

# Influence of the shadows in photovoltaic systems with different configurations of bypass diodes

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**Abstract**— The IU characteristic curve of a photovoltaic module is affected by shadows, depending on the shaded area of the PV module, and the radiation received by the shaded areas. Another factor in the shape of the I-V curve of a PV module, is the configuration of the electrical connection between its cells and bypass diodes. Bypass diodes are installed in the modules to prevent power consumption when they are shaded or damaged; they also prevent cells from working near the avalanche zone.

This paper examines the performance of a photovoltaic array. A PV array consists of modules connected between them. Particularly, the configuration with bypass diodes overlapped is analysed, showing that totally or partially shaded modules can consume some of the power generated by other modules of the PV array. This effect is also present in low power PV arrays. In these cases, the power dissipated by a diode is small; but if there are many diodes, the power dissipated by all the diodes can be comparable with the power produced by various PV modules. Additionally, this article deals with the influence of the inverter in the MPP tracking.

**Index Terms**— photovoltaic energy, bypass diode, shadows

## I. INTRODUCTION

One of the main causes of losses in energy generation within photovoltaic systems is the partial shading on photovoltaic (PV modules). These PV modules are composed of photovoltaic cells (PV cells) serial or parallel connected, with diodes included in different configurations. The curve of a PV cell varies depending on the radiation received [1][2] and its temperature. Furthermore, the modules have diodes that allow the current flows through an alternative path, when enough cells are shaded or damaged. There are two typical configurations of bypass diodes: [3] overlapped (Fig. 1a) and no-overlapped (Fig. 1b). It should be noted that the analysis in modules with overlapped diodes is a more complex one, because there may be different paths for current flow.

There exist many papers containing the analysis of the behaviour of the photovoltaic PV cells under partial shadowing [4][5][6], taking into account the diode. But there are only a few that actually take into account the importance of the diodes configuration [3]. This article studies the individual behaviour of a PV module and a photovoltaic array of PV modules (PV array) connected to an inverter with shadows in both cases.

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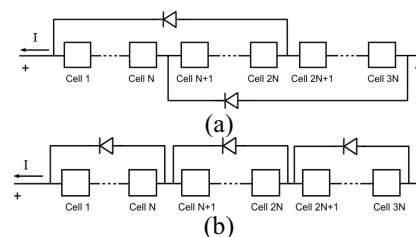


Fig. 1 Bypass diodes (a) overlapped (b) no-overlapped

## II. DEVELOPMENT

### A. Behaviour of a PV cell

So as to analyse the behaviour of a module partially shaded, it is necessary to know:

- the curve of the cells forward and reverse biased Fig. 2
- the curve of the cells in terms of radiation Fig. 3
- the curve of the bypass diodes

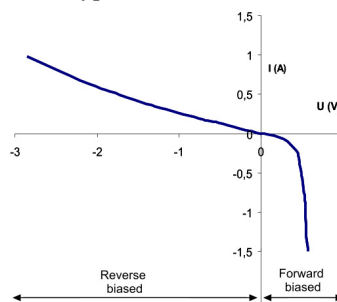


Fig. 2 Curves of a cell forward and reverse biased PV cell for 0 w/m<sup>2</sup>

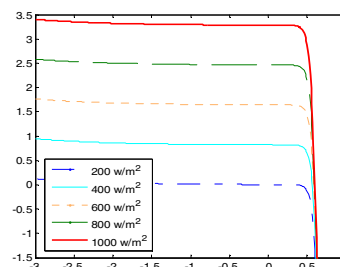


Fig. 3 Curves of a PV cell for different solar radiations

### B. Behaviour of a PV cell array

When shadows are casted over a PV module, the behaviour of a PV cell in its reverse zone (negative voltage) must be taken

into consideration, since the shaded PV cells can be reverse biased: Fig. 4a shows that for a current of 2A a sunny cell has a voltage of 0.55 V, whereas a shaded one has -5.5 V. If the bypass diode is in parallel with 12 PV cells serial-connected, one of them shaded, the group voltage will be 1.1 V (Fig. 4.b) and, therefore, the diode will not conduct because it's reverse biased. By contrast, for current values greater than 3A, the group voltage will be negative, and the currents will flow through the diode because it is forward biased.

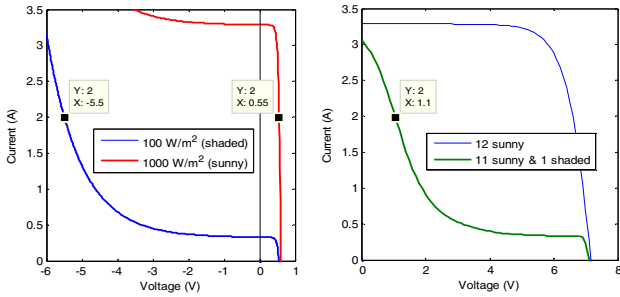


Fig. 4 Curves of individual sunny and shaded cells (a) and curves of 12 sunny ( $1000W/m^2$ ) serial cells and 11 sunny and 1 shaded ( $100W/m^2$ ) serial cells (b)

### C. Behaviour of a PV module

A PV module is made of PV cell arrays, with bypass diodes connected in parallel. The connection setup determines the I-V curve of the PV module when shadows are casted.

In the present paper, a PV module consists of 72 PV cells, distributed in 6 rows of 12 PV cells each row, with the configurations:

- 1) Overlapped bypass diodes
- 2) No-overlapped bypass diodes

#### 1) Overlapped bypass diodes

In the first analysed configuration, each module consists of 72 solar cells connected in overlapped bypass (Fig. 5).

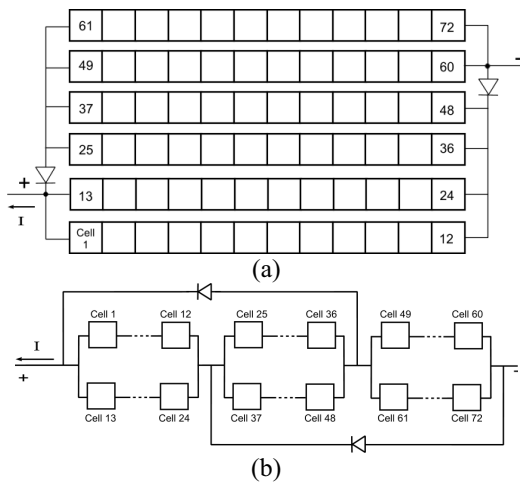


Fig. 5 Photovoltaic module (a) physical distribution (b) electrical scheme with overlapped diodes

I-V and P-V curves of the PV module for solar radiations of 1000 and  $100W/m^2$  are plotted in Fig. 6. When the PV module is shaded, its negative voltage in the working point can be 1/3

of its open-circuit voltage, and the power consumed can exceed 1/3 of the PV module peak power.

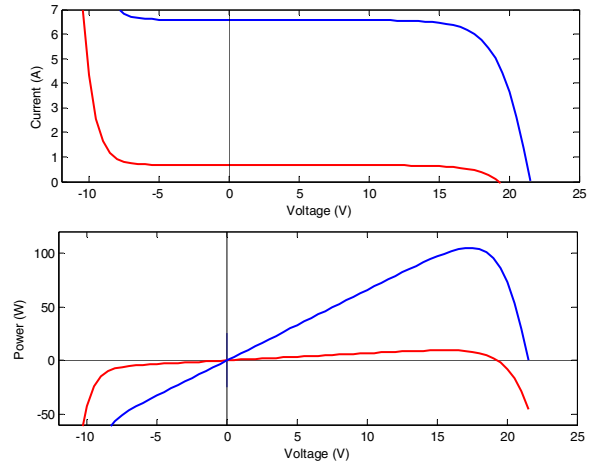


Fig. 6 I-V and P-V curves of a PV module with overlapped bypass diodes

In order to study the typical behaviour of the PV module, a simulation of progressive shading will be made from the bottom PV cell row to the top one. This is a practical approach, since at sunrises and sunsets can occur situations where the PV module has the same shading as the simulated ones. There are three possible paths for the most of electrical current (Fig. 7). The path depends on the diodes forward biased, and the diode biased depends on the PV cells shaded. When both diodes are forward biased, the modules of the two central series are the responsible for a notable power draining. Each of these paths is a point of the I-V and P-V curves (Fig. 8).

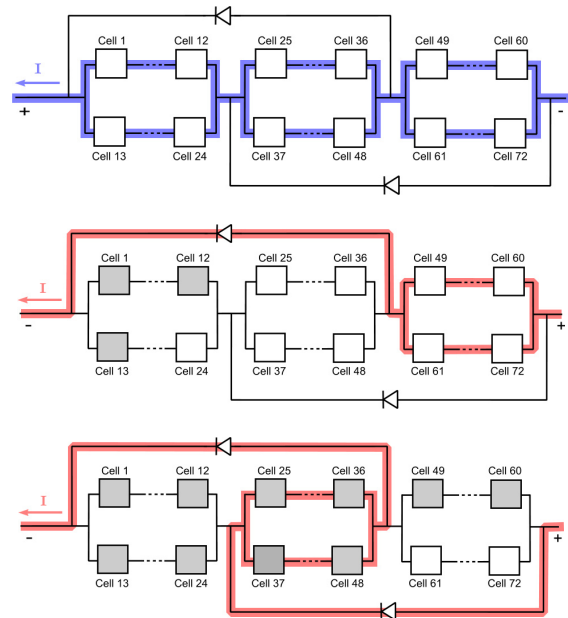


Fig. 7 Electrical current in PV modules with overlapped bypass diodes

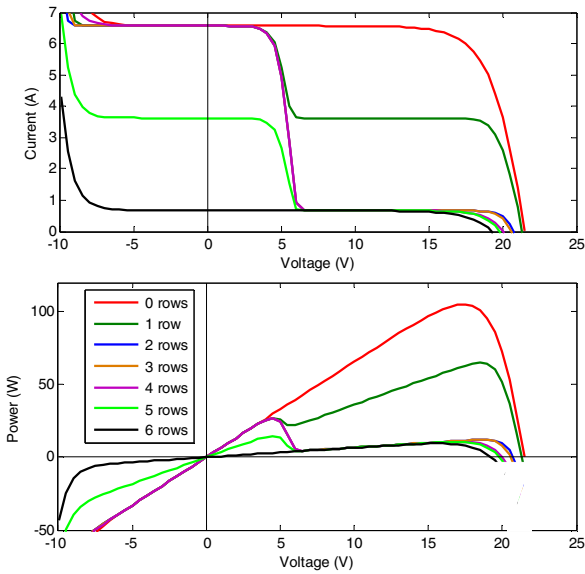


Fig. 8 I-V and P-V curves of a PV module with overlapped bypass diodes progressively shaded

## 2) No-overlapped bypass diodes

In the second analysed configuration, the PV module has no-overlapped bypass diodes, but it has the same physical distribution of the PV cells. In this case, the electrical circuit consists of 3 series, each with 24 PV cells. Every series have a bypass diode (Fig. 9). On account of this configuration, the I-V curve of the PV array has double the open-circuit voltage and half short-circuit current of a PV module with overlapped diodes with the same peak power.

In addition, when the PV module is reverse biased, its voltage and its power consumption are less than the previous case. However, when the power generated is low, this consumption may be appreciable due to the power consumption of the forward biased diodes (3.9 watts/diode).

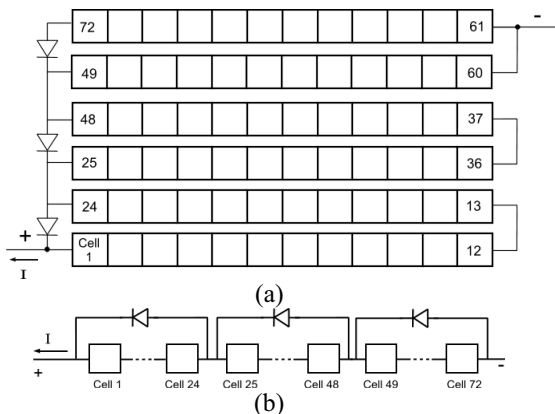


Fig. 9 PV module with non-overlapped bypass diodes (a) physical distribution (b) electrical scheme

In this instance, the number of possible current flow paths is higher (Fig. 10) but the number of I-V and P-V curves is lower (Fig. 11).

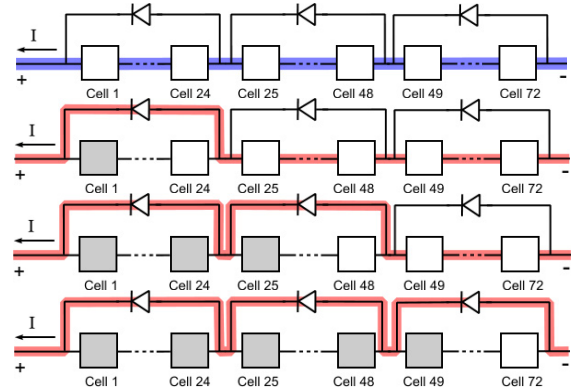


Fig. 10 Current flow in PV modules with no-overlapped bypass diodes

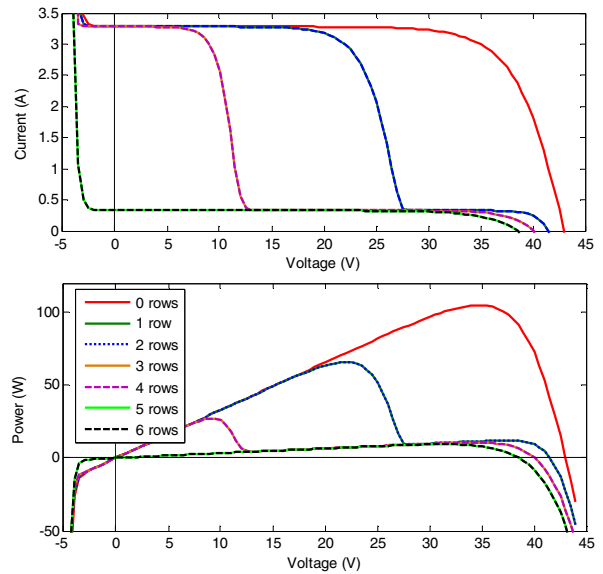


Fig. 11 I-V and P-V curves of a PV module with no-overlapped bypass diodes progressively shaded

## D. Behaviour of an PV array

In a not shaded PV array, with no deteriorated PV modules, all the PV modules have the same MPP. But when some PV modules are totally or partially shaded, the I-V curve of PV array changes, hence, the MPP of each PV module can be different. This would produce energy losses. The energy loss caused by shadows on the PV modules is not proportional to the area of the shadow, it may be much higher. The losses in a PV array will depend basically on:

- the configuration of the bypass diodes
- the inverter voltage limits in the dc side
- the layout of the modules
- the electrical configuration

The analysis will consider a PV array consisting of 20 PV modules with its 11 inferior rows shaded (Fig. 12). The sunny cells are irradiated by  $1000 \text{ w/m}^2$  and the shaded ones by  $100 \text{ w/m}^2$  (Fig. 13).

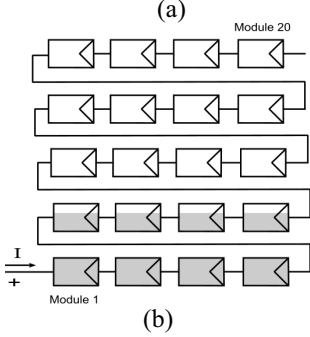


Fig. 12 PV array (a) photo (b) electrical scheme

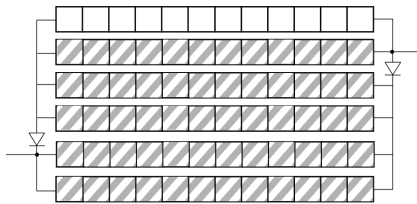


Fig. 13 PV module partially shaded

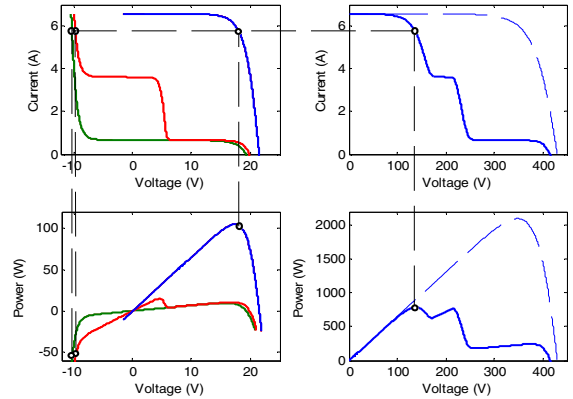
Three PV array Configurations are studied:

- Configuration A: 20 serial-connected PV modules with overlapped diodes
- Configuration B: 20 serial-connected PV modules with no-overlapped diodes
- Configuration C: 2 parallel connected series of 10 PV modules with no-overlapped diodes

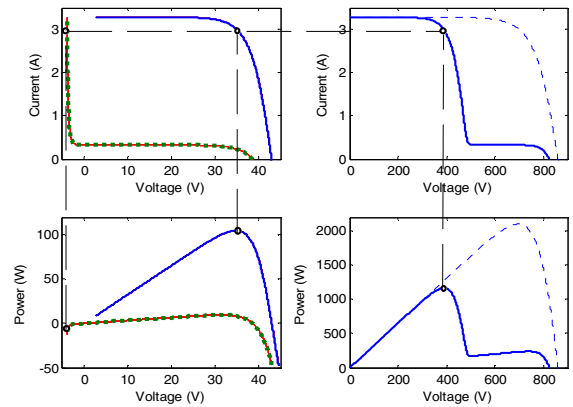
The calculus of the power produced by each PV module from the working point of the PV array is represented in Fig. 14. The curves in the right column are the I-V and P-V curves of the PV array: the dashed line is the curve for a no shaded PV array, whereas the solid one is the curve for the current example. The curves in the left are the curves of their PV modules: the blue one is for no shaded PV module, the red one is for partially shaded PV module, and the green one (dotted or solid) is for a totally shaded PV module. The results are detailed in TABLE I, where a negative value of power (P) represents power consumption.

TABLE I Power of the working points of the PV arrays and PV modules

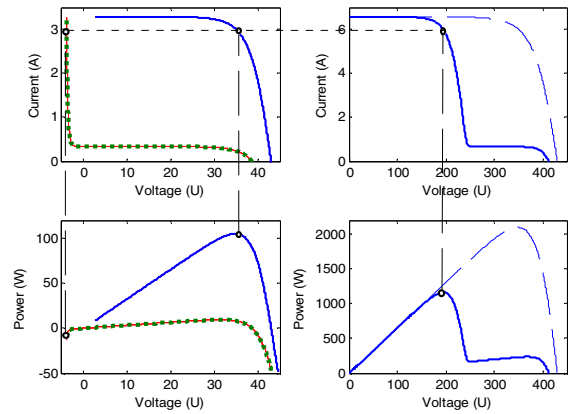
| PV ARRAY      |      | PV MODULES |       |                  |        |                |        |
|---------------|------|------------|-------|------------------|--------|----------------|--------|
| Configuration | P(w) | No Shaded  |       | Partially Shaded |        | Totally Shaded |        |
|               |      | $n^o$      | P(w)  | $n^o$            | P(w)   | $n^o$          | P(w)   |
|               |      | A          | 784.9 | 12               | 103.7  | 4              | -58.5  |
| B             | 1164 | 12         | 104.9 | 4                | -11.82 | 4              | -11.82 |
| C             | 1164 | 12         | 104.9 | 4                | -11.80 | 4              | -11.80 |



Configuration A



Configuration B



Configuration C

Fig. 14 PV and I-V curves of PV modules (left column) and PV arrays (right column)

A similar simulation to that of the previous section has been done, with the aim of analysing the behaviour of PV arrays at sunrise and sunset. The Fig. 15 shows the I-V and P-V curves of the PV array for complete rows of PV cells shaded. The layout of the PV modules has 30 rows of PV cells. Consequently, 31 cases will be calculated:

- Case 0: no shaded cells
- Case 1: the first row of cells are shaded
- Case 2: the first and second row of cells are shaded
- ...
- Case 29: all the rows are shaded except the top one
- Case 30: all the rows are shaded

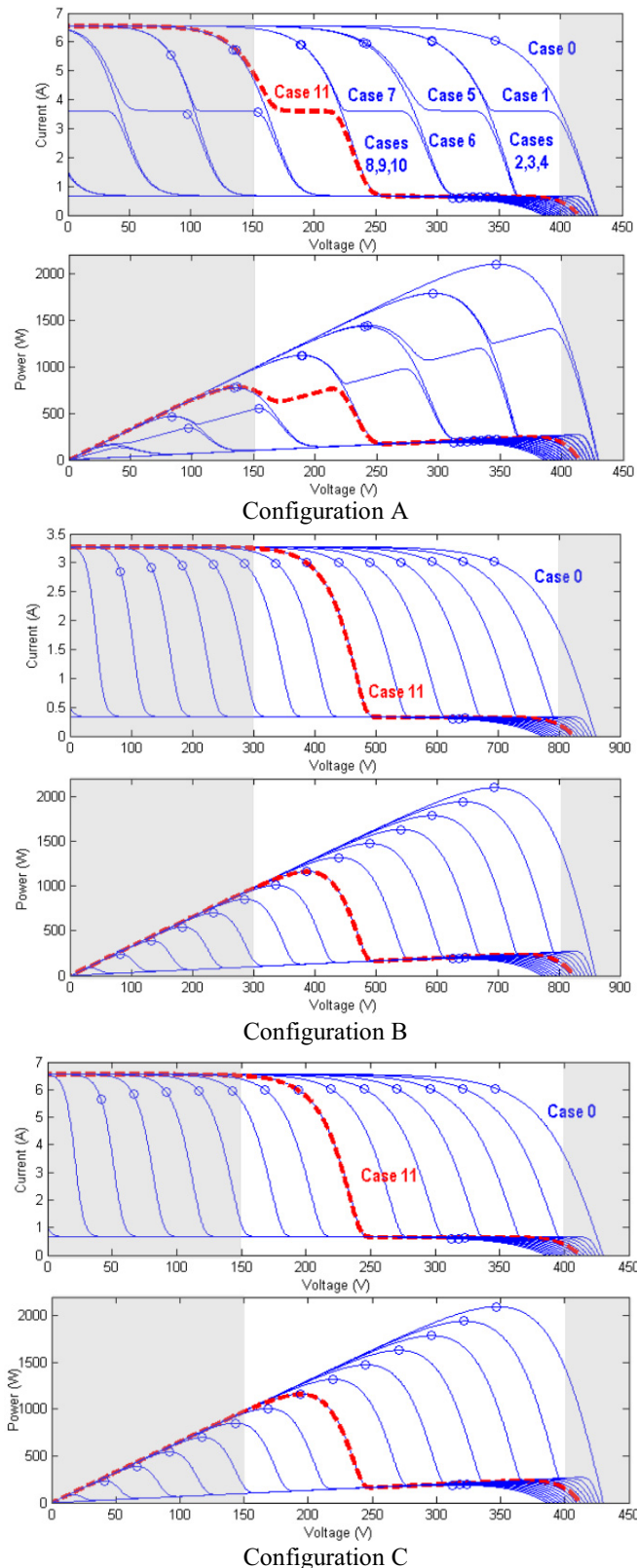


Fig. 15 I-V and P-V curves of PV arrays progressively shaded

Each case is represented by a curve; it seems there are fewer curves than there are number of cases. This is because some of the curves are too close and they can't be clearly distinguished. The highlighted curves represent the case of the

Fig. 12, where the first eleven rows at the bottom of the installation are shaded (Case 11).

The grey zones represent where selected inverters can't work, so, if the MPP is in this zone, the inverter can't achieve it. The selected inverters have a voltage range of work from 150 V to 400 V for Configuration A and Configuration C; 300 V to 800 V for Config. C. The circles represent the MPP (Maximum Power Point) for each case.

### E. Limits of inverter

An inverter that is connected to the PV array can't always achieve the MPP because of his voltage range of work and the tracking MPP algorithm. In Fig. 16, where the P-V curve of Case 17 is represented, there are four types of points where the inverter could think that there it is the MPP. The inverter can only work in three of them. The absolute maximum is out of its working voltage range.

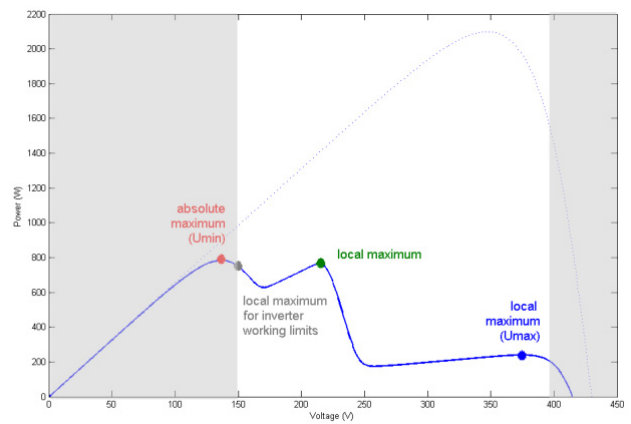
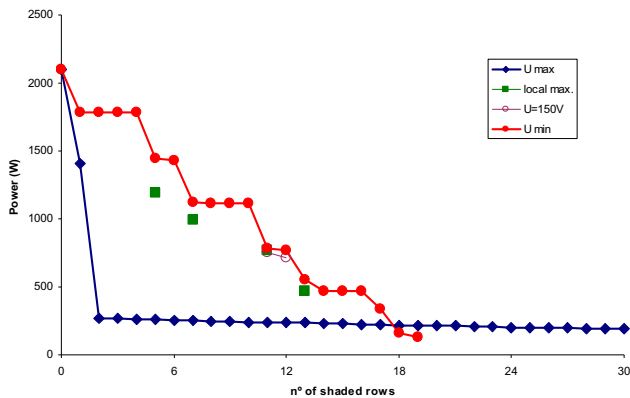


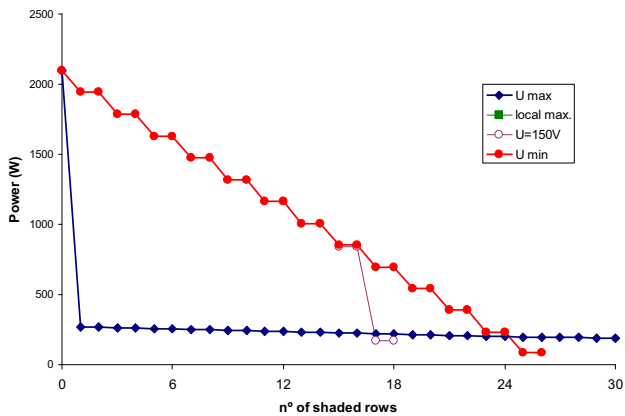
Fig. 16 Maximum and local power points of a P-V curve.

Fig. 17 shows the different types of MPPs against the number of inferior rows shaded in the PV array for the different configurations. On examination, in configuration A, the power losses can reach 40%, while in configuration B and C the losses are 20%. Also, the same power is generated if 12 rows are shaded in configuration A, 20 rows in configuration B and 16 in C. In other words, the PV arrays with bypass diodes (Config. A) are more susceptible to lose power due to the shading of their PV modules.

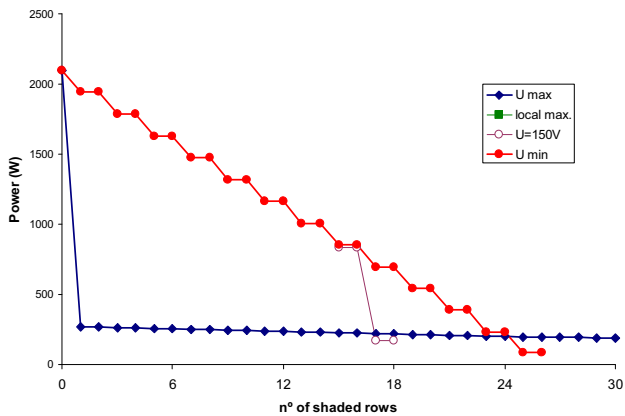
Fig. 18 shows the absolute MPP achieved in the three PV array configurations. The similarity of configuration B and configuration C is apparent.



Configuration A



Configuration B



CONFIGURATION C

Fig. 17 MPPs of the PV arrays in function of the number of bottom rows shaded

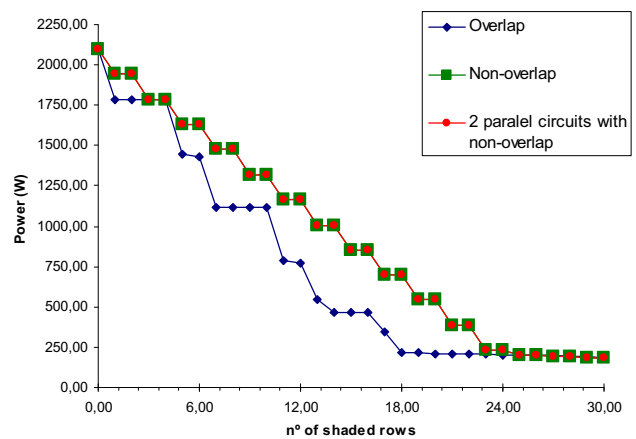


Fig. 18 Maximum MPPs of the PV arrays in function of the bottom rows shaded

### III. CONCLUSIONS

A study of the behaviour of isolated PV modules and PV arrays with different configurations of their bypass diodes has been carried out. It has been proved that losses produced by shadows are dependent of the bypass diodes configuration of the PV modules.

The power losses in PV modules with overlapped diodes can be of one third of its peak power, because besides the bypass diodes, one third of its PV cells can also consume power. In the PV modules with no-overlapped bypass diodes, the power losses are only produced by the power consumption of the diodes; anyway, it would only be noticeable if there were too many bypass diodes and shadowed PV modules.

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