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Experimental study of mismatch and shading effects in the *I–V* characteristic of a photovoltaic module

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Abstract

A conventional photovoltaic module has been prepared with the purpose of accessing its cells either individually or associated. Measurements of every cell and of the whole module have been performed in direct and reverse bias, with the objective of documenting the scattering in cell parameters, working point of the cells and shading effects. Several shading profiles have been tested, and the influence of the reverse characteristic of the shaded cell in module output is stressed.

Keywords: Characterisation; Shading; Hot-spot; PV modules

1. Introduction

When a module or a part of it is shaded some of its cells become reverse biased, acting as loads instead of generators. If the system is not appropriately protected, hot-spot problem can arise and, in severe cases, the system can be irreversibly damaged.

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Nowadays, there are newer cell designs, a growing increase in average cell size and modules that are specially manufactured for their integration into buildings where partial shading can be frequent. This tendency makes the study of partial shading of modules and cell reverse characteristics a key issue. In fact, hot-spot protection has been recently studied through international projects [1] and workshops [2]. Nevertheless, there is still a lack of information related to the behaviour of commercial photovoltaic (PV) cells operating in reverse bias and their effect in case of partial shading. Most of recent works are addressed to the evaluation of maximum temperatures and current distributions in cell surface [3–7] comparing it with the maximum admissible temperatures in common encapsulating systems. The objective is to prevent the shaded cell to reach the thermal breakdown, point in which it could be irreversibly damaged. The characterisation of reverse *I–V* curves is fundamental to extract conclusions in relation to that topic.

Besides, it has been pointed out that the classification of the different cell reverse characteristics is important to determine the worst case with respect to the hot-spot heating [6–8].

The objective of the work presented in this paper is in relation to the hot-spot researching that is being conducted in order to improve current standards, trying to give a experimental background based in real measurements with available commercial PV devices. With this purpose, a commercial PV module has been used as intermediate unit between the elementary solar cell and the PV system, as it permits to establish relations between cell studies and system effects. Several measurements of the *I–V* characteristic of the cells that form the module and of the whole module have been performed both in direct and reverse bias, and the effect of partially shading cells with different reverse characteristic has been examined. The evaluation of this last effect is important to supply information to technicians and programmers, since most commercial PV simulation programmes including shading effects usually do not approach to the cell level and, in case they do, rarely consider the great variability that can be found in reverse characteristics of similar cells [9,10].

Besides, to count on data from a PV module and its cells gives information about the scattering of commercial cells that supposedly have been classified before being inserted in the module, and makes it possible to evaluate the working point of each cell when the module is connected to a load.

2. Experimental details

A conventional PV module has been prepared with the purpose of accessing each one of the cells. The module initially counts on 33 m-Si cells, 100 cm^2 each one, serially connected. In order to measure each one of the cells either individually or associated, rear side tedlar has been cut on cell tabs, and cables have been soldered to an external plug. In this way it is possible to measure each cell or different series associations. Parallel associations are also allowed in 11 cell strings. The scheme of

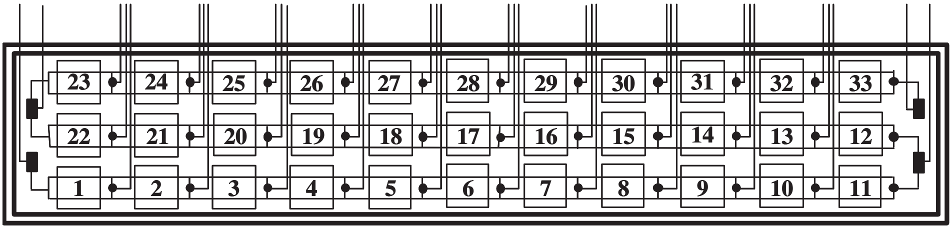

Fig. 1. Structure of the PV module prepared to access the cells either individually or associated in strings.

module connections is presented in Fig. 1, where each cell is identified with a number that indicates its position in the module.

The objectives pursued with this module configuration are the following:

- Characterisation of identically manufactured cells both in direct and reverse bias in darkness and under illumination. Study of the scattering in main cell parameters.
- Documentation of the working point of each cell when the module is connected to a load.
- Evaluation of shading effects on module *I–V* characteristic. Influence of reverse characteristic.

2.1. Measurement system

Several types of measurements have been performed with the test module using two different systems. For one part, the conventional system to measure *I–V* characteristics of PV cells or modules according to the standards [11,12] have been used in the measurement of cells and shading effects. It consists of Keithley multimeters to measure voltage, current and temperature, and a Kepco four quadrant electronic load. The whole is computer controlled via GPIB, with a software that allows the user to select the initial sweeping voltages and final currents, and the data point distribution in order to have enough points in the *I–V* curve areas of interest. A calibrated reference cell acts as irradiance sensor.

Besides, in order to deepen in the behaviour of cells when they are part of an association, a system has been prepared with the purpose of recording both cell parameters and module characteristic at the same time. A Fluke Data Logger with capacity to record up to 120 channels is connected to the terminals of each cell and to the electronic load, and cell voltages were registered at the same time than module data for every data point of the *I–V* characteristic. In this way we can obtain simultaneously the *I–V* characteristic of the 33 cells and of the module, and working point of each cell can be evaluated.

3. Results and analysis

3.1. Initial characterisation

As a previous characterisation, the I–V curve of the module was measured indoors and outdoors to determine module parameters. Temperature coefficients α and β were calculated. Main parameters are presented in Table 1.

3.2. Scattering of cell characteristics

I–V characteristic of each one of the 33 cells has been measured in direct and reverse bias. As reverse bias measurements can lead cells to high power dissipations which could damage them if concentrated in a small area, a first round of measurements was performed in dark conditions to extend measurement range as much as possible in order to detect the profile of each cell characteristic in reverse bias. Fig. 2a–b shows the dark I–V characteristic of each one of the 33 cells that form the module. The figure has been split into two parts in order to have sensitive scales for both forward and reverse characteristics.

First thing that can be observed in Fig. 2a–b is the high dispersion in the reverse characteristic of the cells (Fig. 2a), in comparison with closer similarities in the conventional (forward) curves (Fig. 2b). Reverse measurements present great variations, having cells with a very flat characteristic in the whole measurement negative range (type A or III in literature [11,13,14], voltage limited cells), cells with a high slope in reverse bias, that reach high currents at small negative voltages (type B or I [11,13,14]), or a combination of both, what is sometimes referenced as type II [14]. Cells in which elevated temperatures are produced by power dissipation in reverse bias are usually associated with small shunt resistance values, although in some cases high shunt resistances can produced a localised heating in a small point.

Characterisation under illumination has been performed outdoors in a cold, sunny day with stable meteorological conditions. The initial voltage in this case has been fixed to -15 V in order to avoid high power dissipation damaging the cells. With the same objective, maximum current has been limited to 6 A. The characteristics of all cells are presented in Fig. 3a–b.

Attending to the behaviour in reverse bias, it can be observed that the shape of cell characteristic is similar in darkness and illumination. Cells with high slope in reverse bias dark measurement present the same behaviour under illumination, and cells

Table 1
Main module parameters

	E (W/m^2)	T (°C)	I_{sc} (A)	V_{oc} (V)	P_{max} (W)	FF (%)
Indoors	1000	25	3.08	19.40	42.4	70.4
Outdoors	1000	30	2.97	19.09	39.5	69.7

Temperature coefficients: $\alpha = 0.00143$ A/°C, $\beta = -0.068$ V/°C

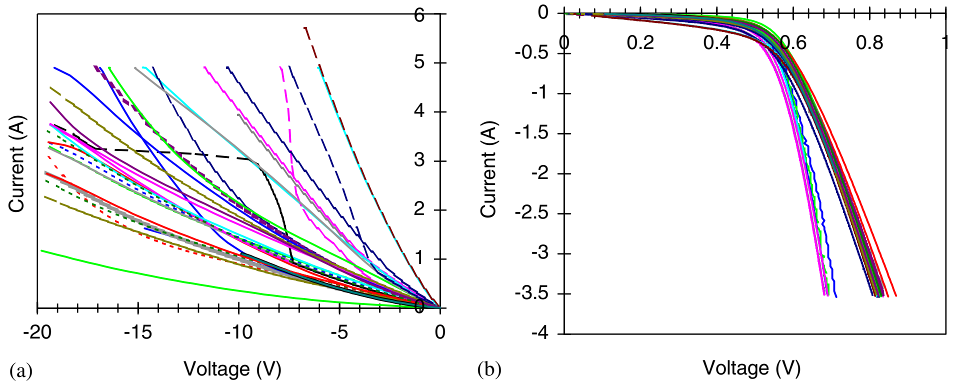

Fig. 2. a–b. I–V characteristic of each one of the 33 cells in the tested module measured in dark conditions in reverse bias (a) and direct bias (b). $T = 22\,^{\circ}\mathrm{C}$.

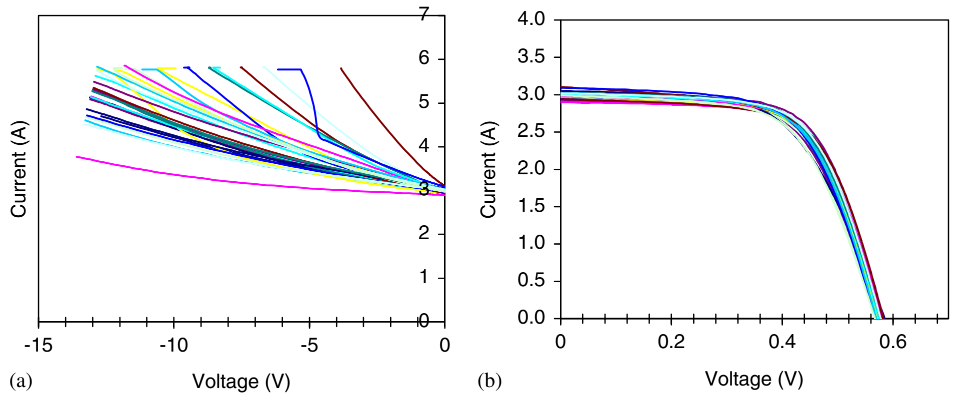

Fig. 3. a–b. I–V characteristic of each one of the 33 cells in the tested module measured under illumination in reverse bias (a) and direct bias (b). $E = 1000\,\mathrm{W/m^2}$, $T = 30\,^{\circ}\mathrm{C}$.

with a very flat shape in reverse bias behave in the same way in the illuminated curve. The reverse characteristic in dark conditions, easier to measure, can be therefore used as a diagnose of cell behaviour in case it is forced to work in the negative voltage quadrant.

With respect to the behaviour in direct bias, certain dispersion among main parameters is observed, although in a smaller range than in the reverse bias case. As a summary of the scattering of the characteristics, Table 2 presents the mean, standard deviation, maximum and minimum values of the main parameters of the curves presented in Fig. 3b. The measurement of the I–V characteristic of single cells and the complete module allows to calculate mismatch power losses among cells

Table 2
Mean, maximum, minimum and standard deviation values of the 33 cells of the test module

	I_{sc} (A)	V_{oc} (V)	P_{max} (W)	FF (%)
Mean value	2.997	0.5750	1.098	63.7
Standard deviation	0.044	0.0049	0.026	1.5
Maximum value	3.103	0.5848	1.154	66.3
Minimum value	2.897	0.5671	1.046	58.7

defined as

$$ML_{P_{\max}} = \left(1 - \frac{P_{\max(\text{module})}}{\sum P_{\max(\text{cell})}}\right)100, \tag{1}$$

where the numerator is the maximum power point of the PV module, and the denominator is the sum of the maximum power of the 33 cells. This expression renders a value of mismatch losses between cells and the module of 0.24%. Besides, internal wiring losses due to manufacturers cell interconnection is estimated in 0.08% (~36 mW) for the current in the maximum power point. Wiring losses due to the additional cabling to separate the three module strings and to measure the module is estimated in 1% (~400 mW), also for the current corresponding to module maximum power point (mpp).

3.3. Working point of the cells with the module in operation

The determination of the working point of each cell with the module in operation has been performed by the measurement of the *I–V* characteristic of the module, registering at the same time every cell voltage for a given current. Fig. 4a–c shows the voltage of every cell for a module operation point corresponding to short circuit, maximum power and open circuit. If the module would work in maximum power point there are not significant differences in the voltage of each cell, with a standard deviation of 0.01 V and a difference between the maximum and minimum values of 0.042 V. For worst case, that is the module working in short circuit conditions, the standard deviation increases to 0.31 V and the difference between extreme values is 1.76 V with one cell that clearly differs from the rest, working in a negative voltage of –1.5 V. It must be taken into account that the module is not submitted to any shading, and these differences are produced in identical cells classified during the manufacturing process.

3.4. Shading effects

The study of shading effects is important to foresee the working point of a system in case of shading. In our work, the advantage of counting on cells individually characterised in direct and reverse bias permits to establish relationships between the deformation of module characteristic and the type of curve of the shaded cell in

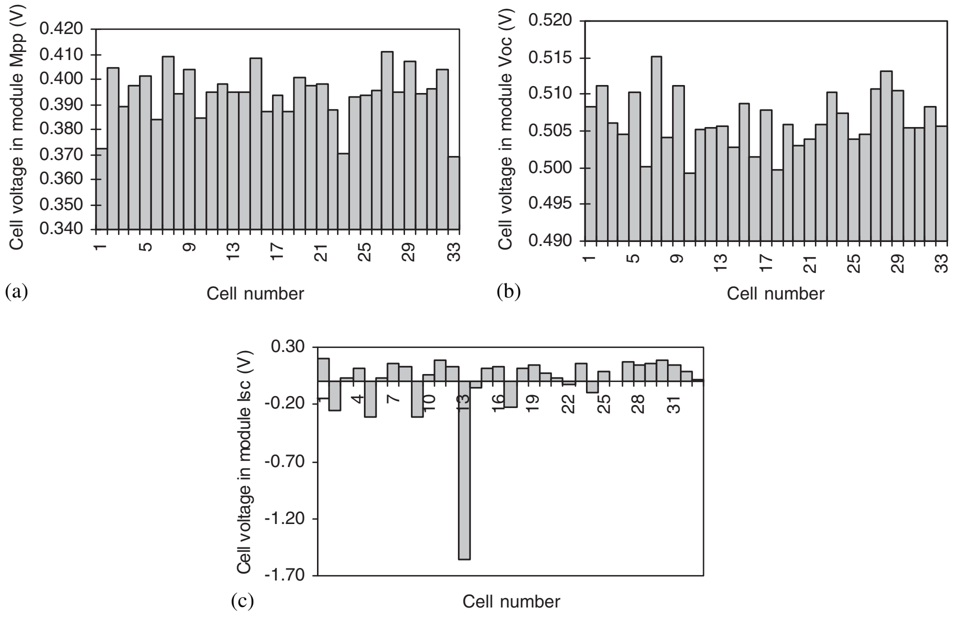

Fig. 4. Cell voltages for different module operation points.

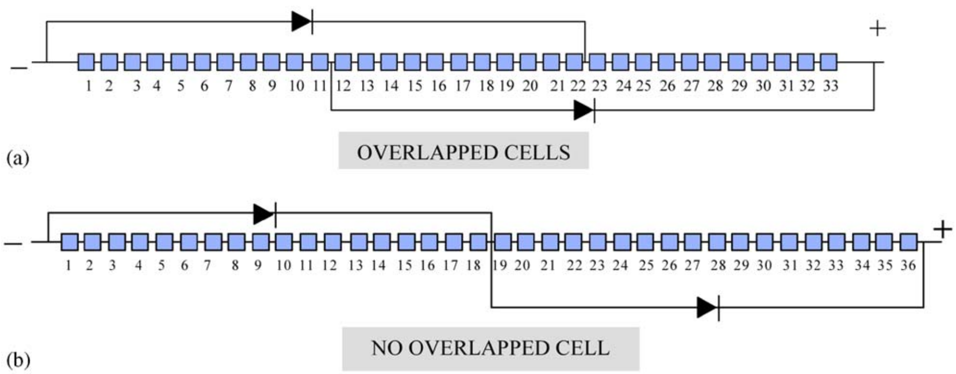

Fig. 5. Position of by-pass diodes in overlapped modules and non overlapped modules. (a) Position of by-pass diodes in the module under test. Cells 12th–22nd are in the overlapped protection area and (b) position of by-pass diodes in other kind of modules. Non overlapped cells.

reverse bias. The objective is to document situations that could be found in the real operation of the module, hence, by-pass diodes have been used. The connection of by-pass diodes has been performed according to the connection used by the manufacturer in this type of overlapped module. This kind of module use a by-pass diode across 22 cells in a recurrent position (see Fig. 5a) with a part of overlapped cells (12 through 22) that are protected by the two surrounding by-pass diodes.

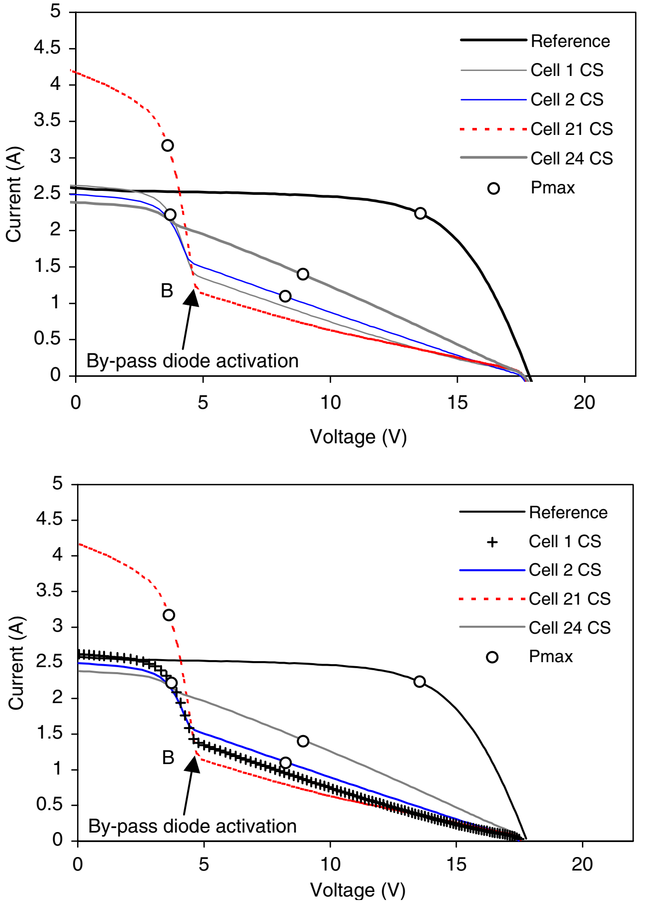

Fig. 6. Comparison of I–V characteristics of the test module in case of no shading or one cell (cell number 1, 2, 21 or 24) completely shaded (CS).

Very often, modules are manufactured without overlapped cells (see Fig. 5b) and the effect of shadowing is similar for all the non overlapped cells (like cells 1–11 or 23–33 in the test module). Especially, there is no increase of the short-circuit current, opposite to what occurs when an overlapped cell is shaded through a single short-circuited module.

Practically, the short-circuit current of a shaded module higher than the short circuit current of the module is uncommon, excepted for very small PV systems, that use only one module per branch (see Fig. 6 or 7, I_{sc} when cell 21 is shaded). Then, when two or more modules are serially connected, even if an overlapped cell is shaded in a module, the short circuit current of the branch remains limited under the I_{sc} value of the other modules.

In the experiments it has been stressed the influence of cell behaviour in reverse bias, the amount of shading and the number of shaded cells.

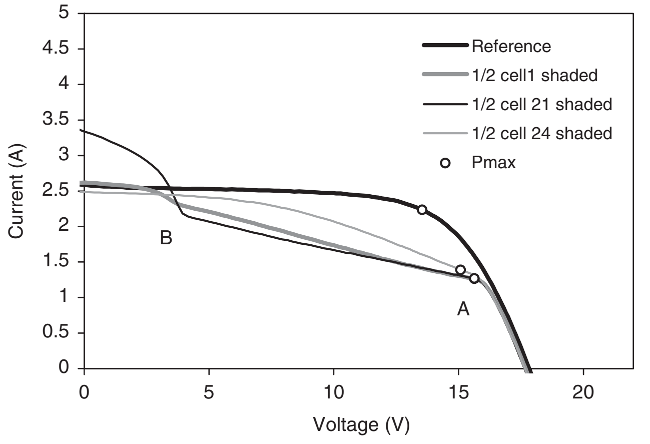

Fig. 7. *I–V* characteristic of test module when shading half of cells 1, 21 and 24, respectively.

Table 3
Leakage current measured at −10 V in the individual characterisation in dark conditions of the shaded cells in Fig. 6

Shaded cell number	*I* at −10 V (A)
1	1.01
2	1.45
21	0.92
24	2.15

3.4.1. Influence of cell type in reverse bias

The influence of cell type is referred to the shape of the characteristic of the shaded cell in reverse bias. Two cases have been analysed: influence of reverse characteristic with one cell completely shaded and with one cell partially shaded.

Fig. 6 shows several module characteristics in which one cell has been completely shaded. Table 3 presents the leakage current at –10 V of the cells that have been shaded in Fig. 6, what gives an idea of the shape of the shaded cell in reverse bias. This voltage has been chosen as it can be taken as a reference in case of hot-spot protection [4]. It can be observed that when the shaded cell shows a high slope in reverse bias (high current at –10 V in Table 3), the deformation of module *I–V* characteristic is smaller, varying its slope in the same way as reverse characteristic of shaded cell does until by-pass diode begins to work (point B in Fig. 6).

With respect to power losses and operating voltages and currents, Table 4 presents the maximum power point values and its correspondent voltages and currents, together with the losses in power for the cases presented in Fig. 6. It has to be noticed the different power losses, for the same amount of shading, depending only on the characteristics of the cell that is shaded, varying from 59% to 73%. Besides, the recurrent configuration of by-pass diodes in this type of modules considerably

Table 4
Maximum power point with its current and voltage for the characteristic presented in Fig. 6

Case	P_{max} (W)	V_{max} (V)	I_{max} (A)	ΔP (%)
Reference	30.3	13.5	2.24	—
Cell 1CS	12.5	8.9	1.40	−58.8
Cell 2 CS	9.0	8.2	1.10	−70.2
Cell 21 CS	11.5	3.6	3.17	−62.2
Cell 24 CS	8.2	3.7	2.22	−72.8

CS: completely shaded.

increases current when the shaded cell is positioned in the central row of the module, placing the values of maximum power point in an abnormally low voltage, high current area (see case of cell 21 completely shaded in Fig. 6).

Another outstanding feature is the displacement of maximum power point voltage to values considerably lower than the ones that would be expected for this type of modules (it changes from 14 to 9 or 4 V depending on which cell is shaded). This effect produced by the shading of a part of a system must be taken into account in the inverter selection in case of grid-connected systems with mpp tracking. In this type of systems, the reduction in voltage due to the shading can situate the voltage of mpp out of the permissible inverter values, what could cause erratic behaviour and increase losses due to the continuous searching of mpp [15].

The influence of the shape of the reverse characteristic with a cell partially shaded is shown in Fig. 7. Here, half of cells 1, 21 and 24 have been shaded in successive measurements. Two characteristic points are marked in Fig. 7, point A in which the effect of the shaded cell begins to be noticed in the module characteristic, and point B, in which by-pass diode begins to work. The change in curve profile is lower in this case, as the amount of shading is lower too. It can also be noticed that when the cell with the higher slope in reverse bias (cell 24) is shaded, the point in which by-pass diode is activated is not reached. Finally, when the shaded cell belongs to the central row of the module, an increase in current is produced as it happened in the former case presented.

3.4.2. *Influence of the amount of shading*

The influence of the amount of shading has been studied by shading different portions of one cell. Cells 1, 21 and 24 were selected, shading them either completely or only half of them. Results are presented in Fig. 8a–c, where it can be observed the effect of increasing the amount of shading in the same cell on the deformation of the *I–V* characteristic. Besides, the influence of reverse characteristics of shaded cells must be emphasised. As an example, a calculation of power losses of the curves presented in Fig. 8 has been performed supposing the system is connected to a 12 V battery. Table 5 presents the differences in power losses, including also the working current. It can be observed that power losses can change from 19% in the best case (cell number 24 half shaded), to 79% in the worst case (cell 21 completely shaded).

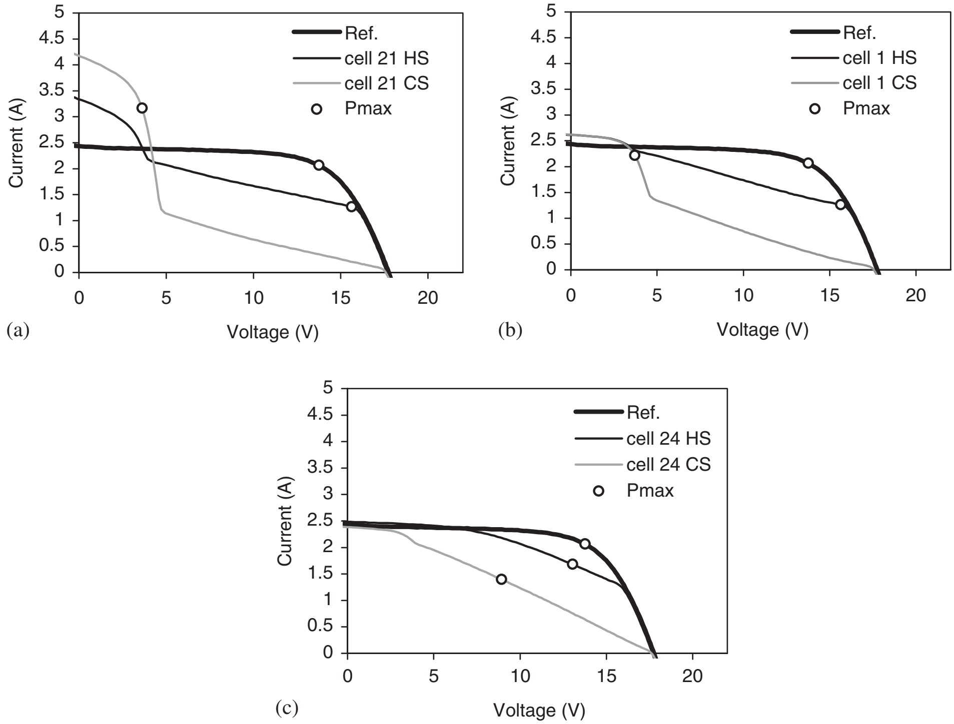

Fig. 8. a–c. *I–V* characteristics of test module with cells 21, 1 or 24 CS or half shaded (HS).

Table 5
Variations in power for a working point of 12 V when shading cells 21, 1 or 24 CS or only the HS

	No shading	Cell 21 HS	Cell 21 CS	Cell 1 HS	Cell 1 CS	Cell 24 HS	Cell 24 CS
I at $V = 12\,V$	2.25	1.52	0.47	1.54	0.51	1.82	0.92
ΔP (%)	0	−32%	−79%	−32%	−77%	−19%	−59%

4. Conclusions

The experiment here designed has permitted to document the spreading in the characteristic of cells that have been previously classified, and to show the working point of cells when they are a part of an association. Relations between the behaviour of cells when they are isolated or form part of a PV module, specially in case of partial shading, are established.

Large scattering has been found in the reverse characteristic of the 33 cells that are part of a conventional PV module, compared with the small dispersion in the direct bias range. This large variability has great influence in module output in case of partial shading, causing significant variations in module *I–V* characteristic and power losses depending on the shape of the reverse curve of the shaded cell. The importance of the characterisation of cells in reverse bias is outlined in order to foresee the behaviour of the module in case of partial shading.

For the same cell shaded, the deformation of the module *I–V* curve increases with the amount of shading, moving the maximum power point to lower voltage values.

In case of by-pass diodes placed in a recurrent position as the one presented, the shading of cells belonging to the overlapped section of the module produces a displacement of the maximum power point to an abnormally low voltage high current area.

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