optimization design of solar cells. This study has motivated us to manufacture full scale PV modules with low breakdown voltage solar cells which will be monitored outdoors to complete the validation of our findings.

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